10th ASRC International Workshop “Nuclear Fission and Decay of Exotic Nuclei”
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A fully microscopic study of multinucleon transfer processes in $^{136}Xe+^{198}Pt$: An application of the time-dependent Hartree-Fock theory

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INTRODUCTION: Interests for multinucleon transfer reactions

✔ As an interesting quantum dynamics — *Fundamental interest*

➢ **Multinucleon transfer reaction =** A non-equilibrium quantum transport phenomenon

Static properties

Nuclear shell structure and binding energies, shapes, N/Z ratios, ...

Dynamical effects

Quantum tunneling, neck formation, matching of Q-values and momenta, ...

✔ Both static properties and time-dependent dynamics are related to its reaction mechanisms

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✔ As a mean to produce unstable nuclei — *Experimental interest*

➢ **KISS project (2010-2015)** (KISS: KEK Isotope Separation System)

cf. S.C. Jeong et al., KEK Report **2010-2** (2010)

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Aim: To measure lifetime of neutron-rich unstable nuclei with A~200 along the neutron magic number N=126

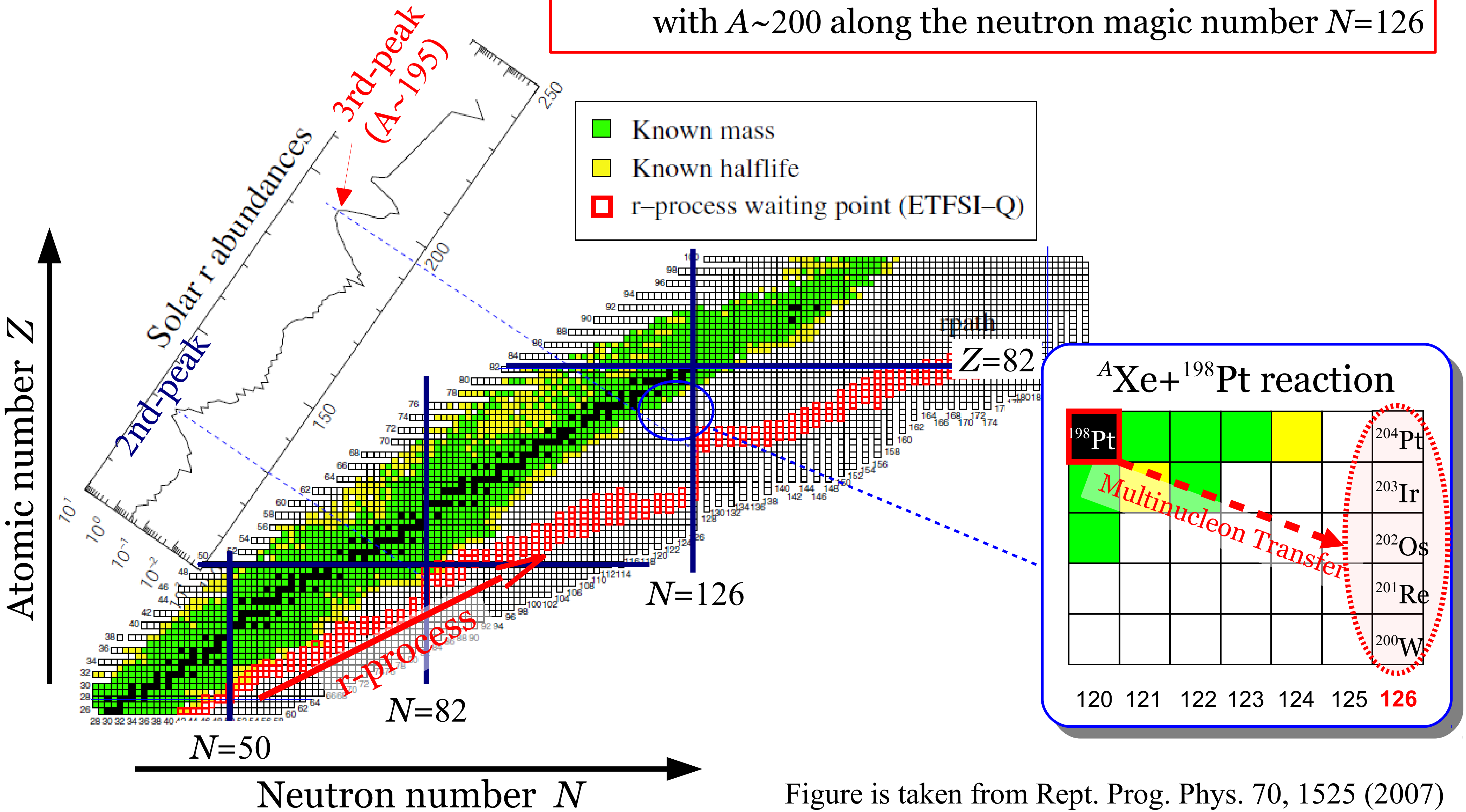

Figure is taken from Rept. Prog. Phys. 70, 1525 (2007)

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➢ **It is highly desired to develop a fully microscopic description with minimum assumptions on the dynamics**

Outline

1. Introduction

2. TDHF calculations for multinucleon transfer processes in ^{40}Ca+^{124}Sn reaction

3. A systematic TDHF calculation of ^{136}Xe+^{198}Pt reaction

4. Summary and Perspective

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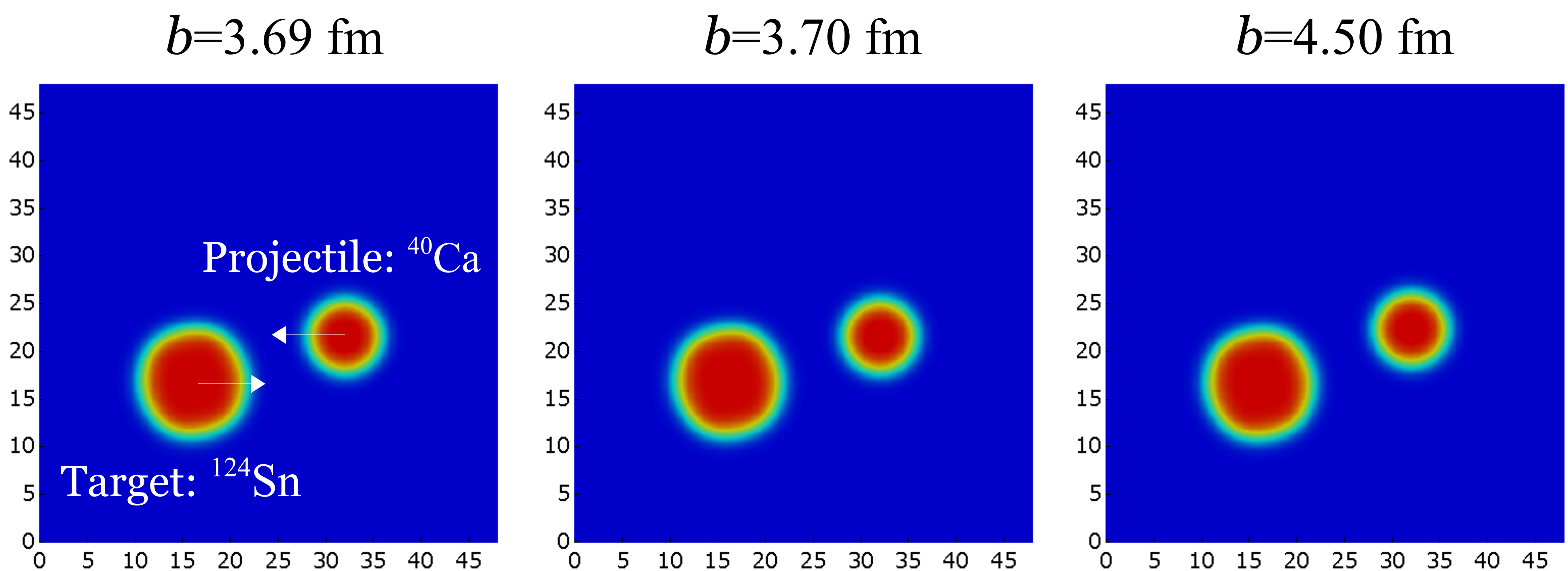
Results of the TDHF calculation: ^{40}Ca+^{124}Sn *at* E_{lab}=170 MeV

K. Sekizawa and K. Yabana, arXiv:1303.0552 [nucl-th]

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* ≦ 3.69 fm), Binary reactions (*b* ≧ 3.70 fm)

Density evolution obtained from the TDHF calculation



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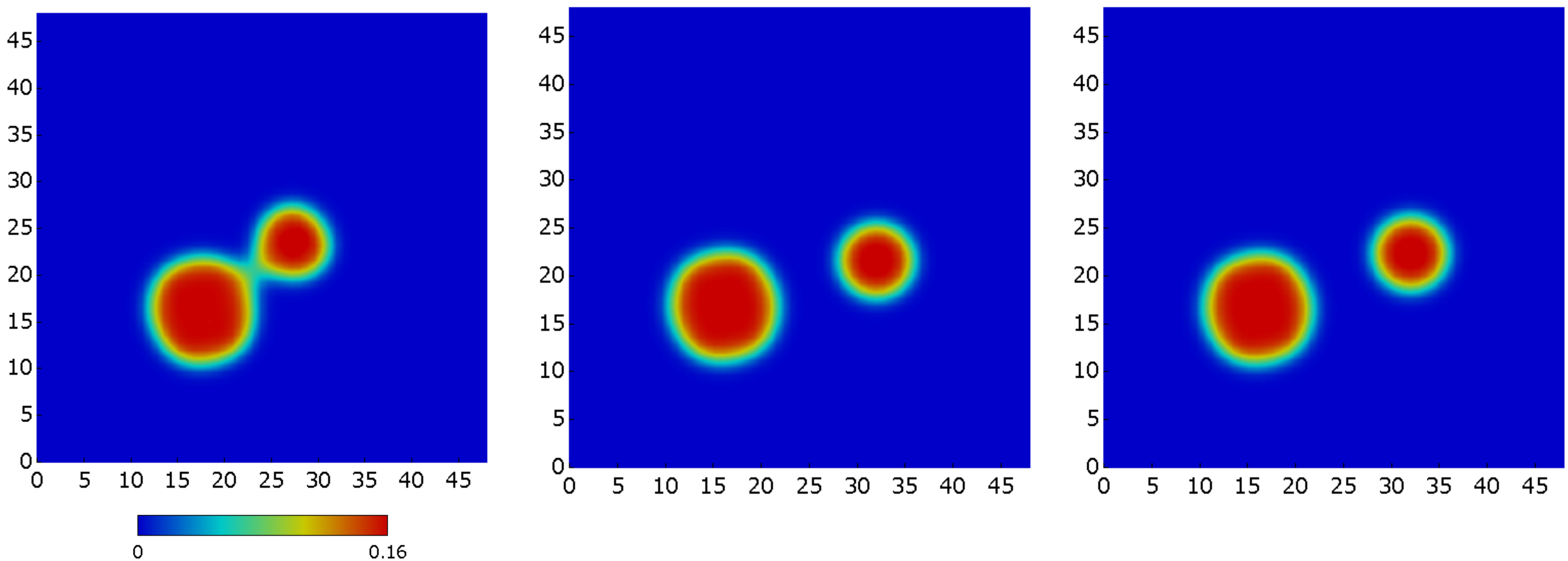
b=3.69 fm | *b*=3.70 fm | *b*=4.50 fm



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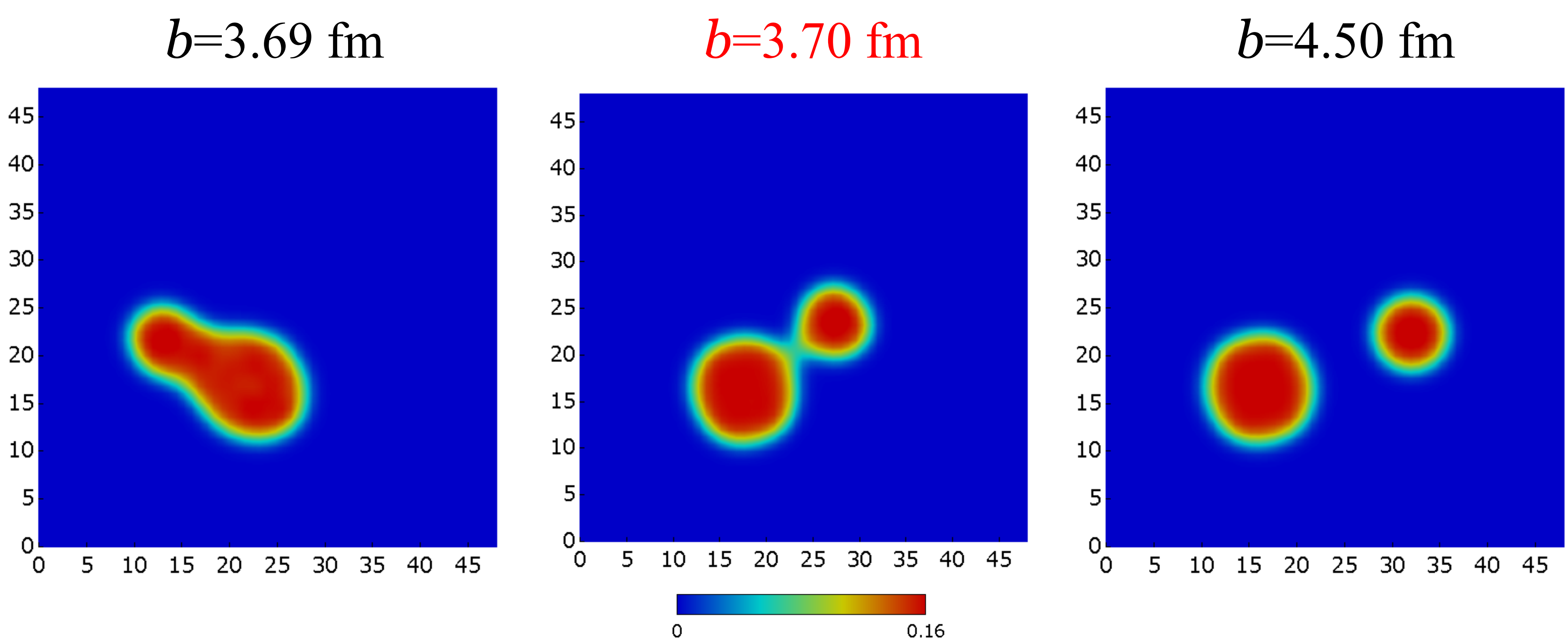

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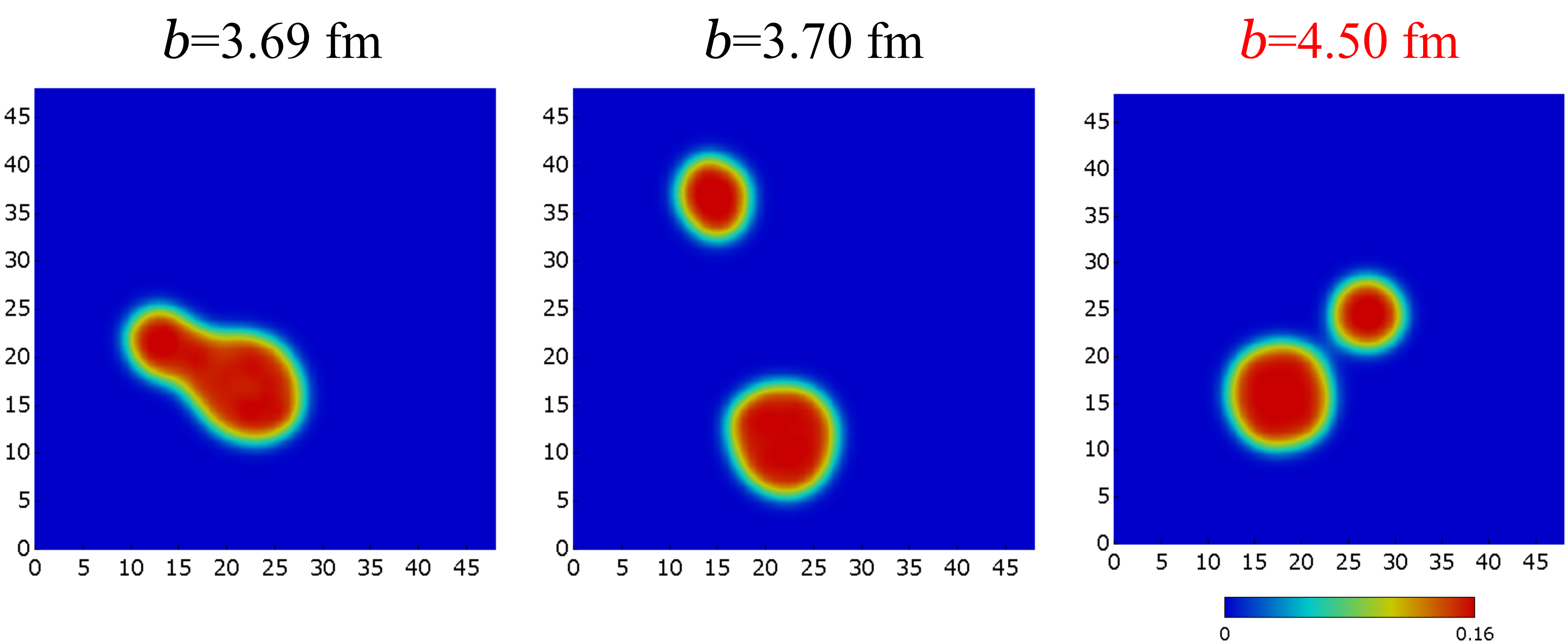

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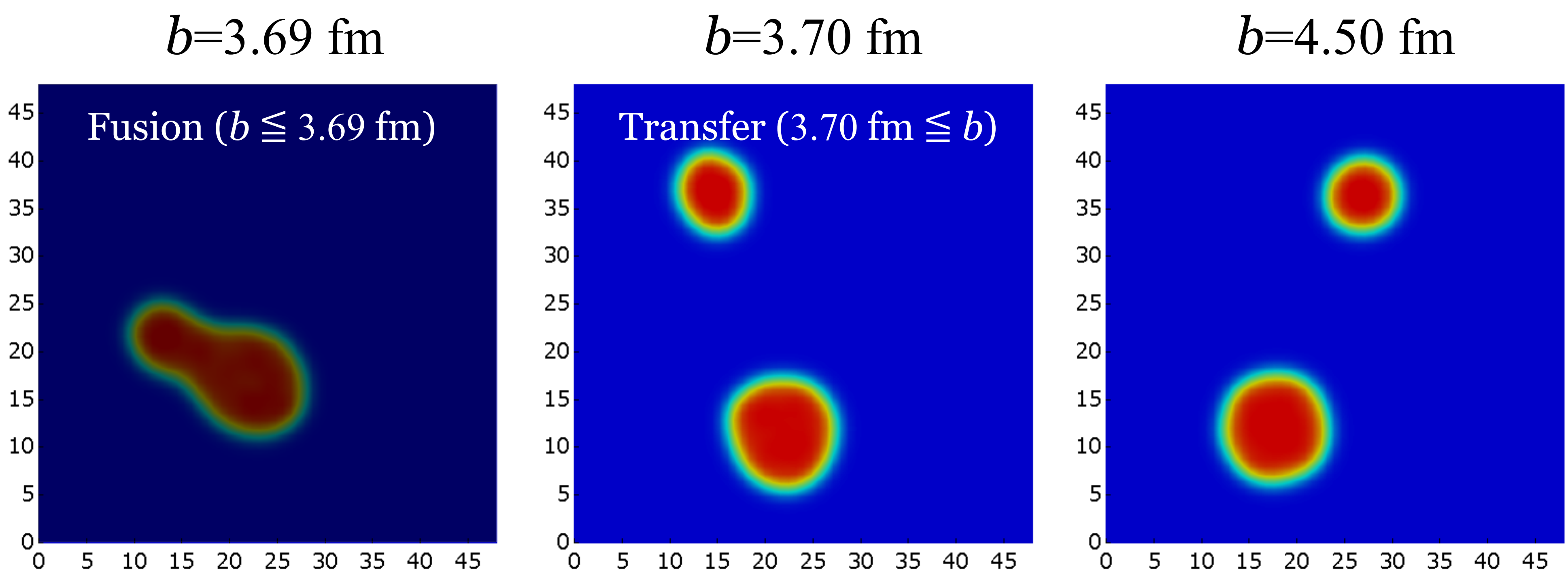


Particle number projection method

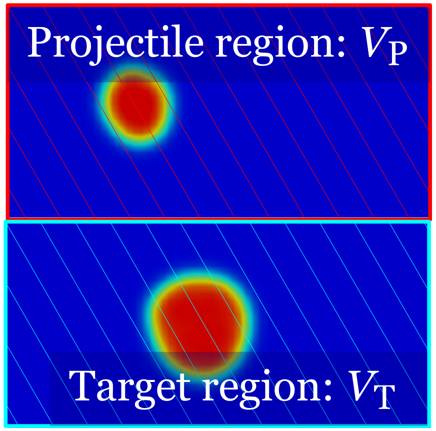
C. Simenel, Phys. Rev. Lett. **105**, 192701 (2010)

✔ Particle number projection operator

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

$\hat{N}_{\rm P}$: Number operator of the spatial region $V_{\rm P}$

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



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

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

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

Slater determinant

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

Single-particle w.f.

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

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

Overlap integral in respective regions

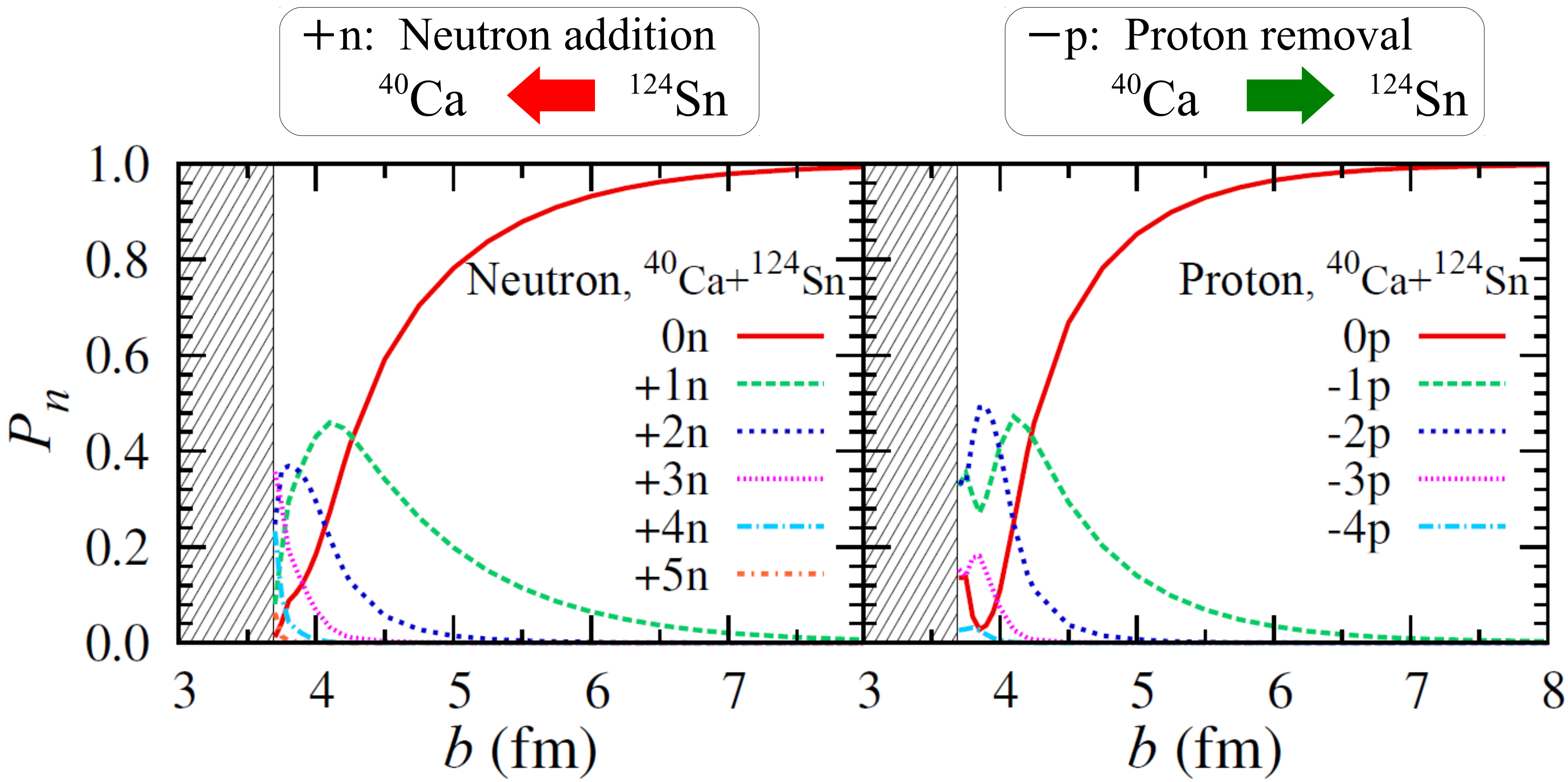
$$\langle\phi_i|\phi_j\rangle_\tau = \int_\tau d^3x\, \phi_i^*(\boldsymbol{x})\phi_j(\boldsymbol{x})$$

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

K. Sekizawa and K. Yabana, arXiv:1303.0552 [nucl-th]

Transfer probabilities

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



✔ Nucleons are transferred towards the directions of the charge equilibrium.

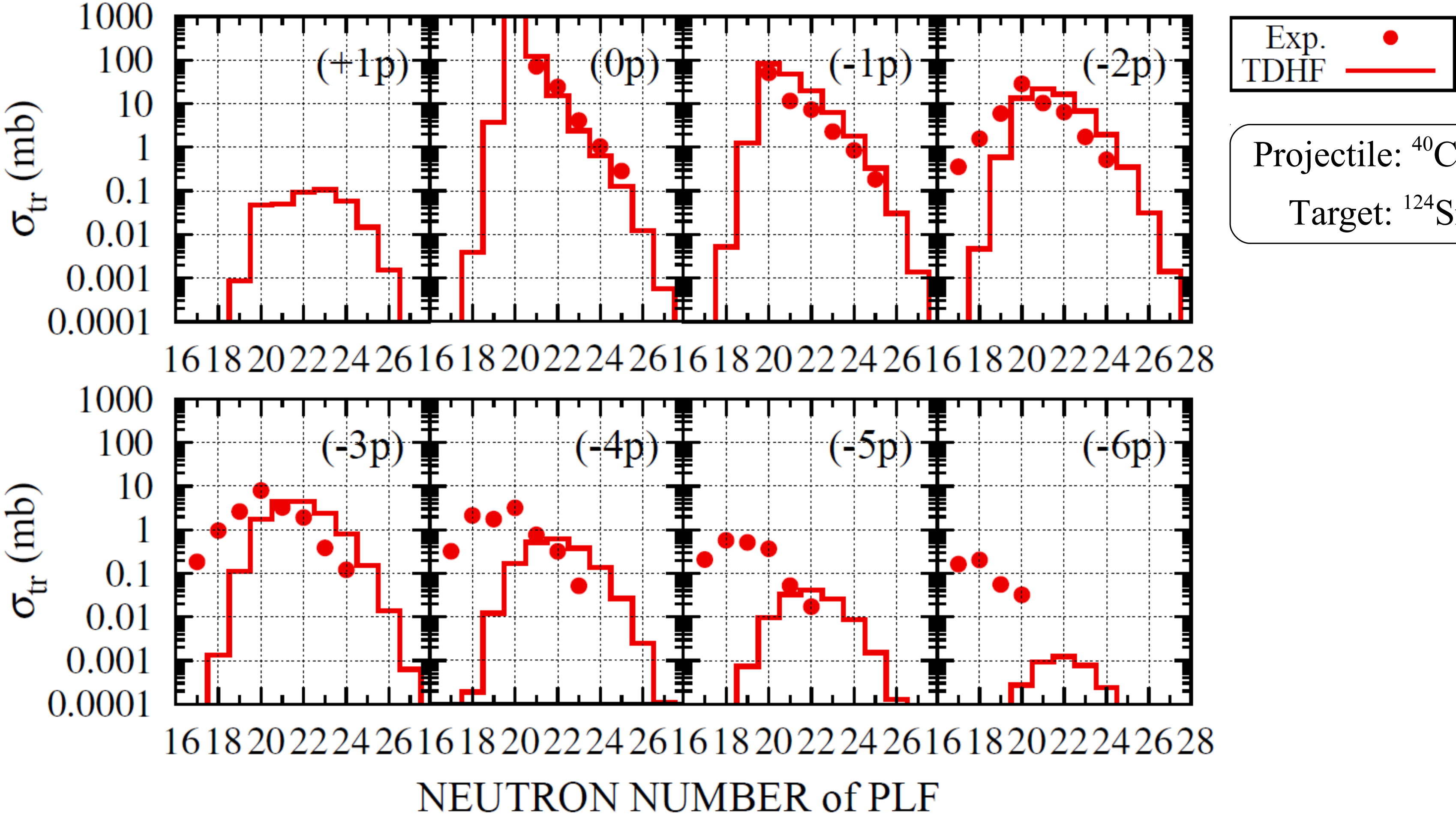
✔ Transfer probabilities of several nucleons become sizable just outside the fusion region.

K. Sekizawa and K. Yabana, arXiv:1303.0552 [nucl-th]

Transfer cross sections

- Transfer cross section: $\sigma_{tr}(Z,N) = 2\pi \int_{b_{min}}^{\infty} b\, P_Z^{(p)}(b) P_N^{(n)}(b)\, db$
- Exp.: L. Corradi *et al.*, Phys. Rev. C **54**, 201 (1996)

- Horizontal axis: Number of neutrons of lighter (^{40}Ca-like) fragment
- Labels "(*x*p)", *x*=+1, ...,-6: Number of protons added to (+)/removed from (-) ^{40}Ca



Projectile: ^{40}Ca (Z=20, N=20)
Target: ^{124}Sn (Z=50, N=74)

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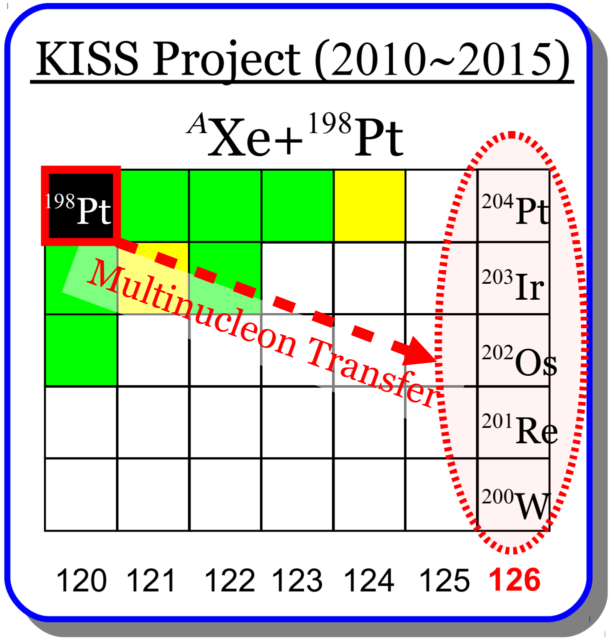
Key points

Aim of the calculation

✔ To predict a preferable condition to produce neutron-rich unstable nuclei with A~200 along the N=126 line



What we have done

✔ TDHF calculations for ^{136}Xe+^{198}Pt reaction at various impact parameters and incident energies

5, 6, 7, 8, 9, and 10 MeV/A (680, 816, 952, 1088, 1224, and 1360 MeV, respectively)

b = 0, 1, 2, ..., 12 fm

3D-grid: 70×70×30 (56 fm×56 fm×26 fm), Mesh size: 0.8 fm

Skyrme force: SLy5, Δt: 0.2 fm/c, Initial separation distance: 25 fm

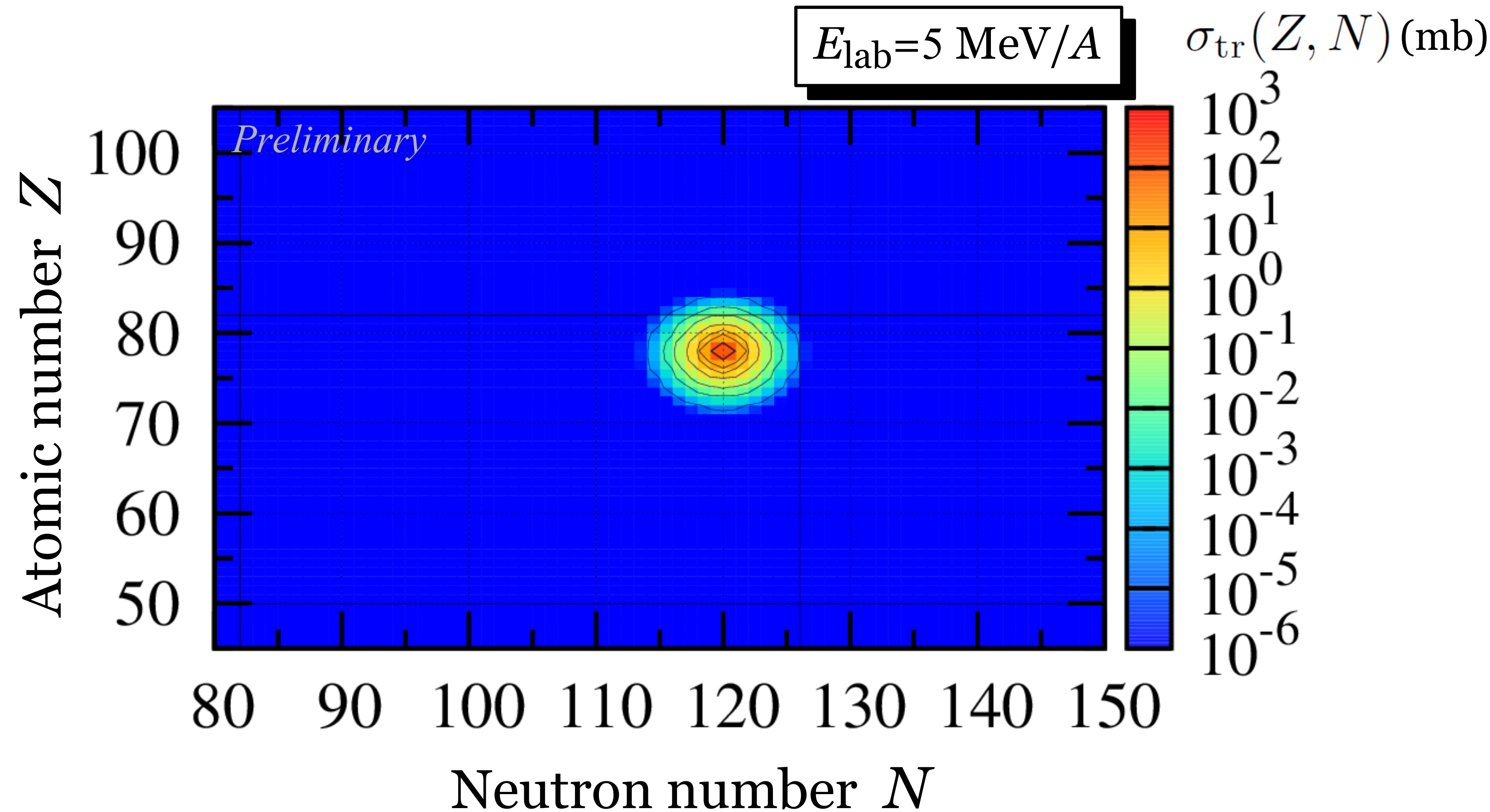
Results of the TDHF calculation: ^{136}Xe+^{198}Pt *reaction*

Primary production cross sections of heavier (^{198}Pt-like) fragment

※ Note: We have not yet taken into account the particle evaporation effect.

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

^{136}Xe (Z=54, N= 82, N/Z~1.52)
^{198}Pt (Z=78, N=120, N/Z~1.54)



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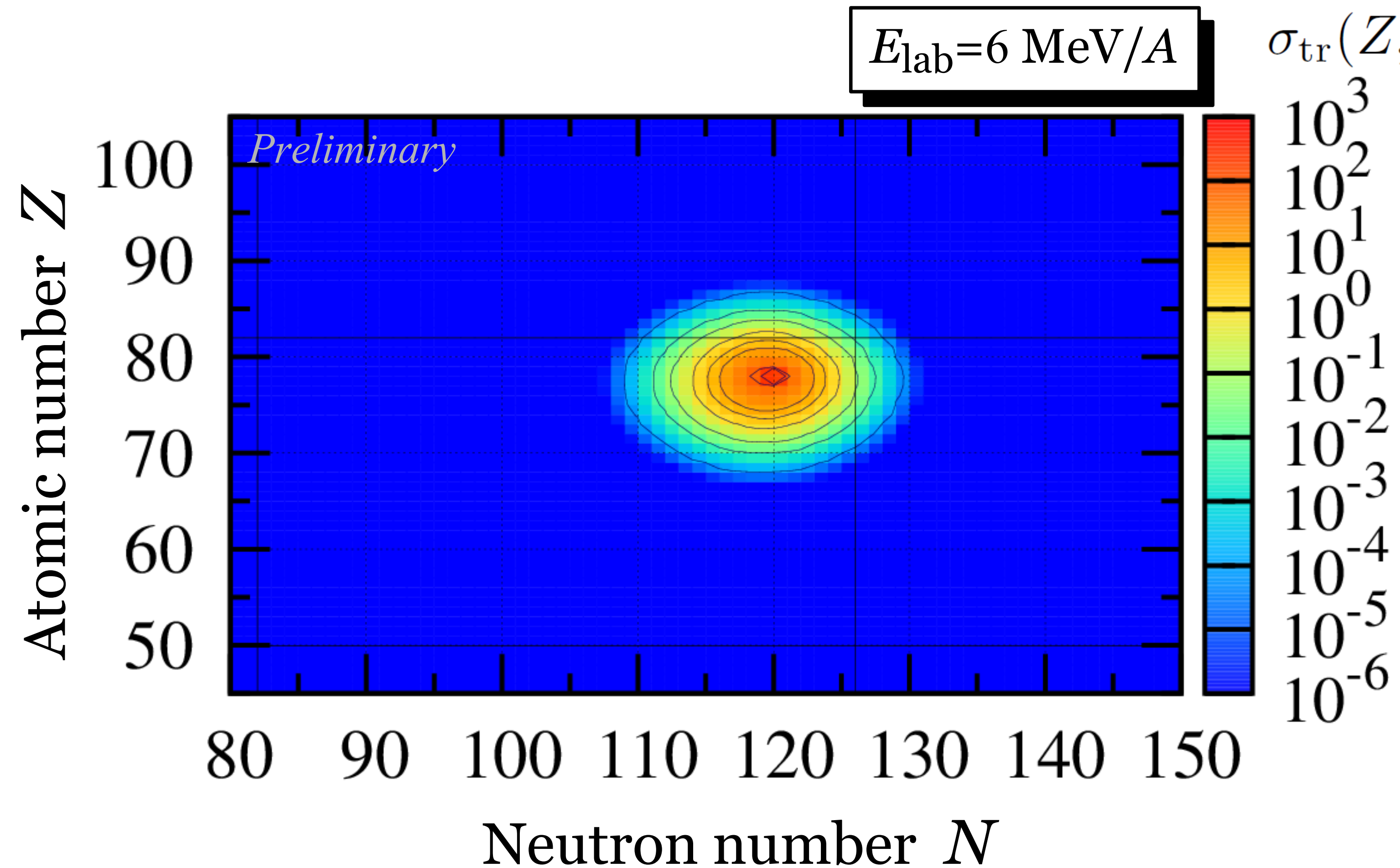

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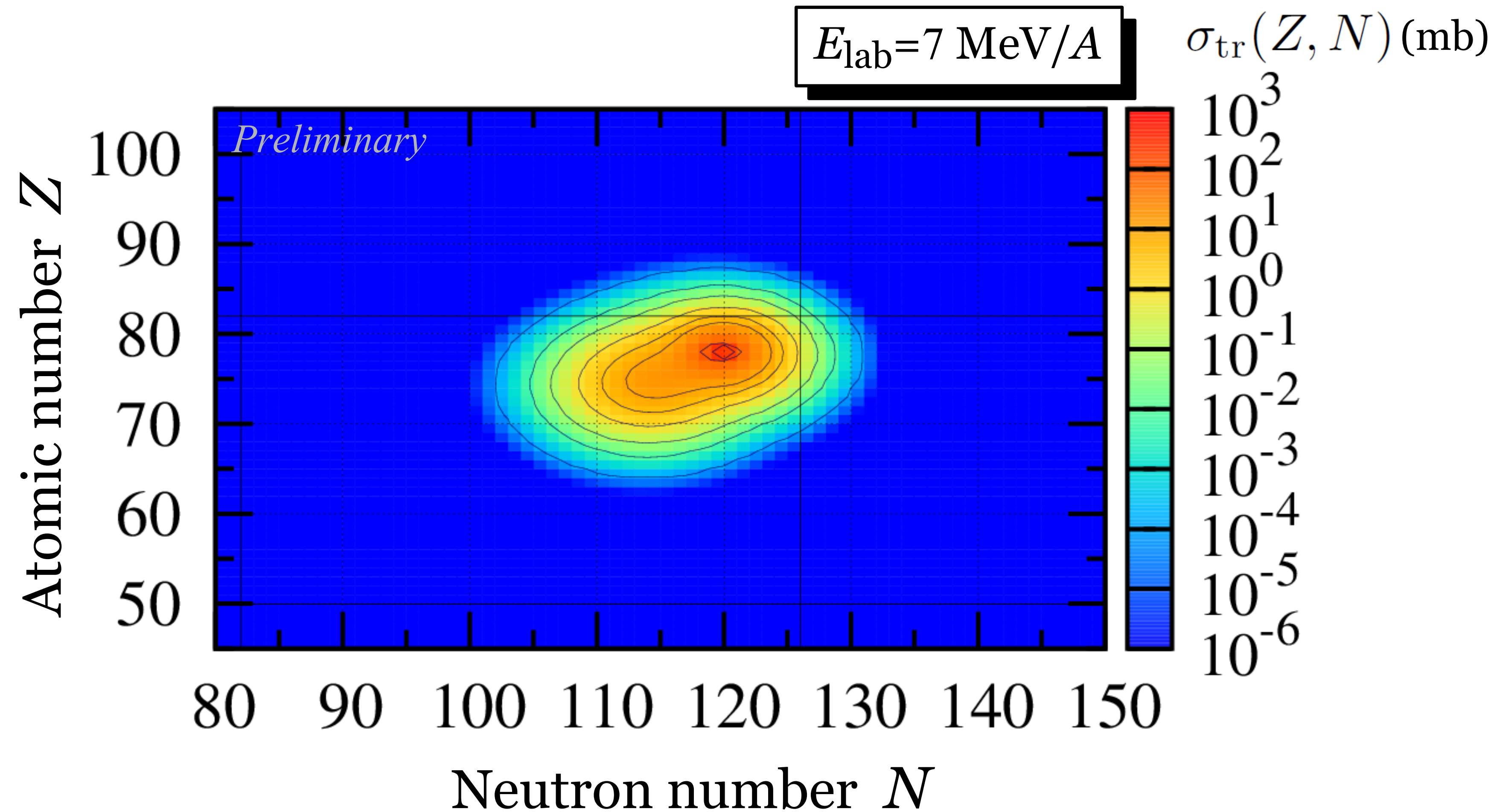

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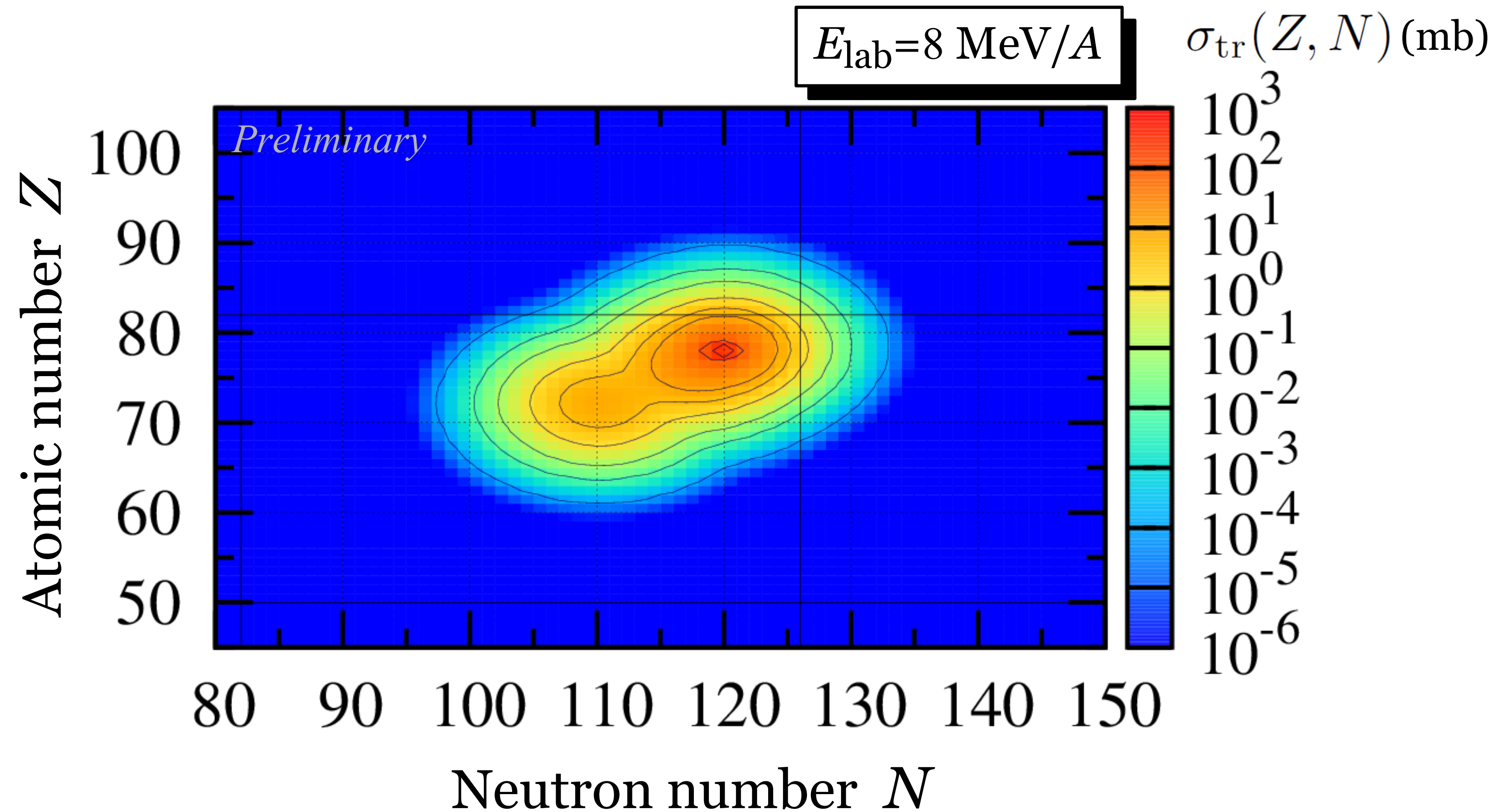

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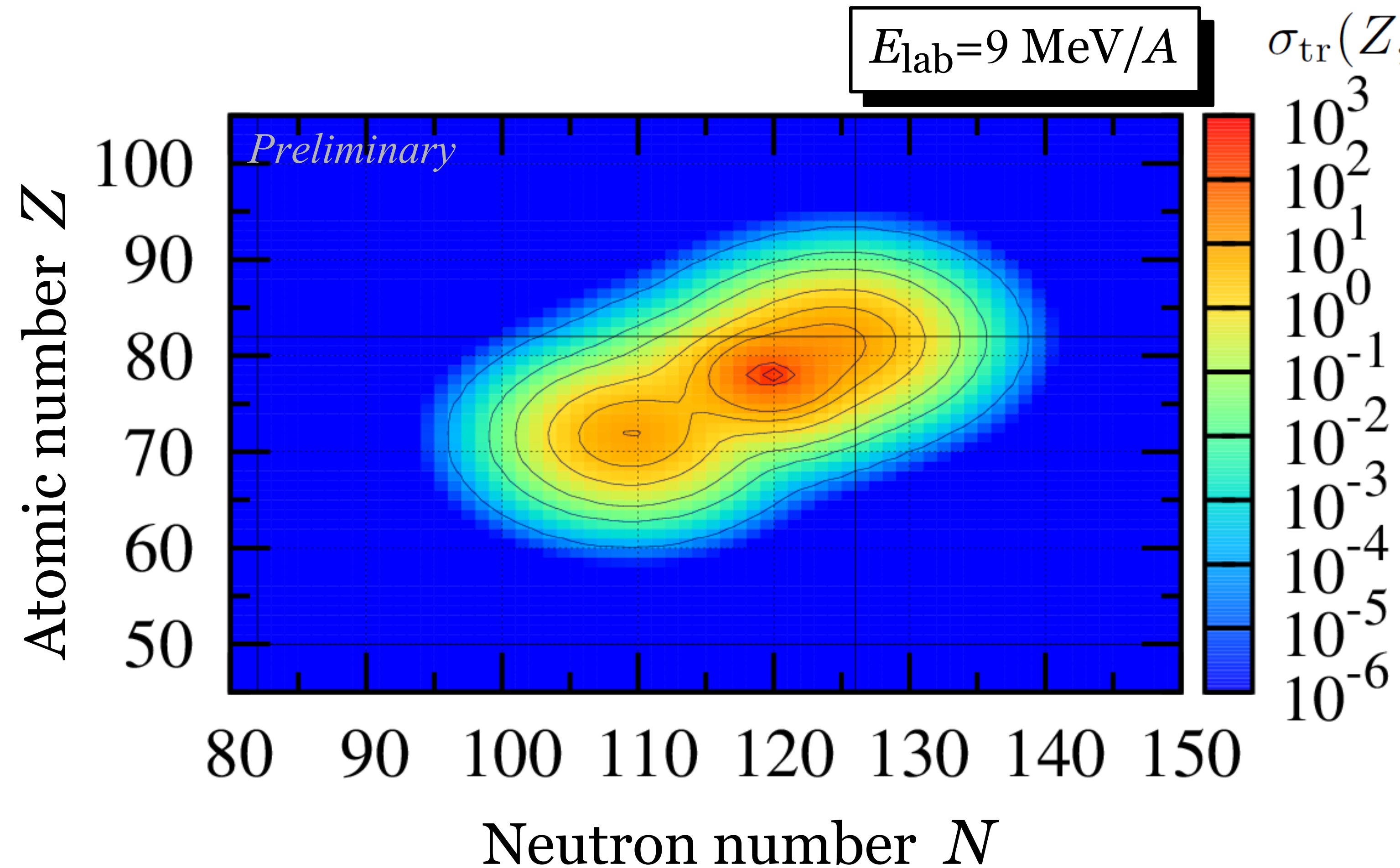

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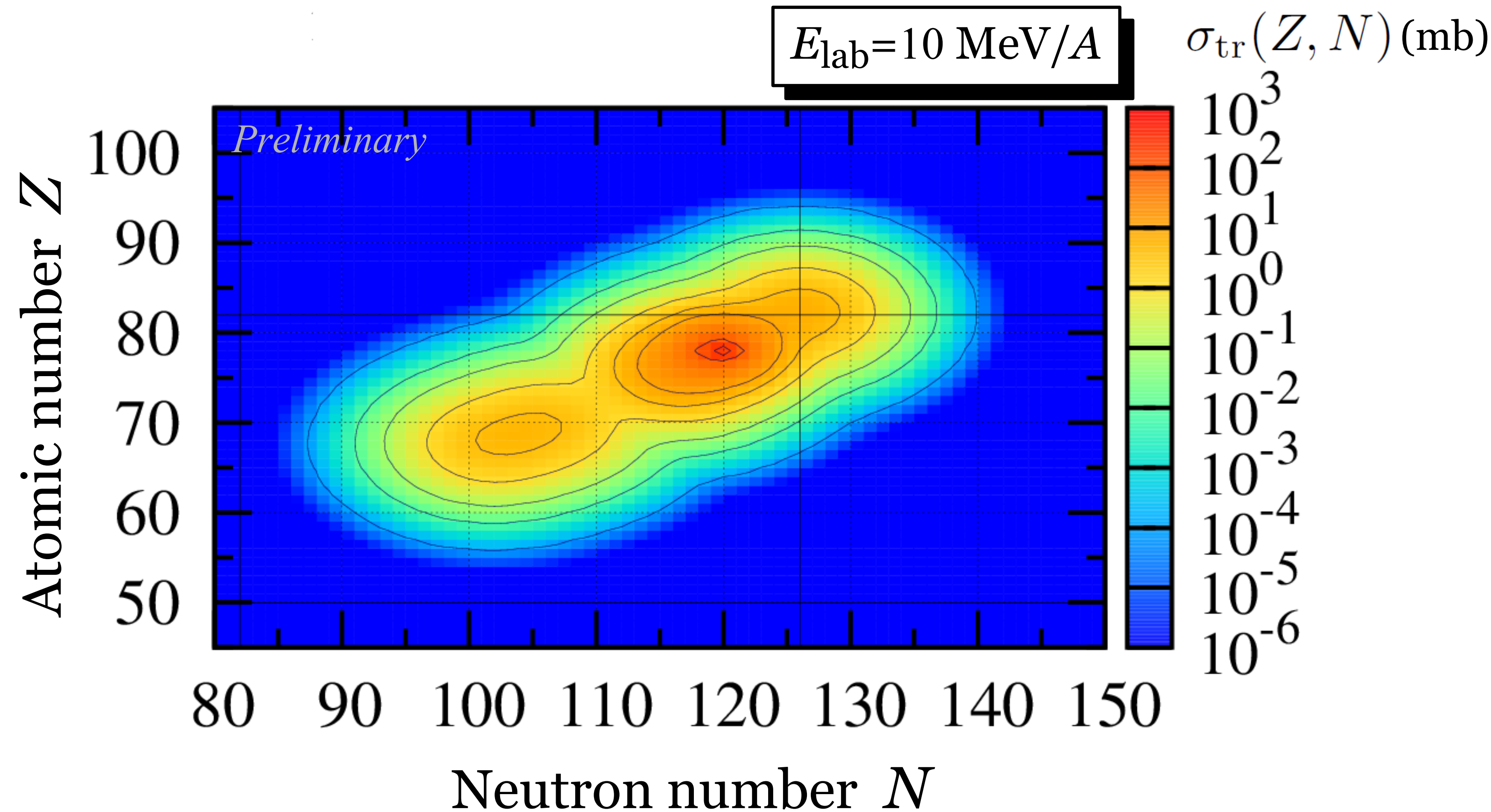

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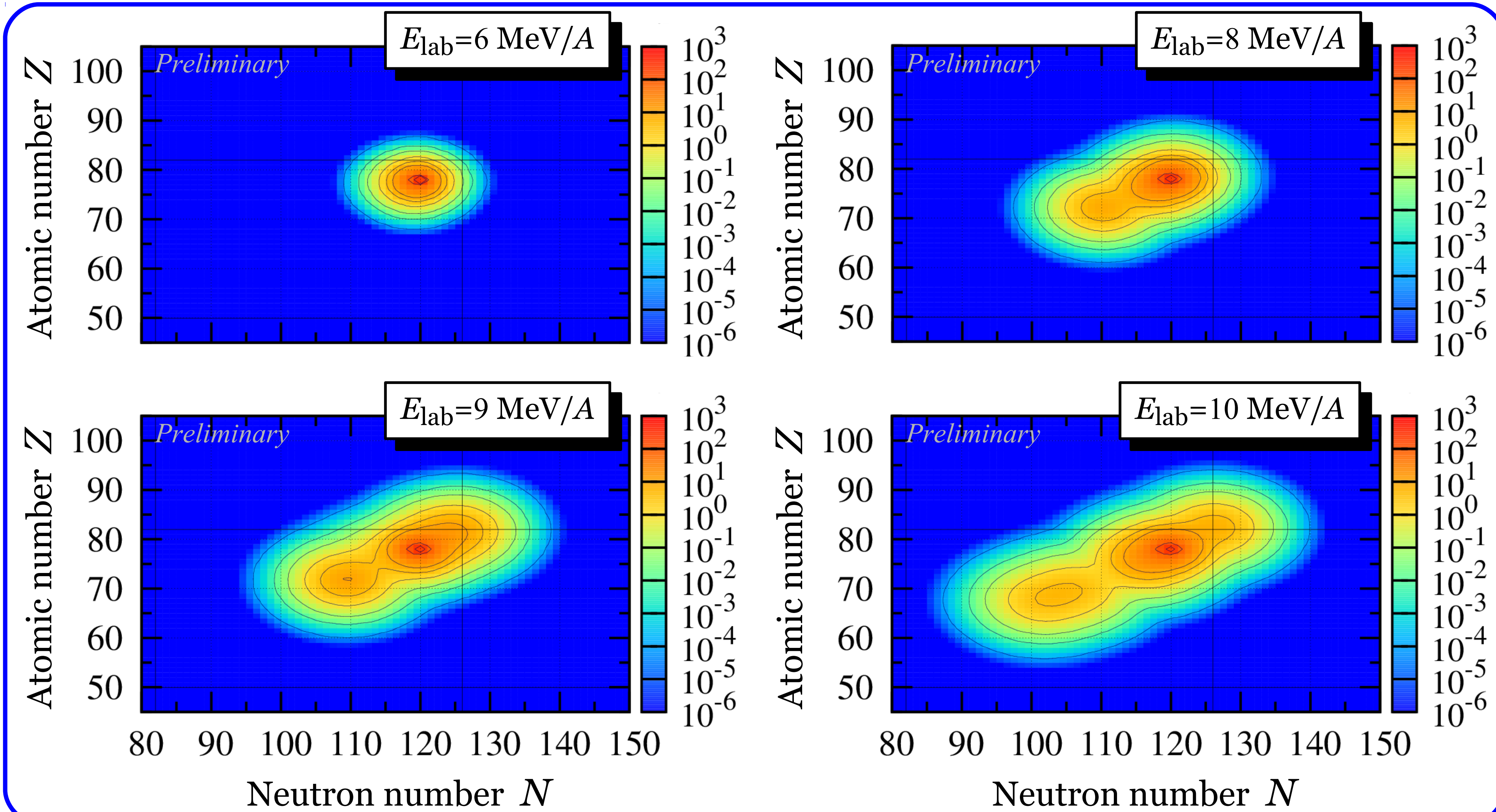
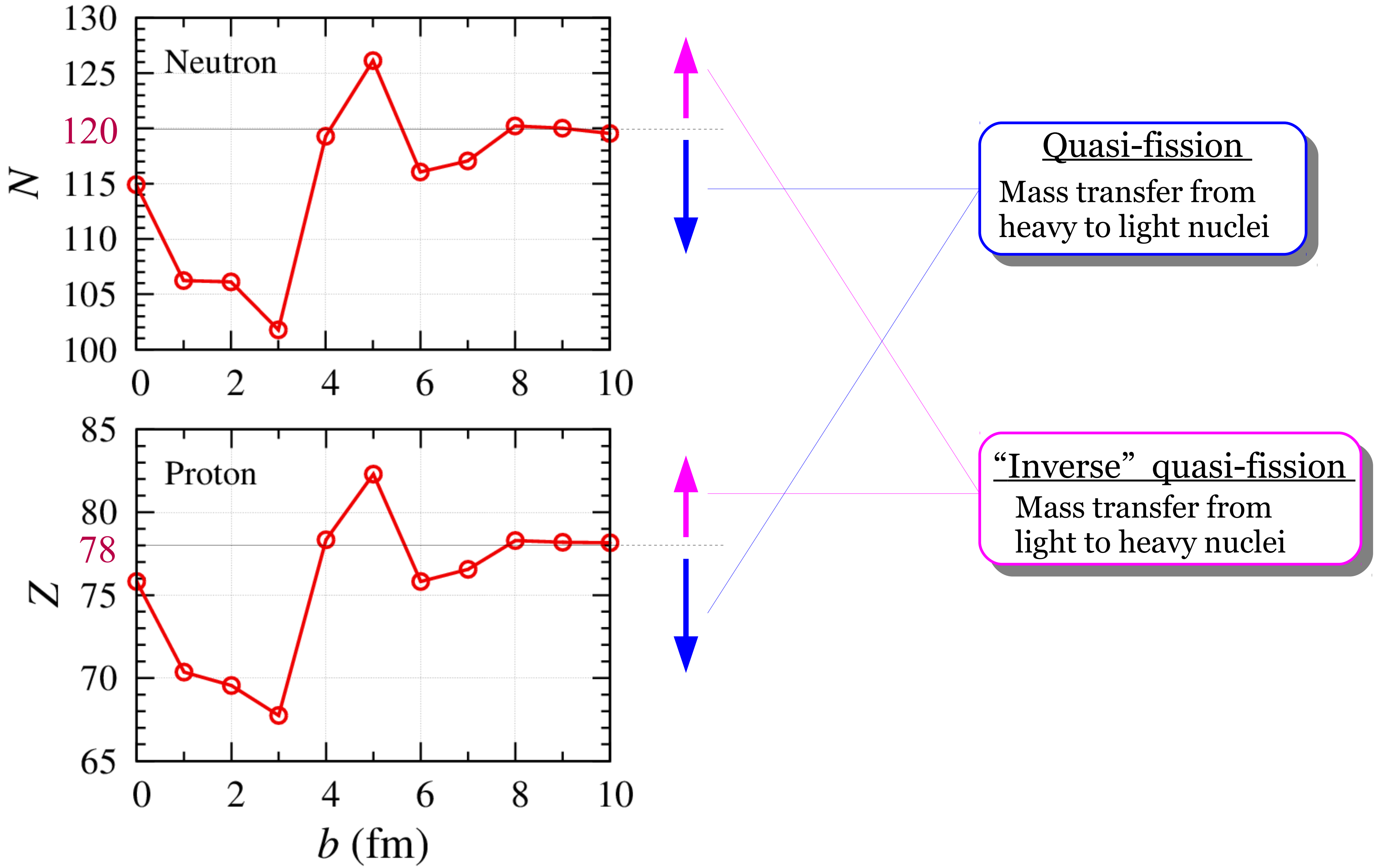
➢ **Cross sections extend wider and wider, as the incident energy increases.**



✔ Average number of nucleons in heavier fragment (10 MeV/*A*)



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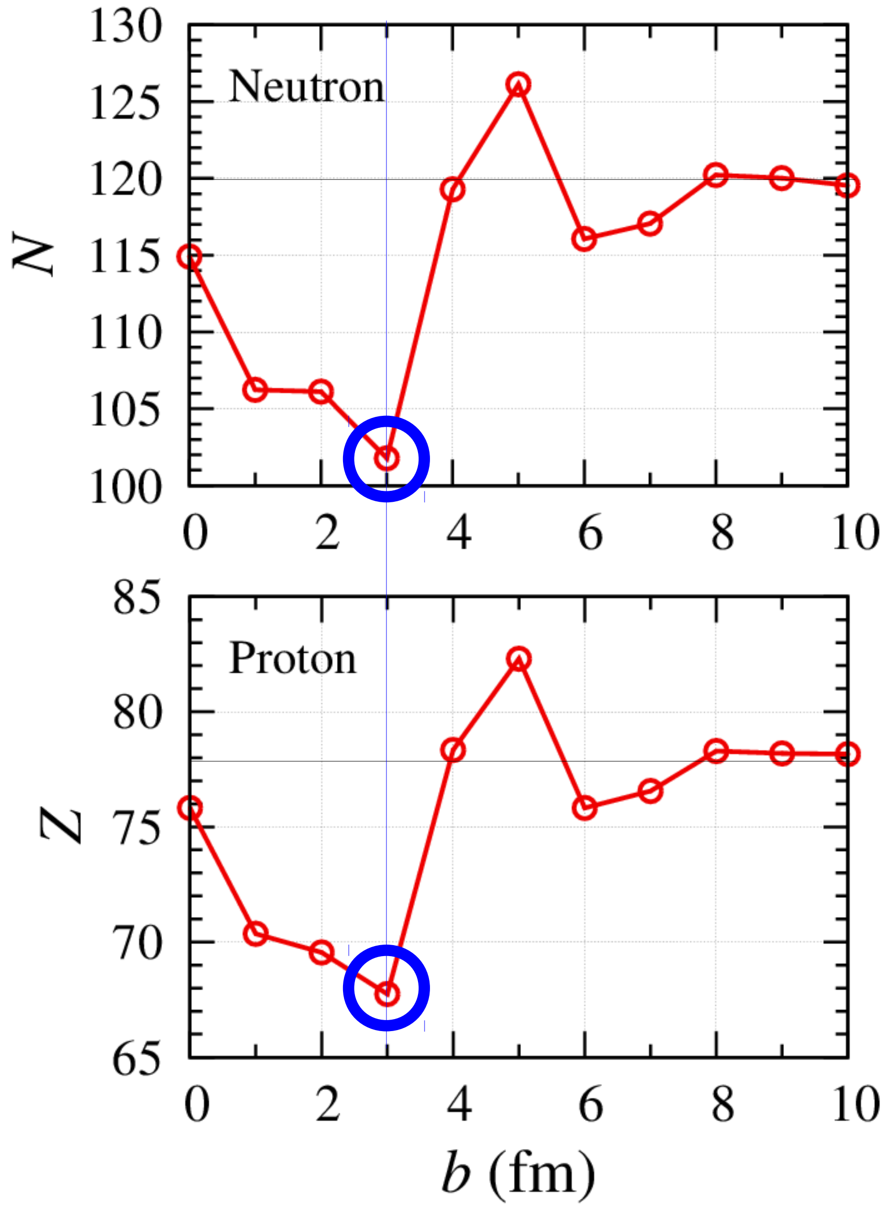
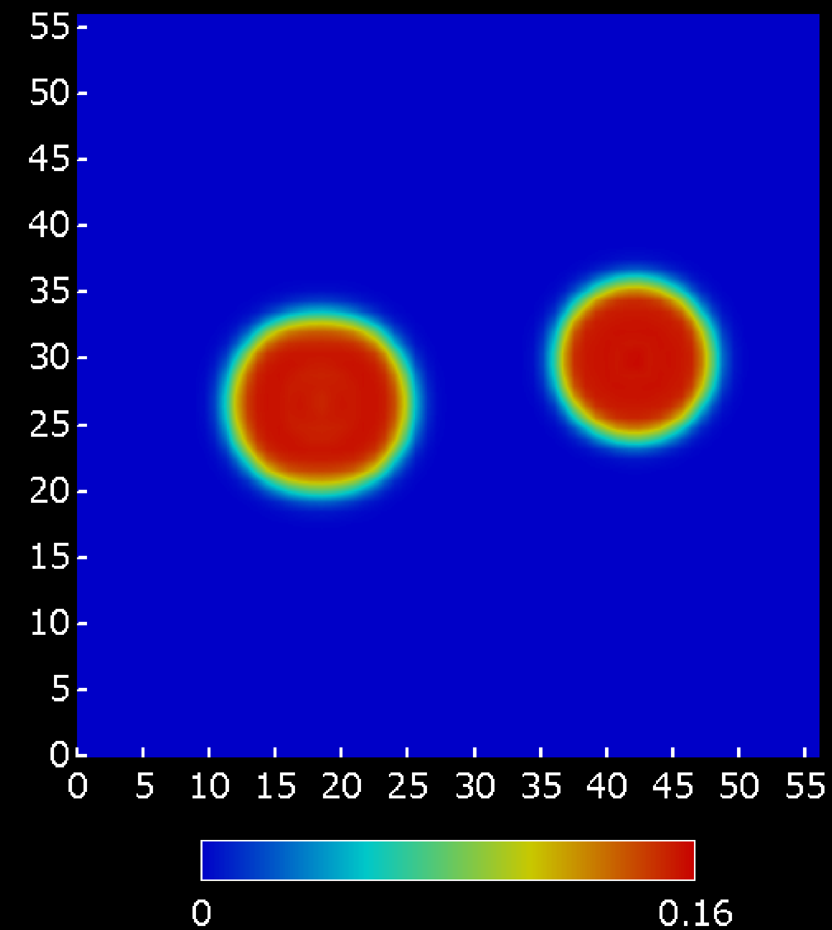
✔ Average number of nucleons in heavier fragment (10 MeV/A)



E_{lab}=10 MeV/A, b=3 fm



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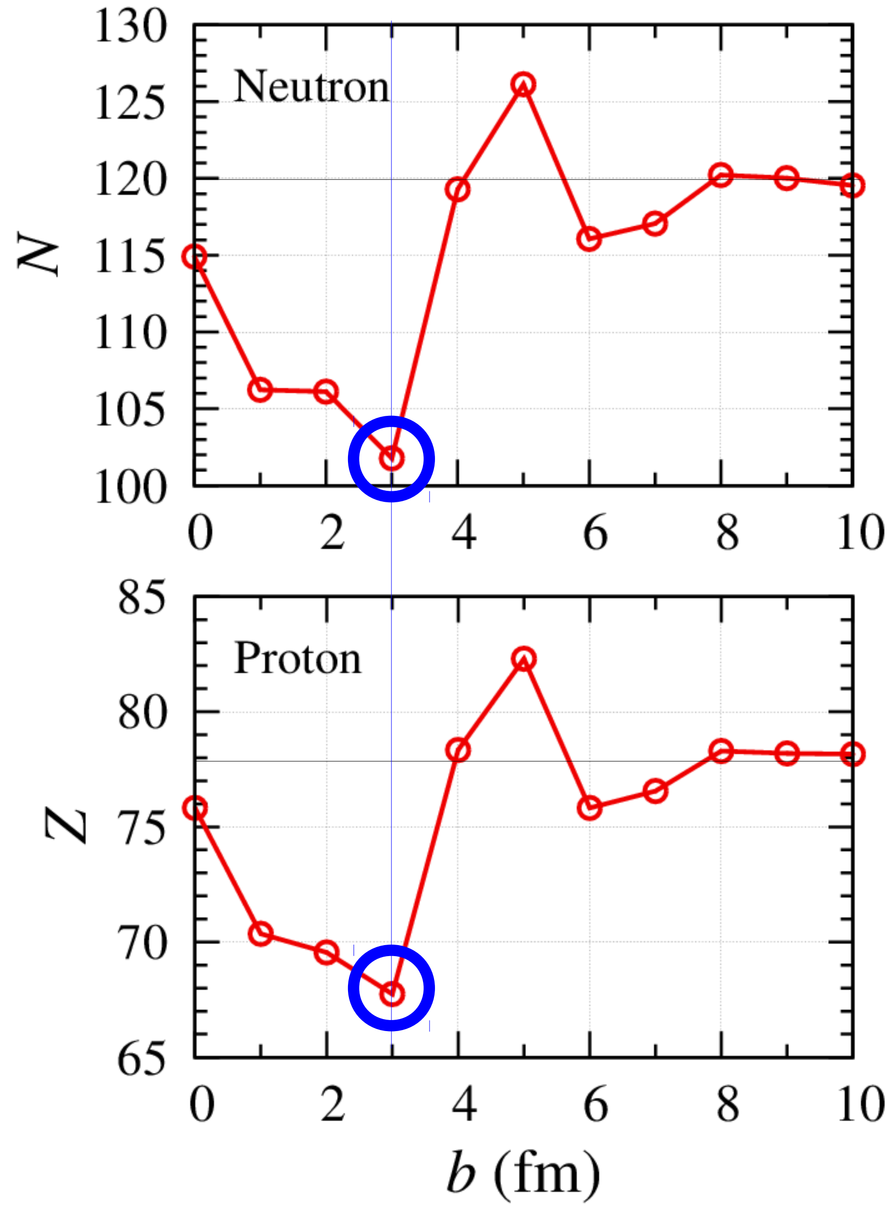
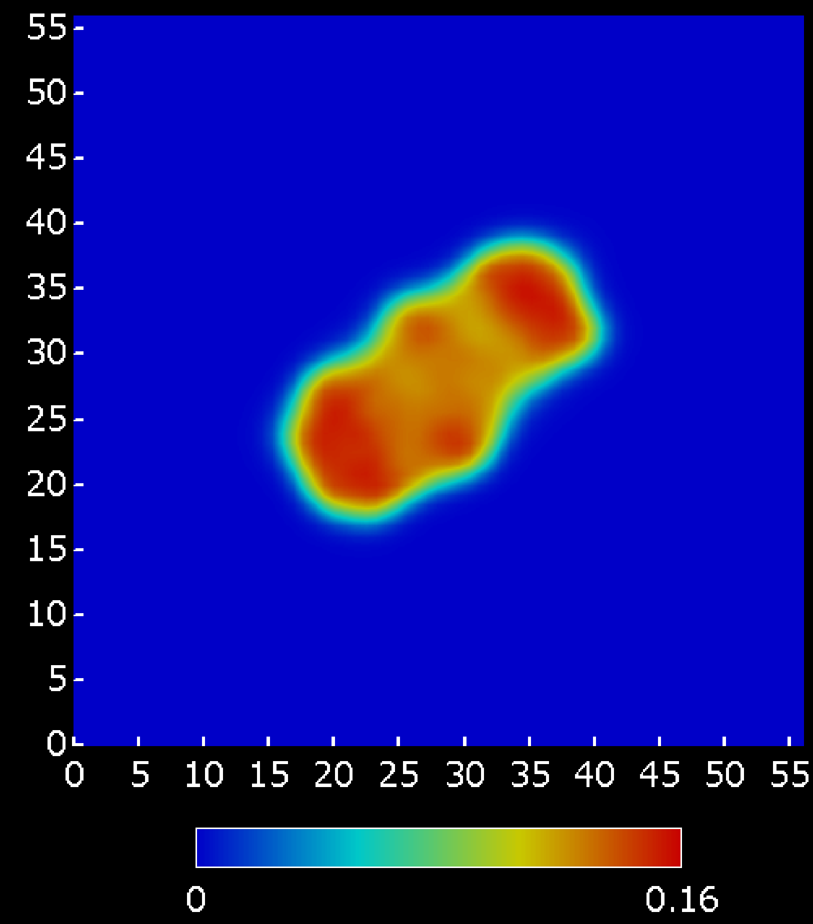


$E_{\rm lab}$=10 MeV/*A*, *b*=3 fm



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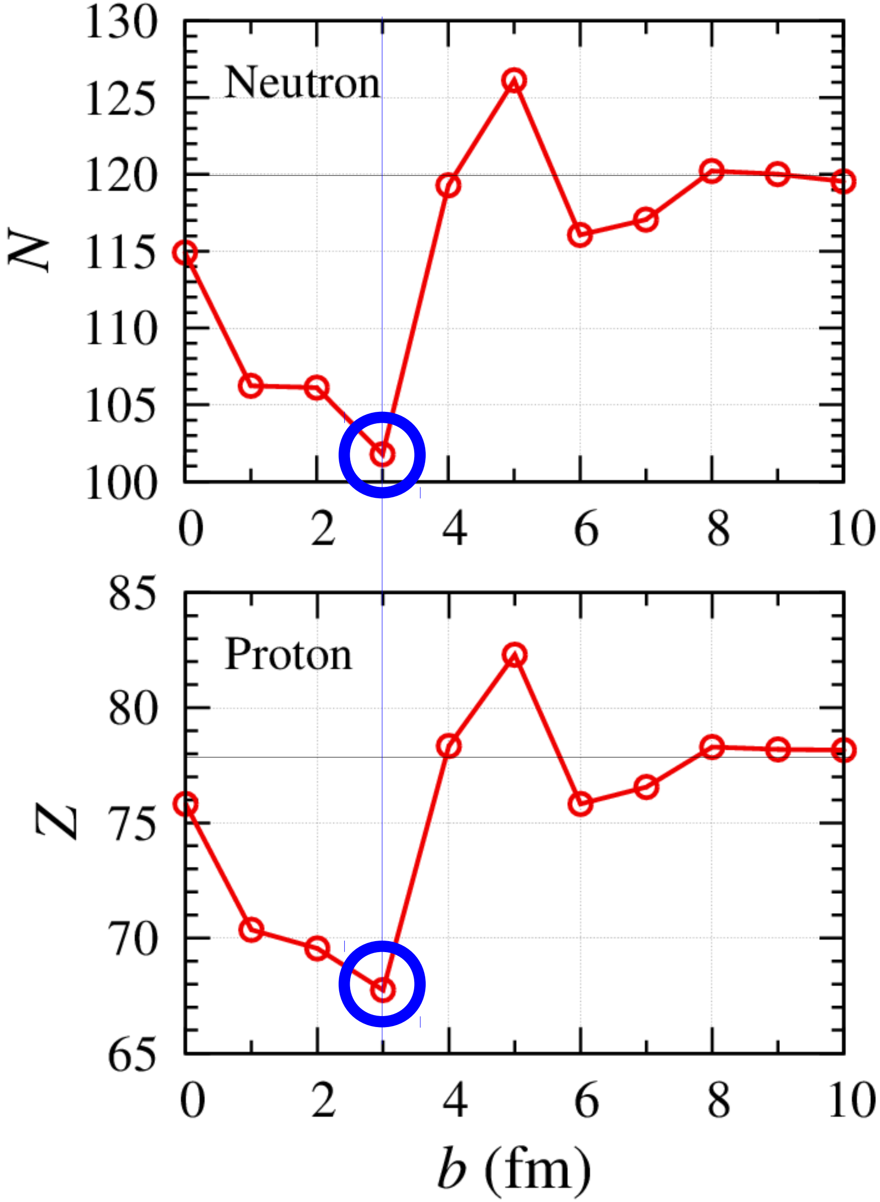

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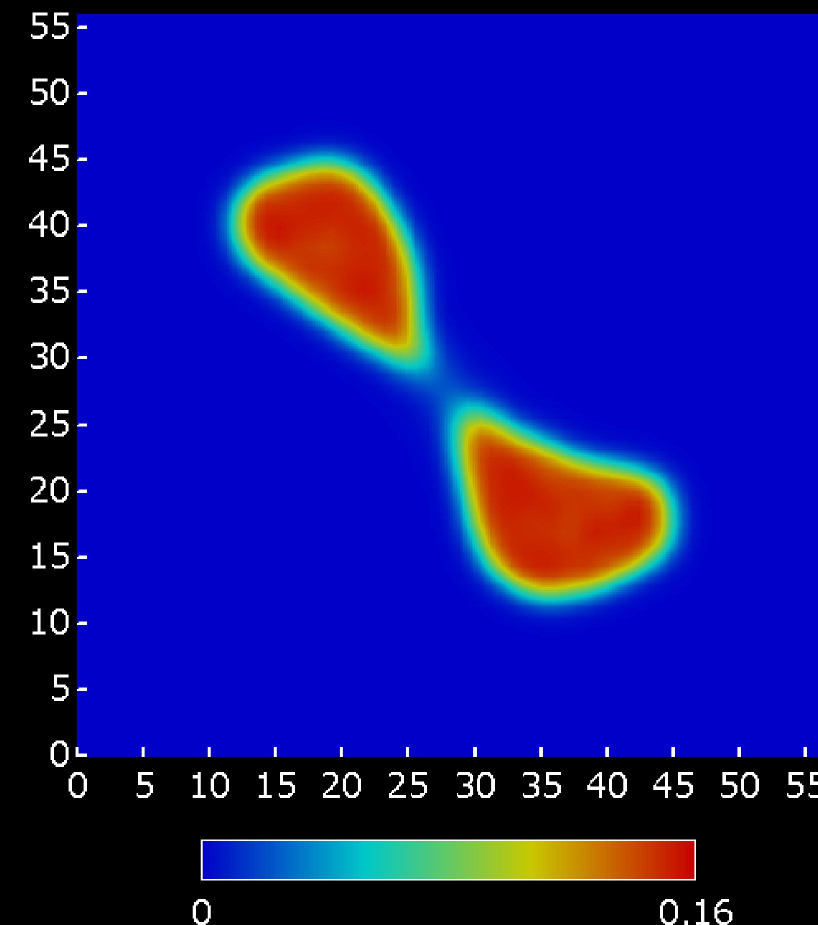
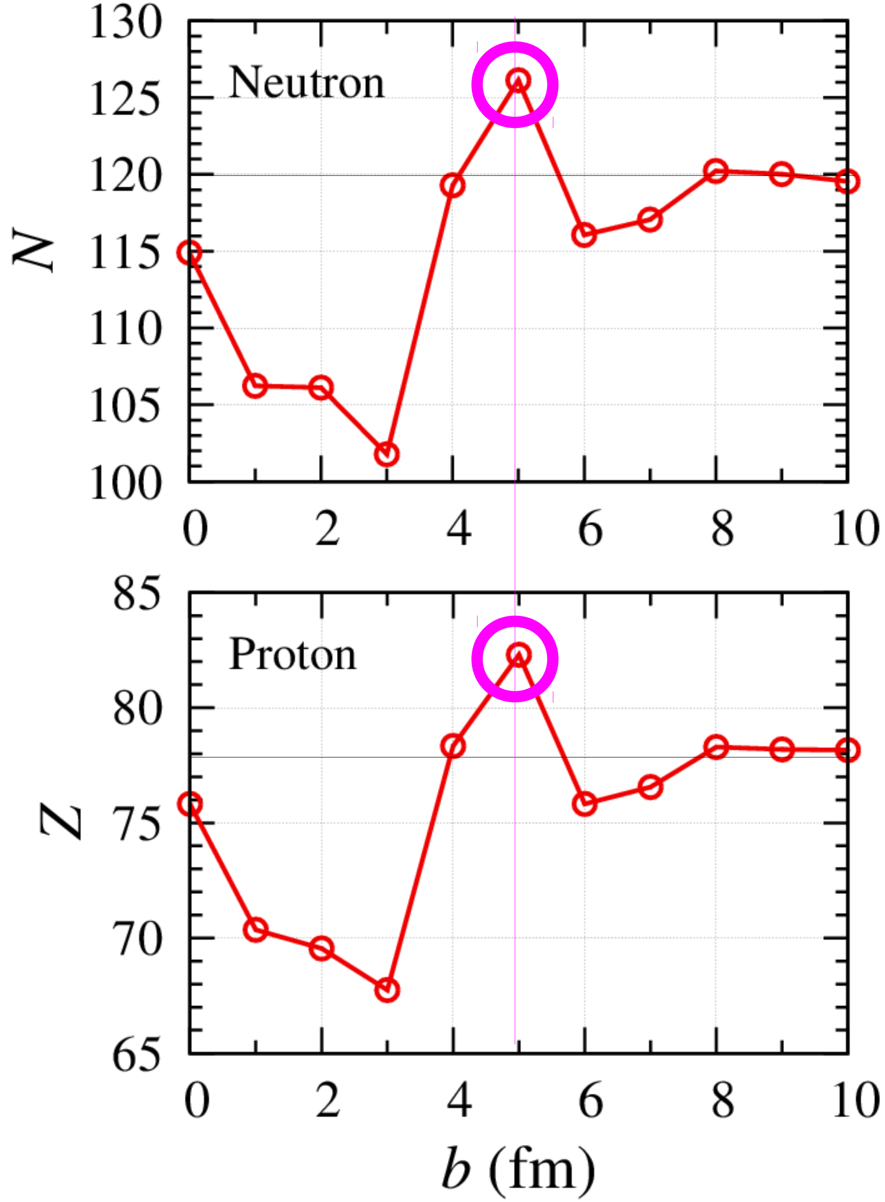


✔ After forming very thick neck, quasi-fission process proceeds to produce mass-symmetric fragments

✔ Average number of nucleons in heavier fragment (10 MeV/A)



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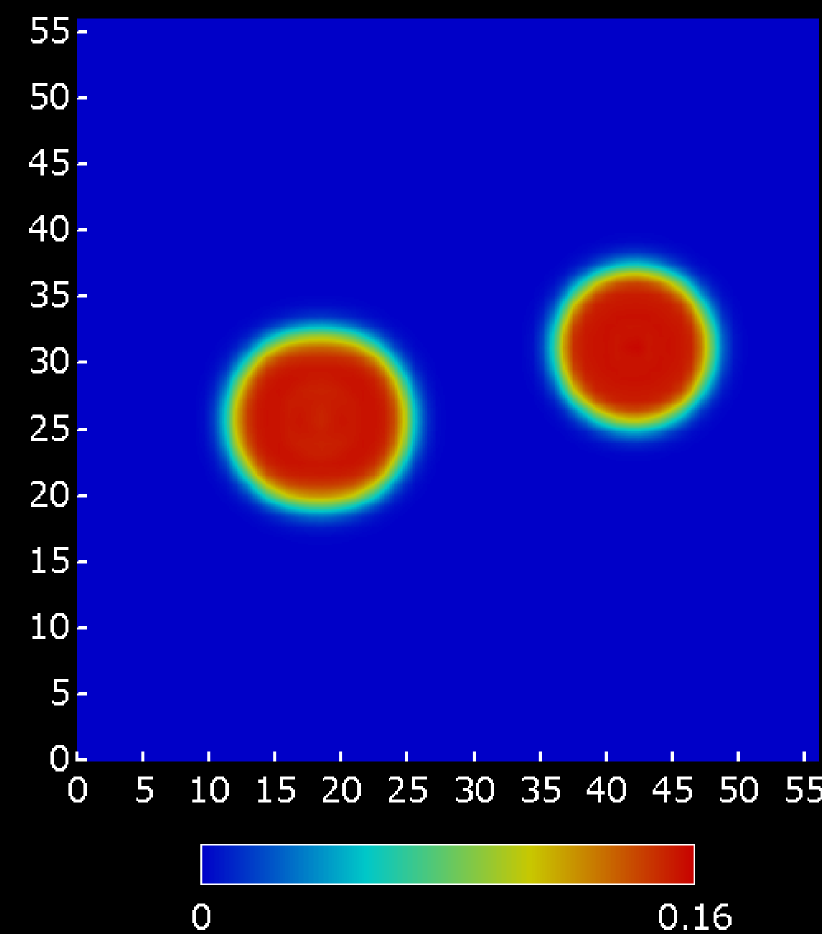
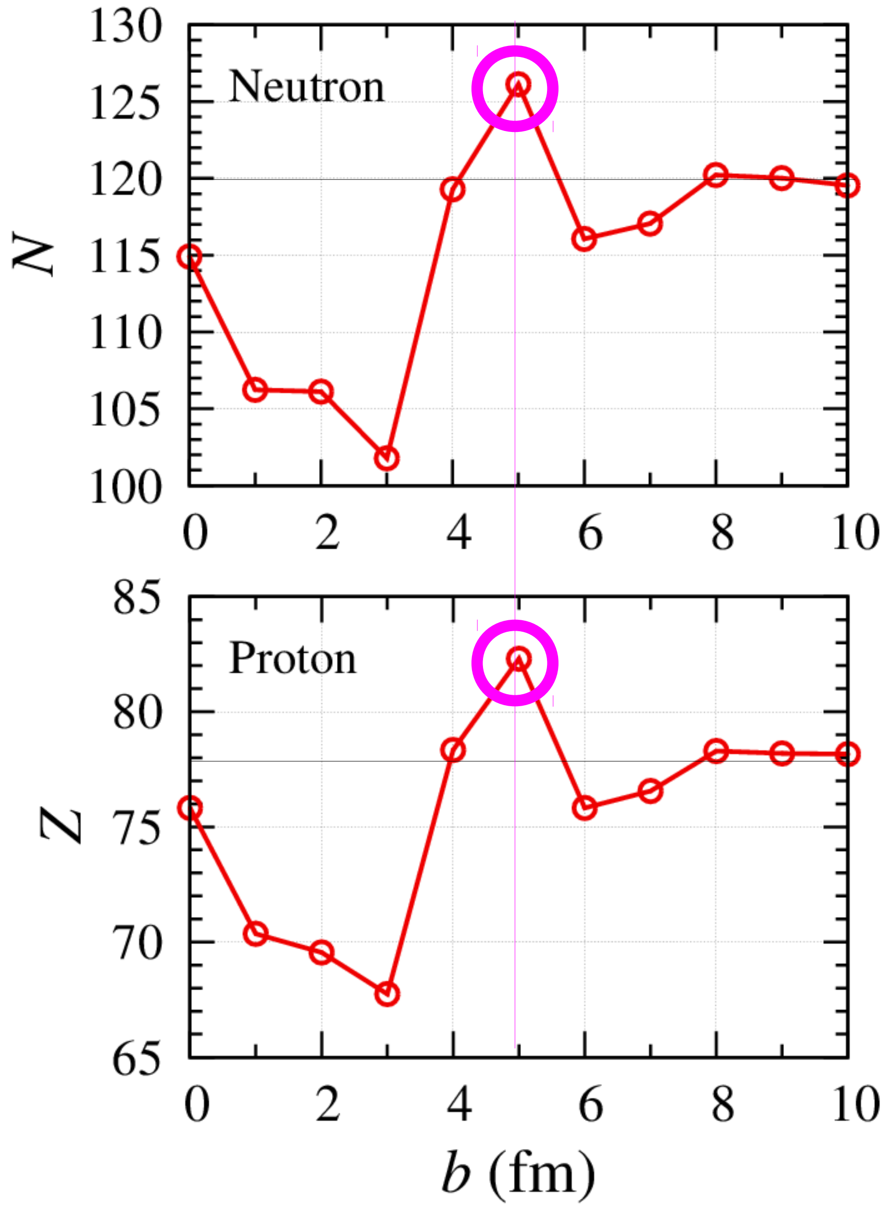


Results of the TDHF calculation: ^{136}Xe+^{198}Pt *reaction*

✔ Average number of nucleons in heavier fragment (10 MeV/A)



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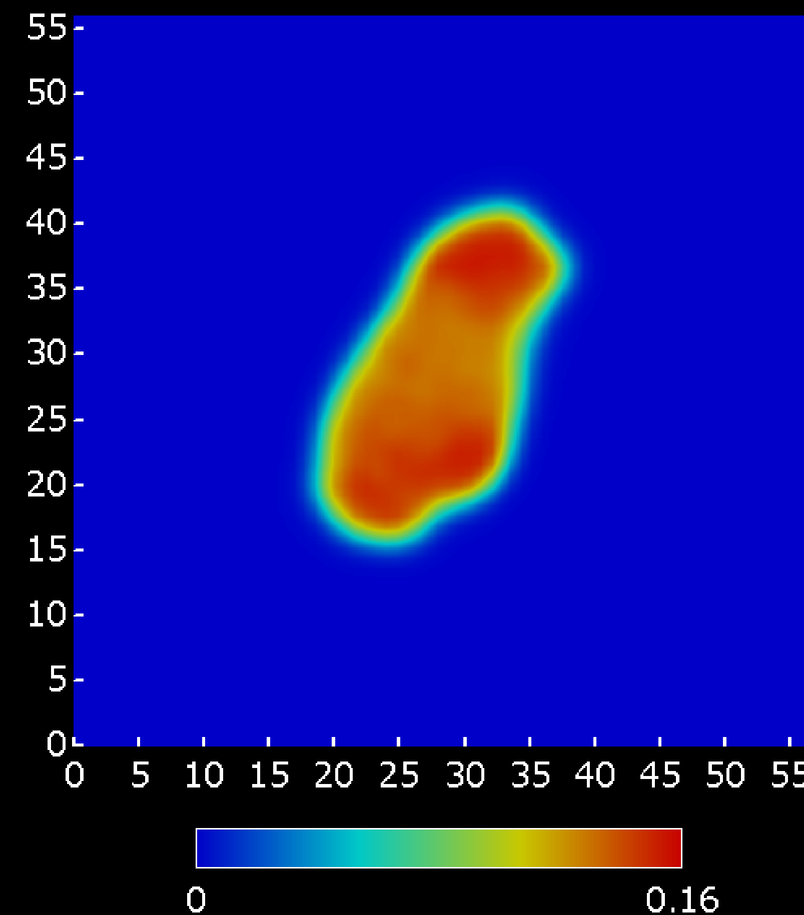

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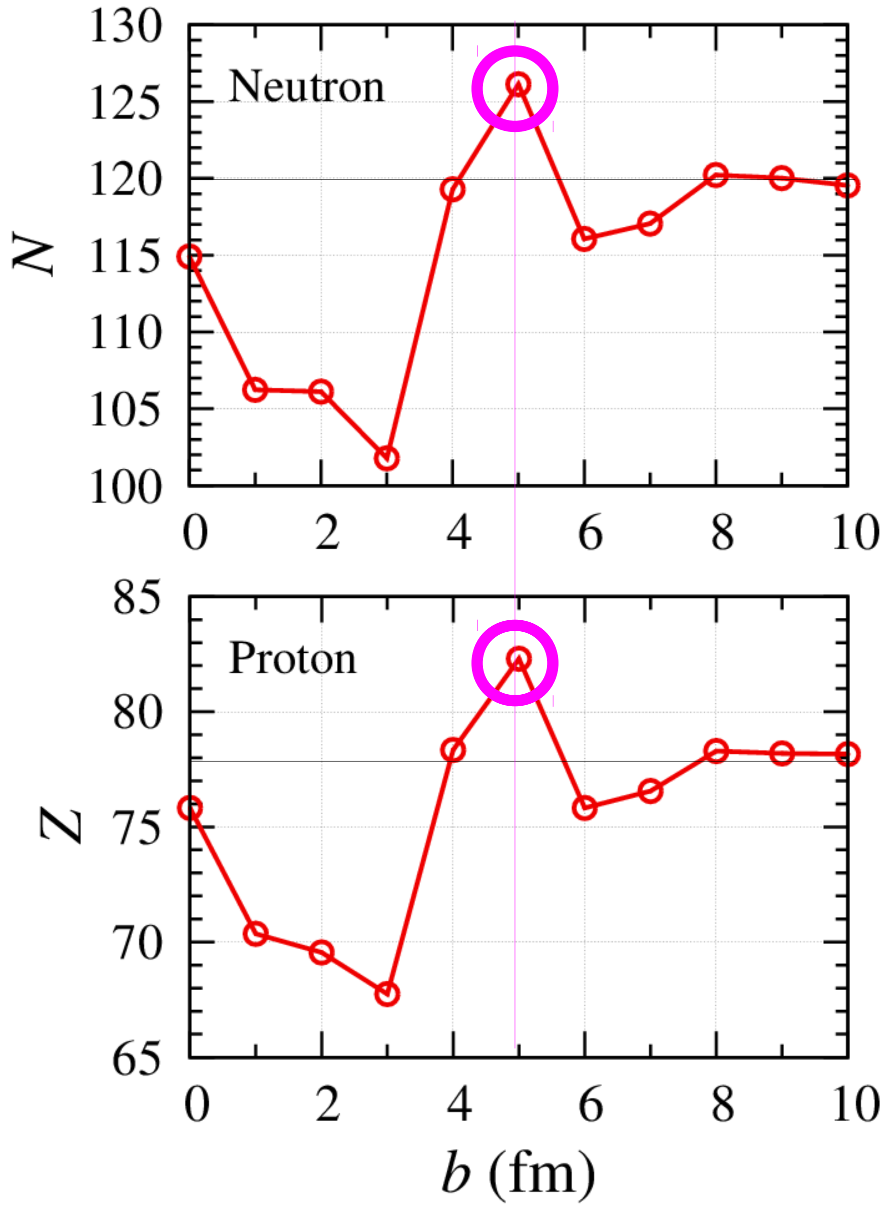

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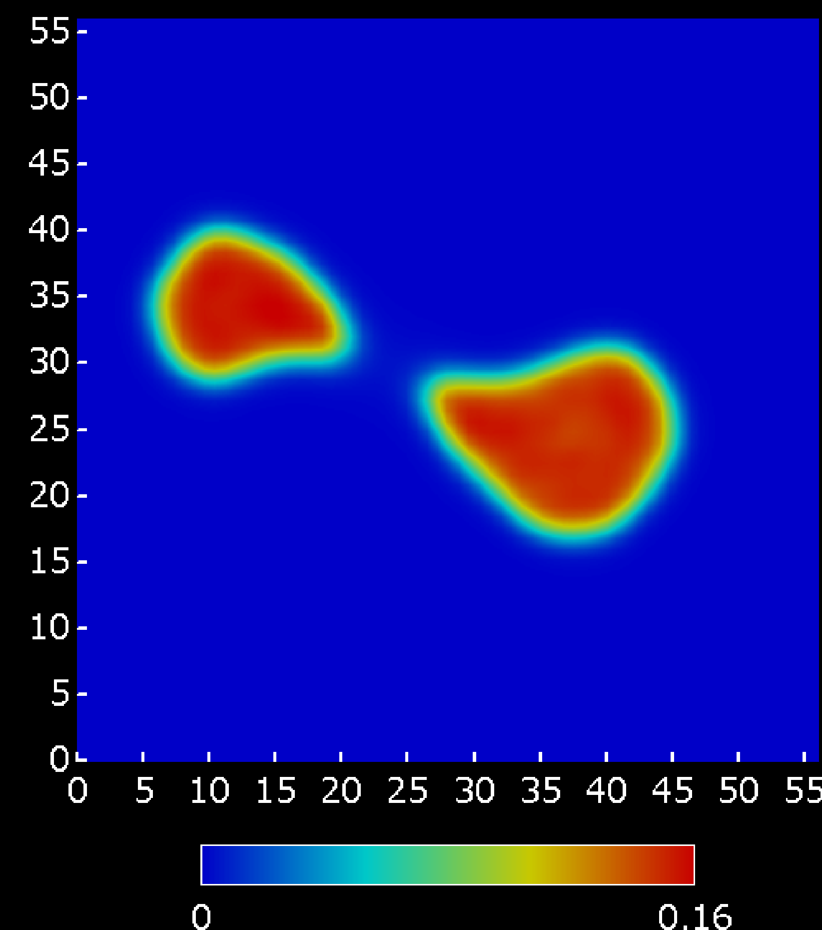

✔ Inverse quasi-fission process occur, may be due to the shell effect of ^{208}Pb in the exit channel.

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 reviewed results of the TDHF calculation for ^{40}Ca+^{124}Sn reaction.
  (K. Sekizawa and K. Yabana, arXiv:1303.0552 [nucl-th])

- ✔ I presented a current status of a systematic THDF calculation for ^{136}Xe+^{198}Pt reaction.

- ✔ Production cross sections depend much on the incident energy, corresponding appearance/disappearance of (inverse) quasi-fission processes.

Perspective

- ✔ Perform ^{136}Xe+^{198}Pt reaction at more small impact parameter step, *b*= 0.5, 1.5, ...
- ✔ Evaluate particle evaporation effects.
- ✔ Conduct similar calculations with neutron-rich projectile, such as ^{144}Xe+^{198}Pt reaction.

Thank you for your attention.