YONUPA "Young Nuclear and Particle Physicist Group of Japan"
Summer School 2021: August 6-10, 2021 (via Zoom)
8/7 (Sat) 13:00-14:30 Sekizawa - Lecture 2

時間依存密度汎関数法で探る原子核ダイナミクス: 原子核反応から超流動現象，中性子星まで

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Tokyo Institute of Technology

東京工業大学
Tokyo Institute of Technology

Lecture Plan

Theory (8/7 10:00-11:30)

#1. An introduction to microscopic mean-field approaches and (TD)DFT

Nuclear reactions (8/7 13:00-14:30)

#2. Recent advances in microscopic approaches for heavy-ion reactions

Superheavy element synthesis & deep-inelastic collisions

Neutron stars (8/8 10:00-11:30)

#3. Neutron-star "glitch" and neutron superfluid

Dynamics of quantized vortices in the inner crust of neutron stars

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Dynamics of quantized vortices in the inner crust of neutron stars

Voyage towards the limit of existence

The continent of stability has been well explored..

The Great Wall of China by Stacy Funderburke @shutterstock

Now we are sailing towards the edge of the nuclear landscape..

Stable nuclei: 288

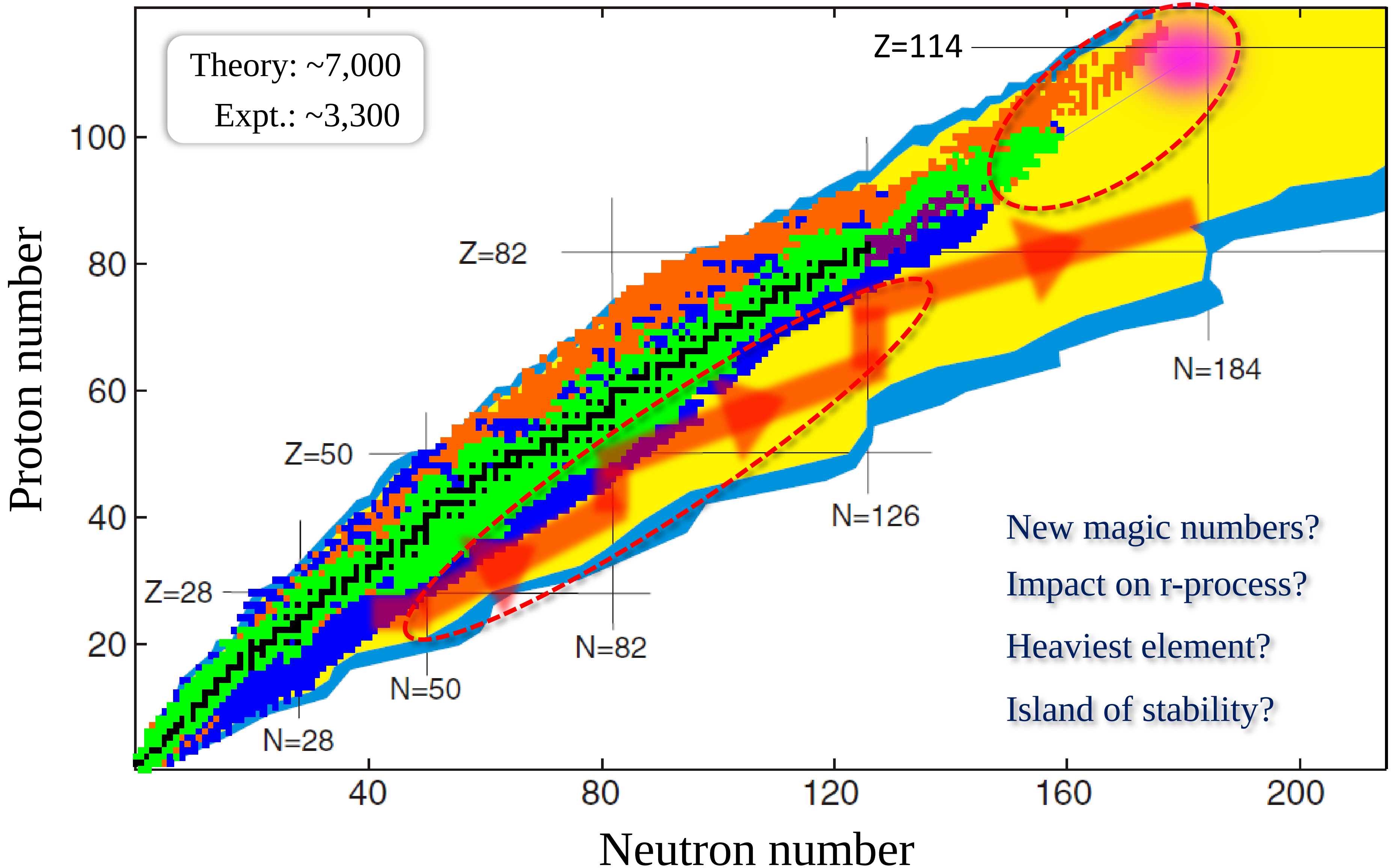
Experiment: ~3300

Theory: ~7000-10000

- drip lines
- shell structure
- deformation
- skin, halo
- nuclear matter properties
- nucleosynthesis
- ...

"Flat Earth" by iStock; "Fanciful view of ship sailing over edge of Earth" by Georgia Studies Images

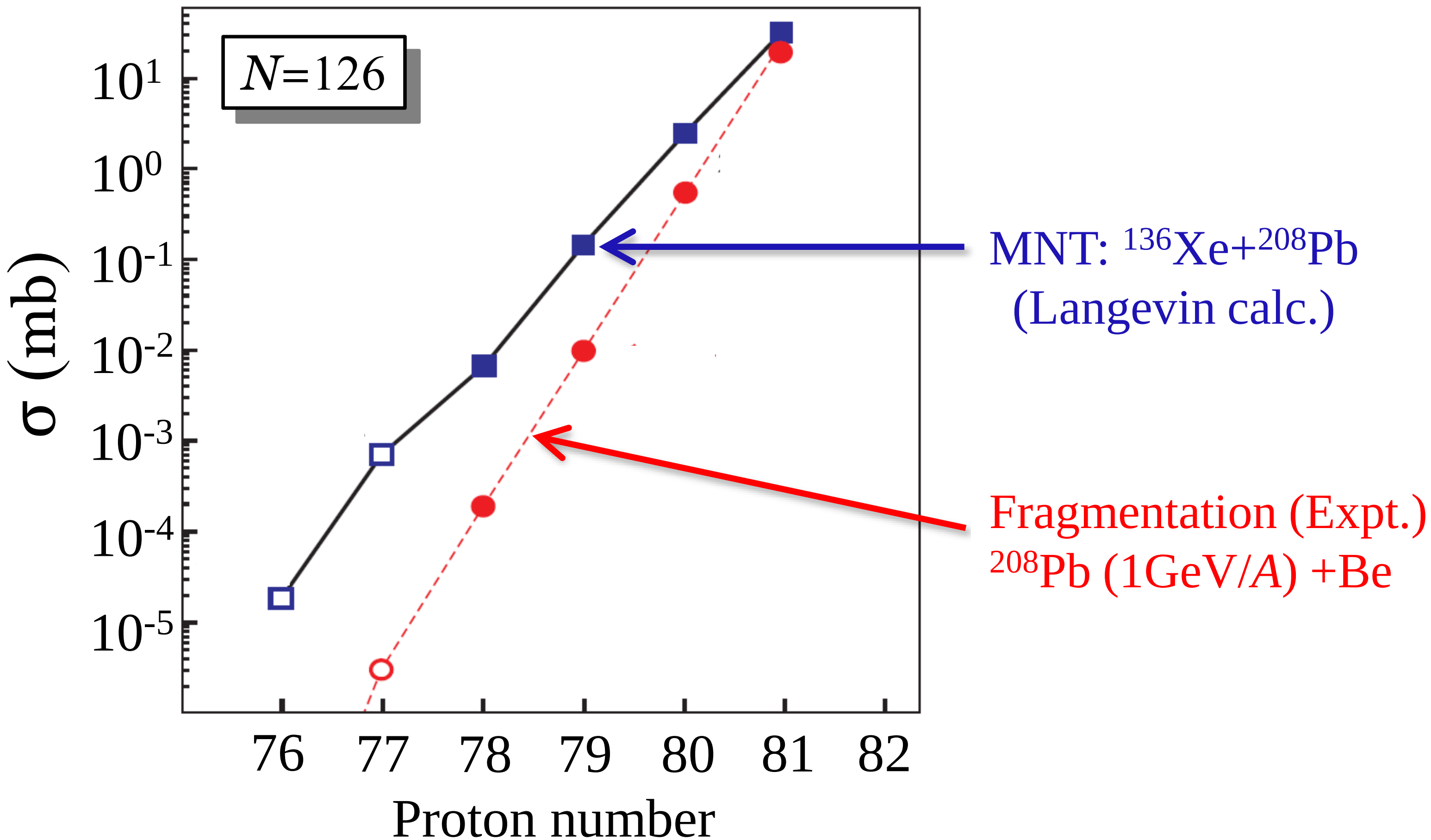
How can we create yet-unknown neutron-rich nuclei?



M. Thoennessen, Rep. Prog. Phys. **76**, 056301 (2013)

Multinucleon transfer (MNT) and quasi-fission (QF) may be useful

Production cross section for *N*=126 isotones in ^{136}Xe+^{208}Pb

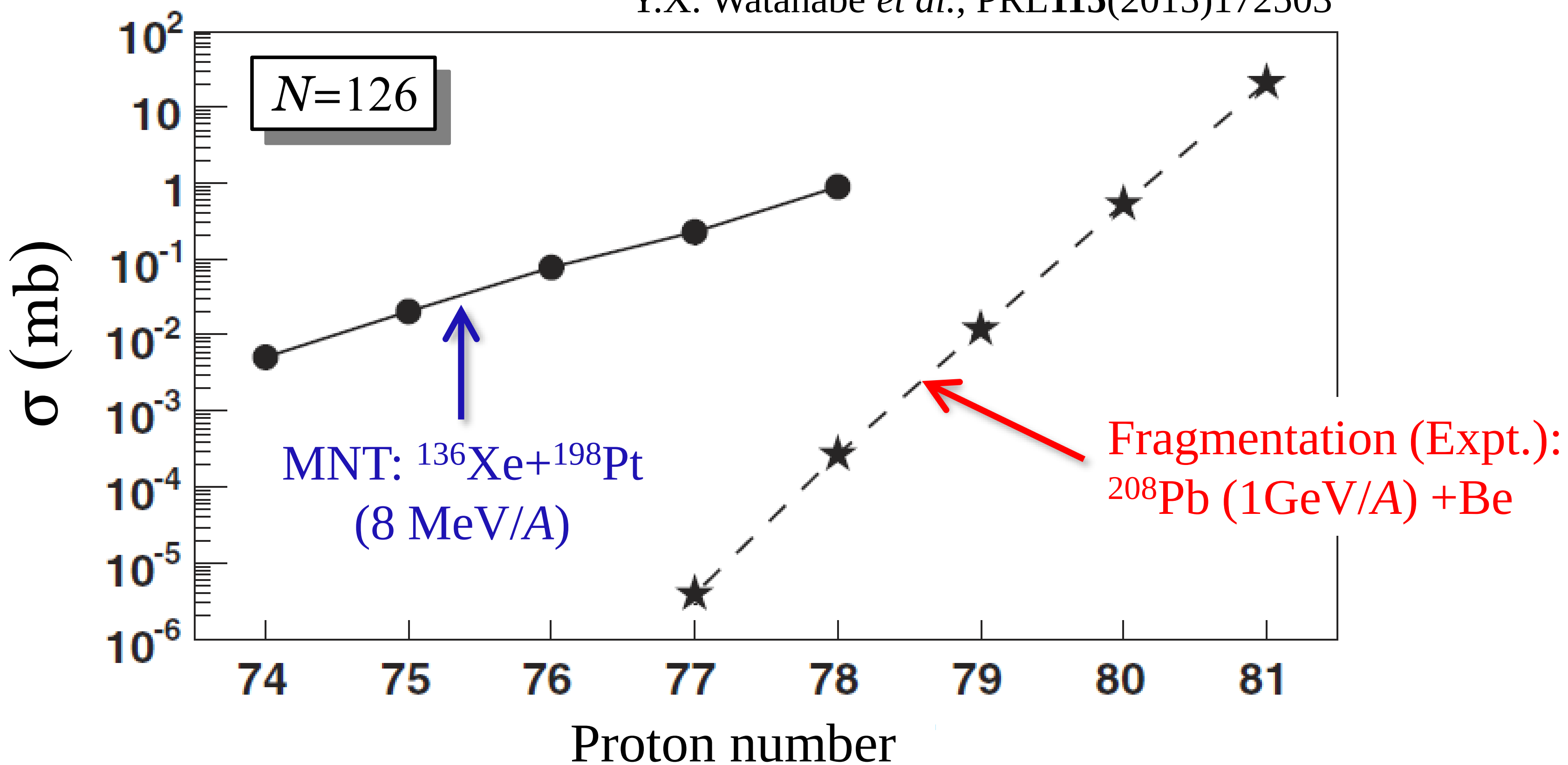


Langevin: V.I. Zagrebaev and W. Greiner, PRC**83**(2011)044618
Fragmentation: T. Kurtukian-Nieto *et al.*, PRC**89**(2014)024616

Multinucleon transfer (MNT) and quasi-fission (QF) may be useful

Production cross section for N=126 isotones in ^{136}Xe+^{198}Pt

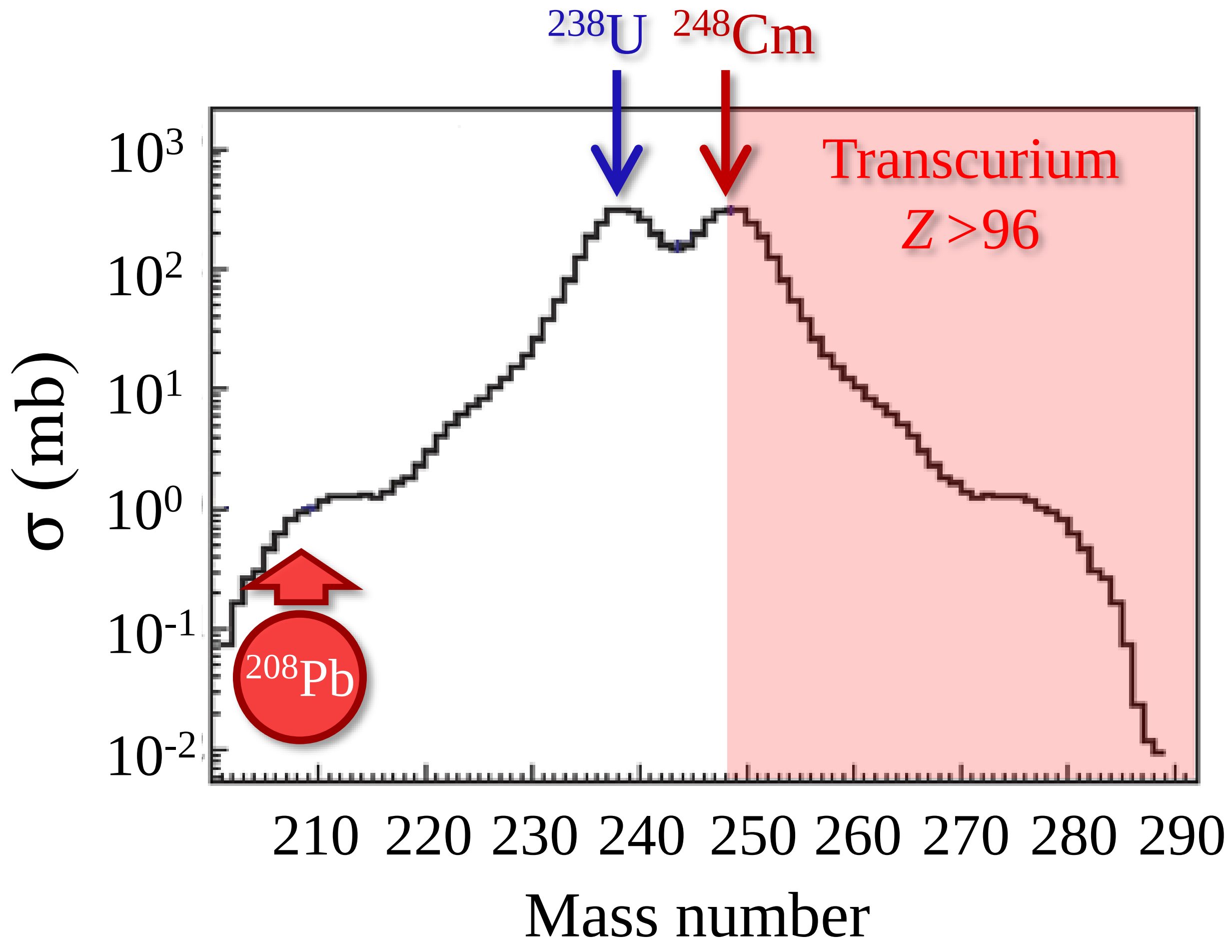
Y.X. Watanabe *et al.*, PRL**115**(2015)172503

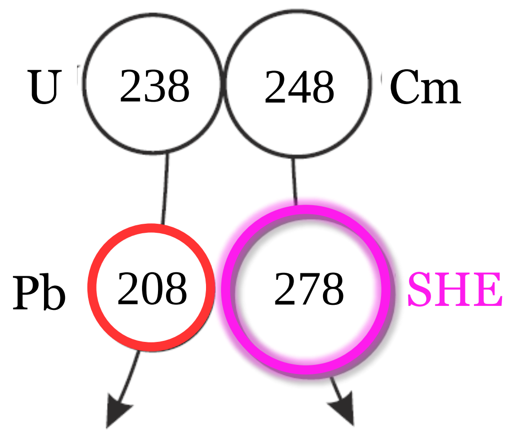


Fragmentation: T. Kurtukian-Nieto *et al.*, PRC**89**(2014)024616

Multinucleon transfer (MNT) and quasi-fission (QF) may be useful

Production cross section for primary products in $^{238}U+^{248}Cm$





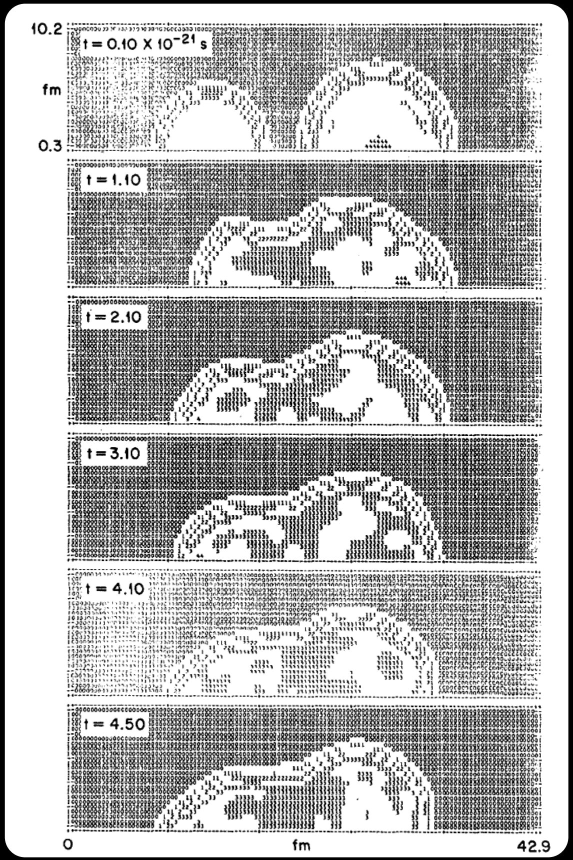
Langevin calculation by: V.I. Zagrebaev and W. Greiner, PRC**87**(2013)034608

Let's see how TDDFT works in practice

"TDHF" - past and present

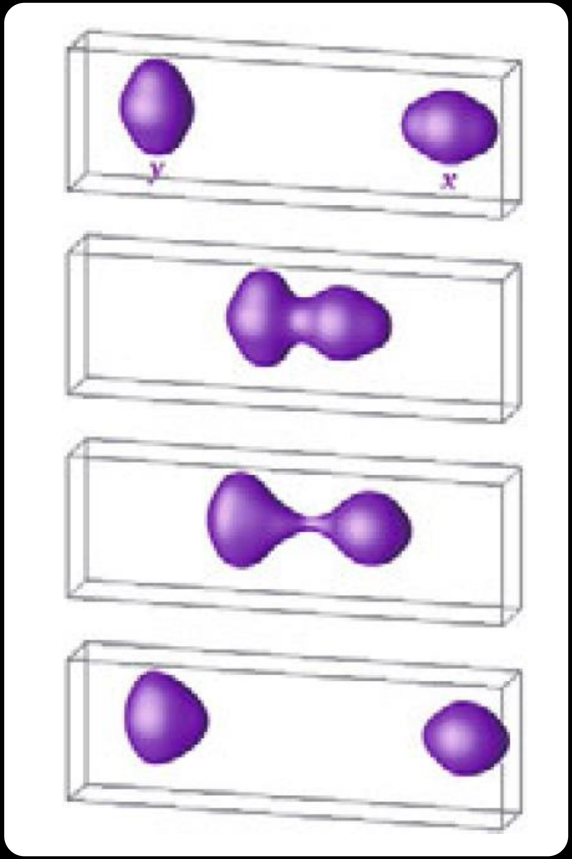
For reviews, see: J.W. Negele, Rev. Mod. Phys. **54**, 913 (1982); C. Simenel, Eur. Phys. J. A **48**, 152 (2012); T. Nakatsukasa *et al.*, Rev. Mod. Phys. **88**, 045004 (2016); C. Simenel and A.S. Umar, Prog. Part. Nucl. Phys. **103**, 19 (2018); P.D. Stevenson and M.C. Barton, Prog. Part. Nucl. Phys. **104**, 142 (2019); K.S., Front. Phys. **7**, 20 (2019)

- ✓ Various symmetry restrictions
- ✓ Simplified interactions
- ✓ Limited computational power



^{84}Kr+^{209}Bi, E_{lab} = 850 MeV
K.T.R. Davis, K.R.S. Devi, and M.R. Strayer, PRL**44**(1980)23

- ✓ Full 3D
- ✓ Modern interactions (or EDF)
- ✓ Accurate numerical methods and use of supercomputers



^{238}U+^{238}U, E_{lab} = 900 MeV
C. Golabek and C. Simenel, PRL**103**(2009)042701

Remarks on TDDFT (or TDHF, TDEDF)

✓ There is no adjustable parameter on reaction dynamics

Parameters in an EDF are determined to reproduce known nuclear properties

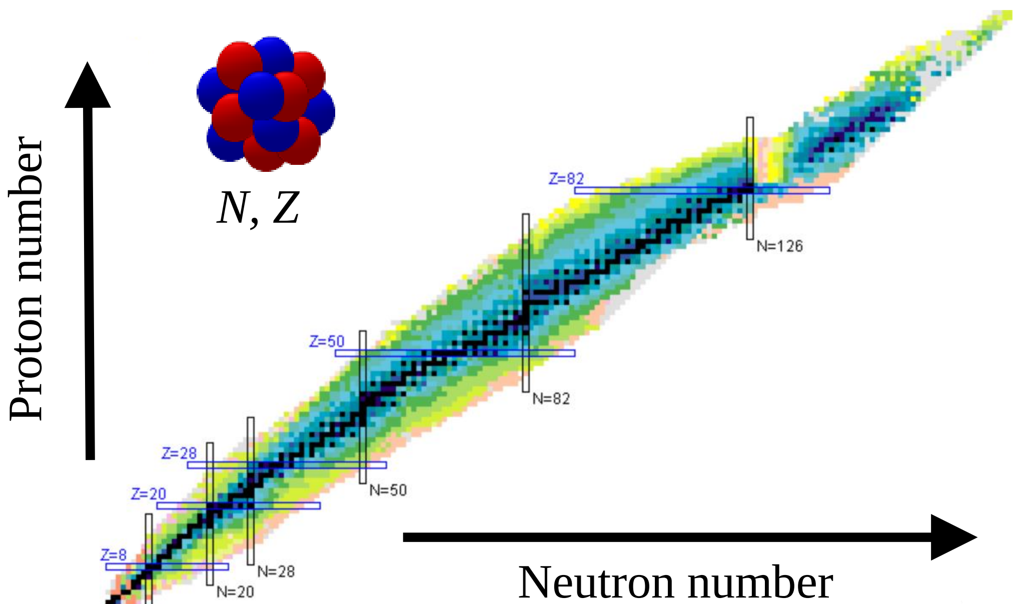
$$S = \int_{t_0}^{t_1} dt \left(i\hbar \sum_i \langle \phi_i(t) | \frac{\partial}{\partial t} | \phi_i(t) \rangle - \boxed{E[\rho(t)]} \right)$$

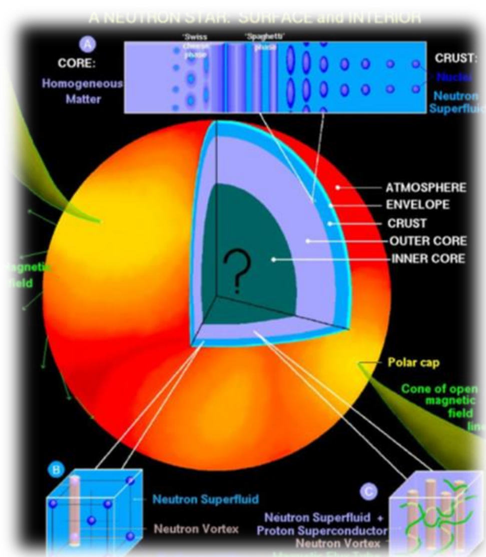
$$i\hbar \frac{\partial \phi_i(\boldsymbol{r}\sigma q, t)}{\partial t} = \hat{h}[\rho(t)]\phi_i(\boldsymbol{r}\sigma q, t) \quad \text{: TDKS eq.}$$

Effective interaction

$$E[\rho] = \langle \Phi | \hat{H} | \Phi \rangle$$

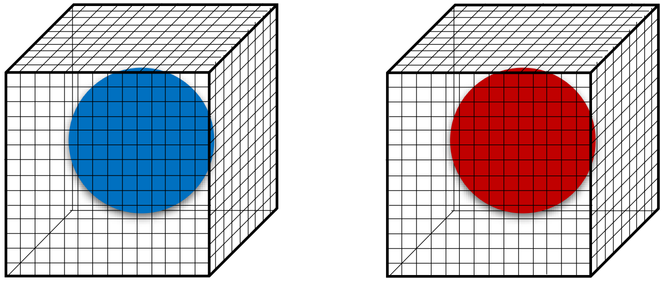
Energy Density Functional (EDF)





Once an EDF is given, there are no empirical parameters

1. Prepare ground states of projectile and target nuclei

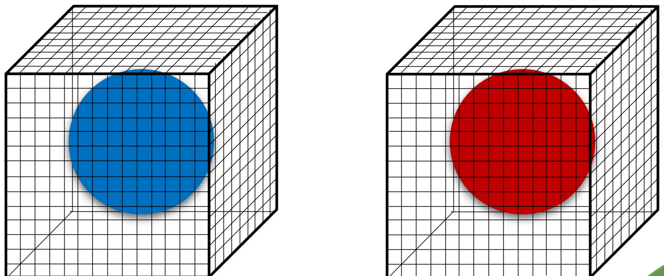


KS equations

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + v_{\text{KS}}[\rho(\boldsymbol{r})]\right]\phi_i(\boldsymbol{r}) = \varepsilon_i\,\phi_i(\boldsymbol{r})$$

Once an EDF is given, there are no empirical parameters

1. Prepare ground states of projectile and target nuclei

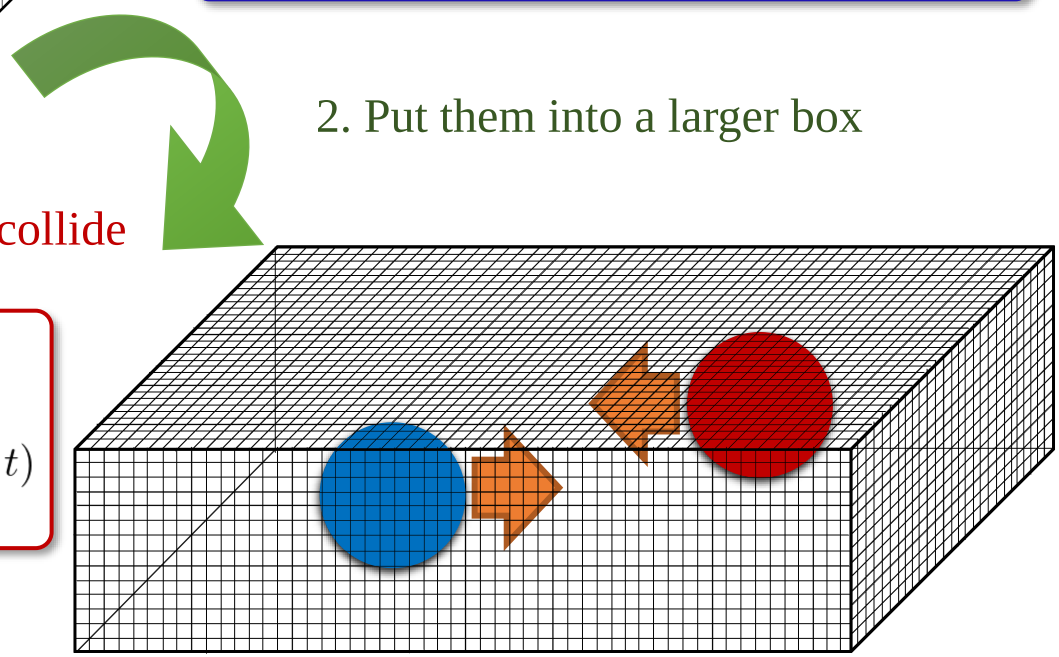


KS equations

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + v_{\rm KS}[\rho(\boldsymbol{r})]\right]\phi_i(\boldsymbol{r}) = \varepsilon_i\,\phi_i(\boldsymbol{r})$$

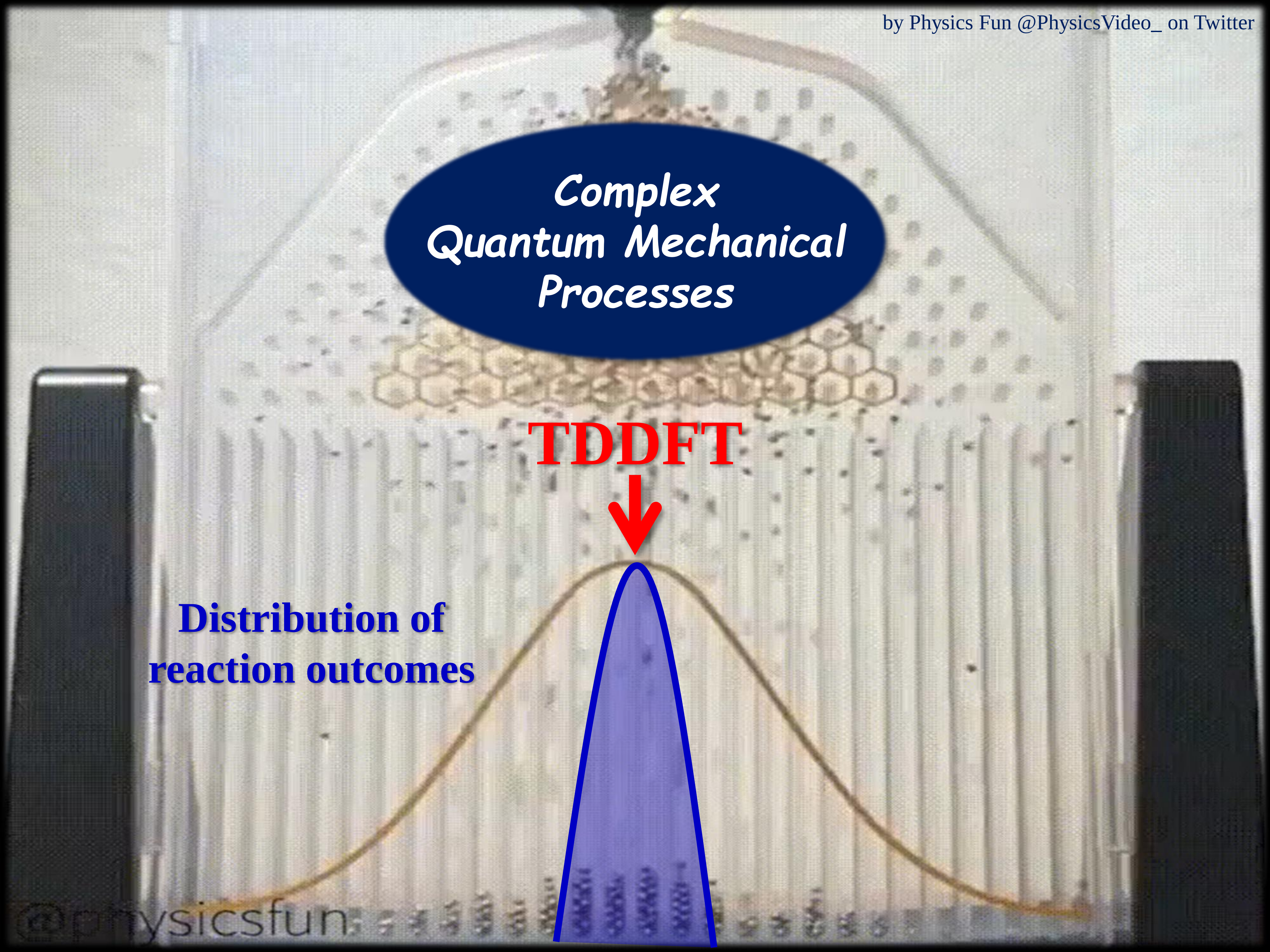
2. Put them into a larger box

3. Give relative momentum, and let them collide



TDKS equations

$$i\hbar\frac{\partial\phi_i(\boldsymbol{r},t)}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + v_{\rm KS}[\rho(\boldsymbol{r},t)]\right]\phi_i(\boldsymbol{r},t)$$



by Physics Fun @PhysicsVideo_ on Twitter
Complex
Quantum Mechanical
Processes
TDDFT
Distribution of
reaction outcomes
@physicsfun

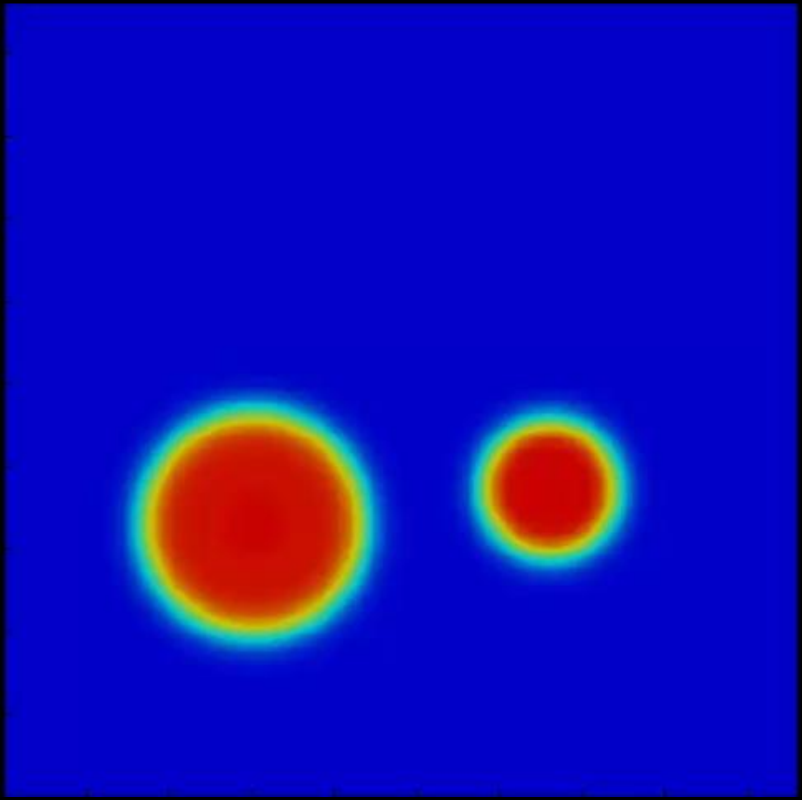
1. Multinucleon transfer reactions

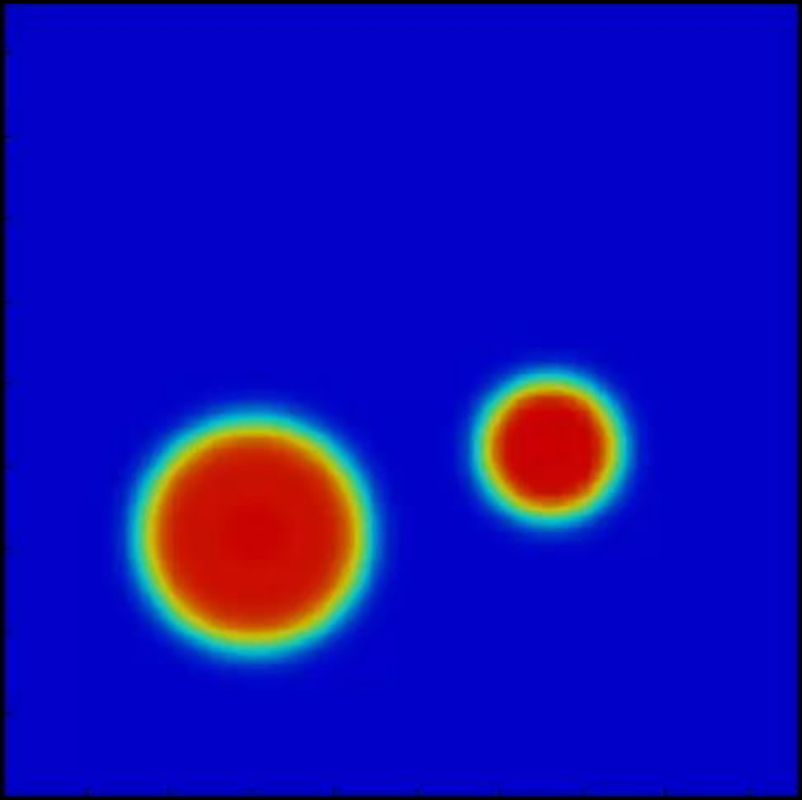
$^{58}Ni+^{208}Pb$ at E_{lab}=328.4 MeV

K.S. and K. Yabana, PRC**88**(2013)014614

TDDFT predicts two distinct transfer mechanisms

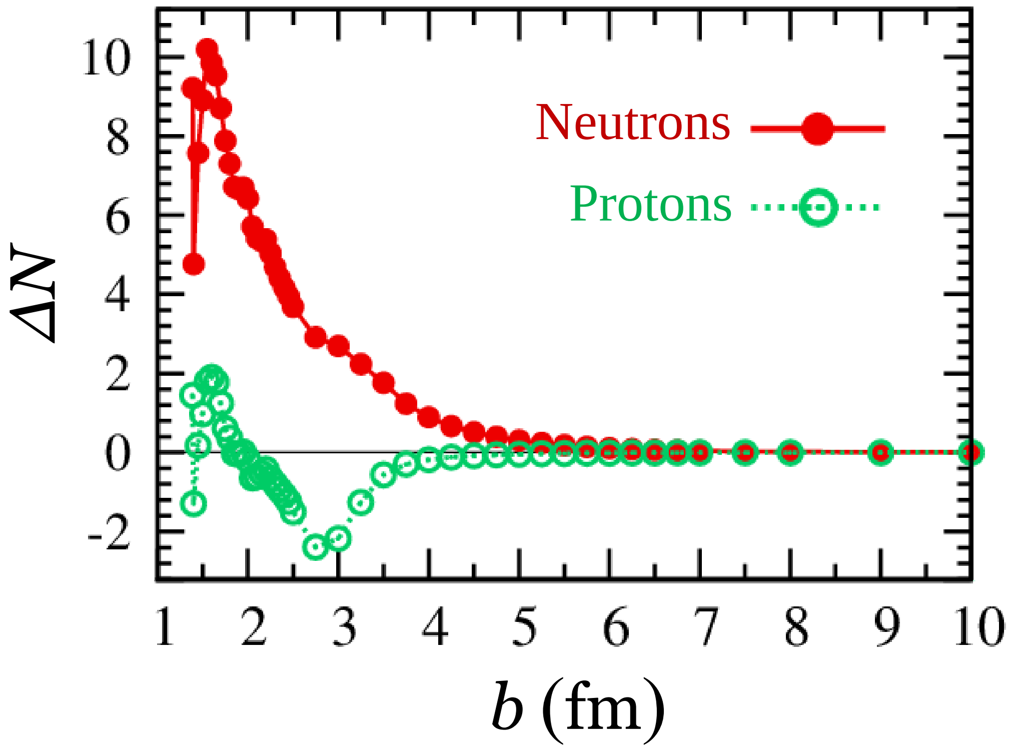
b=1.6 fm	b=4 fm
Neck formation/breaking	Fast charge equilibration





Average number of transferred nucleons *vs.* impact parameter

There appear two transfer mechanisms



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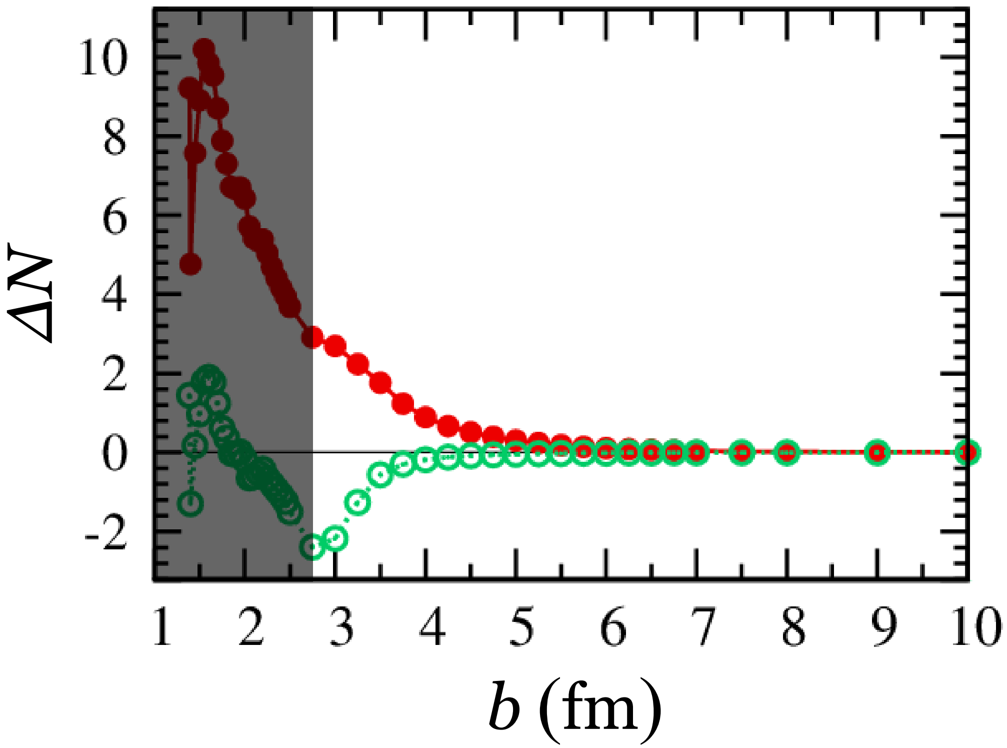

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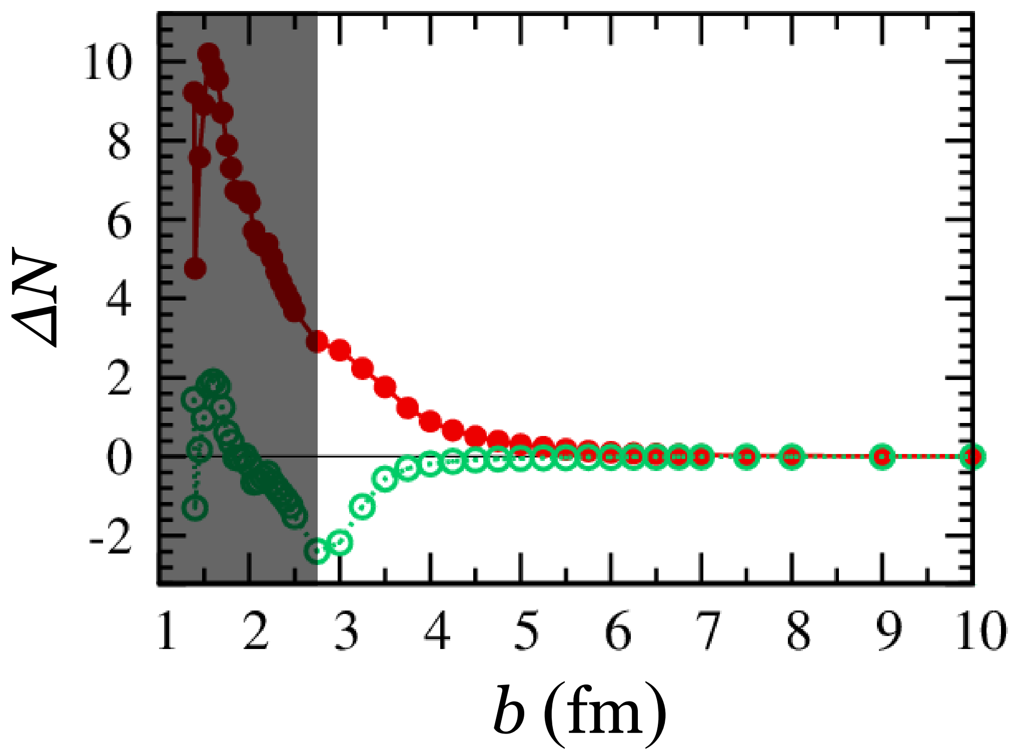
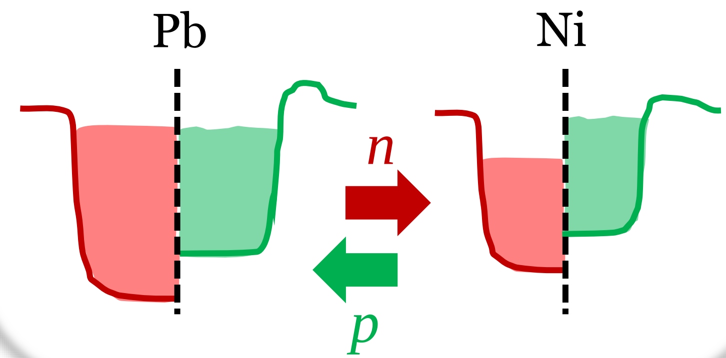


Charge equilibration process

Transfer towards opposite directions



Average number of transferred nucleons *vs.* impact parameter

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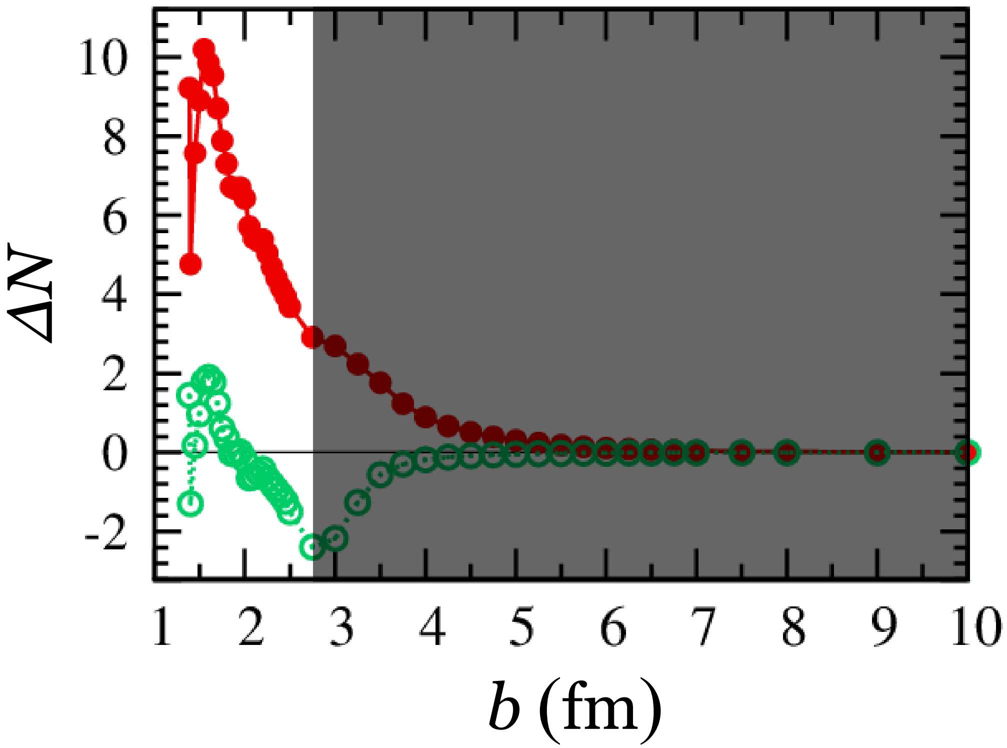

Average number of transferred nucleons *vs.* impact parameter

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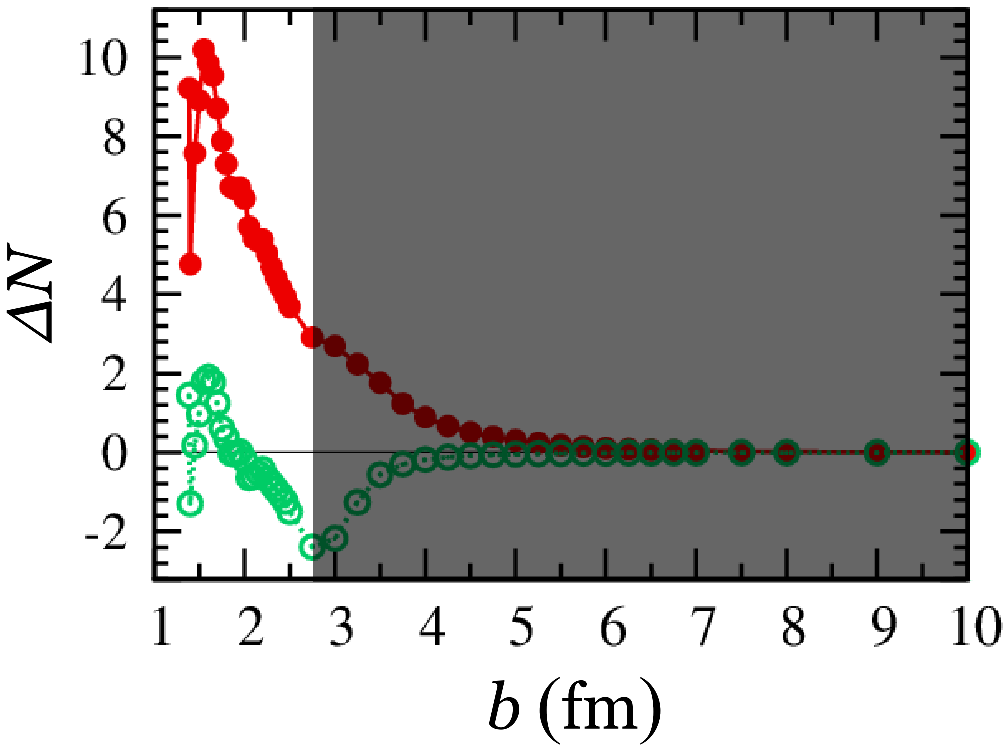

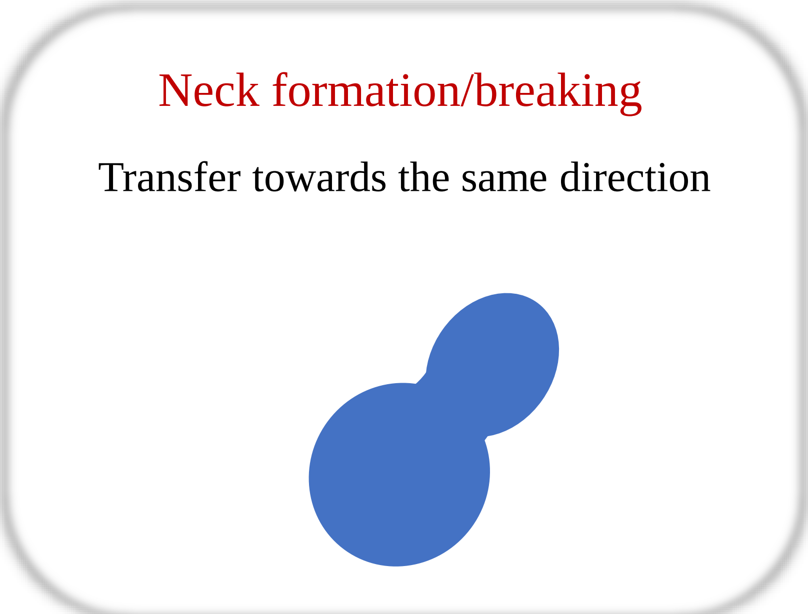

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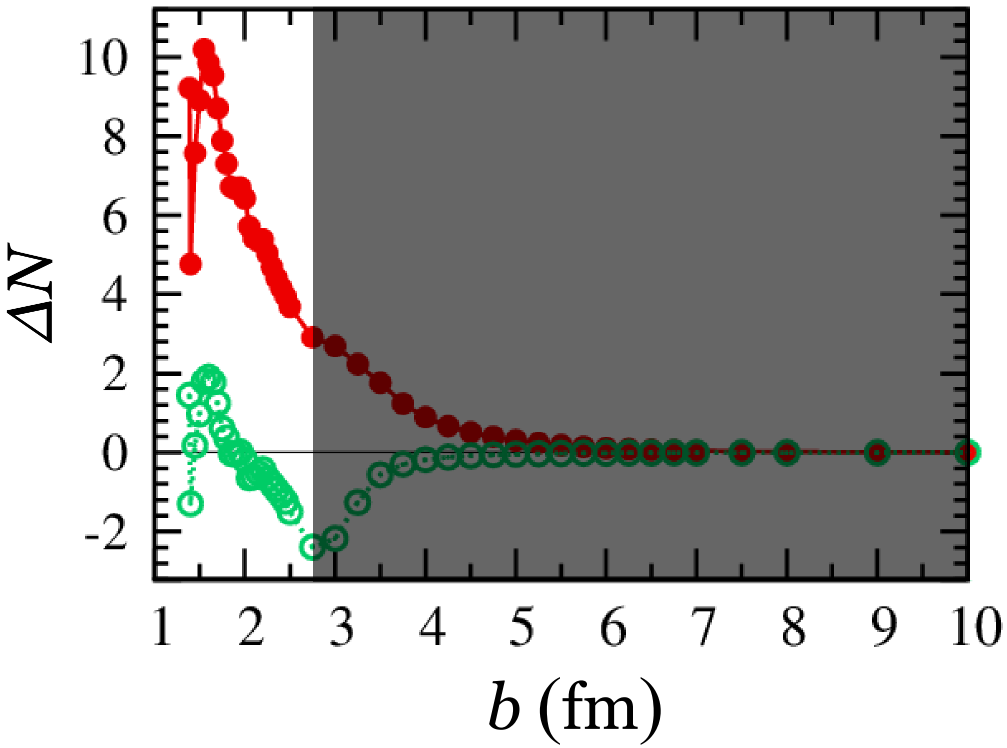
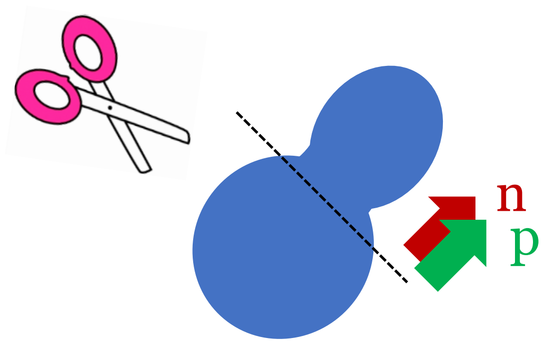


Neck formation/breaking

Transfer towards the same direction

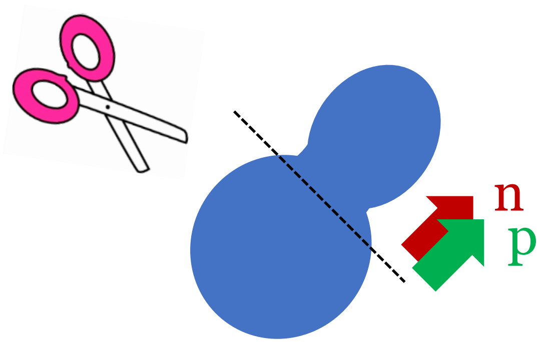


Average number of transferred nucleons *vs.* impact parameter

There appear two transfer mechanisms

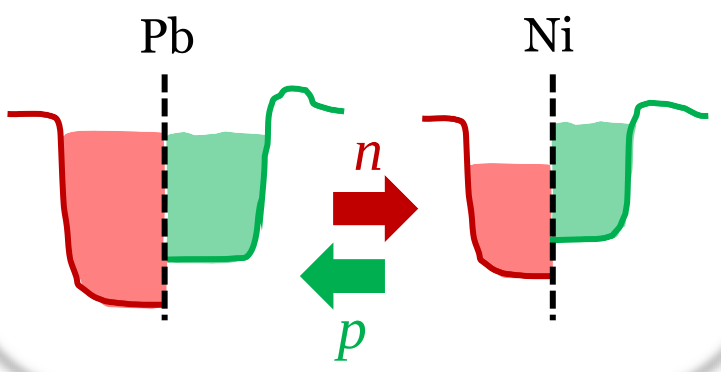
Neck formation/breaking

Transfer towards the same direction



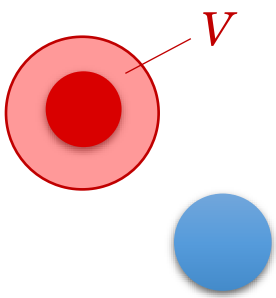
Charge equilibration process

Transfer towards opposite directions



Particle-number projection method

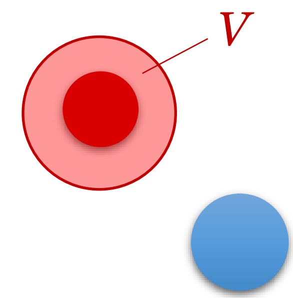
$$P_n = \langle \Phi | \hat{P}_n | \Phi \rangle$$



$$\hat{P}_n = \frac{1}{2\pi} \int_0^{2\pi} e^{i(n-\hat{N}_V)\theta}\, d\theta$$: Particle-number projection operator

Particle-number projection method

$$P_n = \langle \Phi | \hat{P}_n | \Phi \rangle$$



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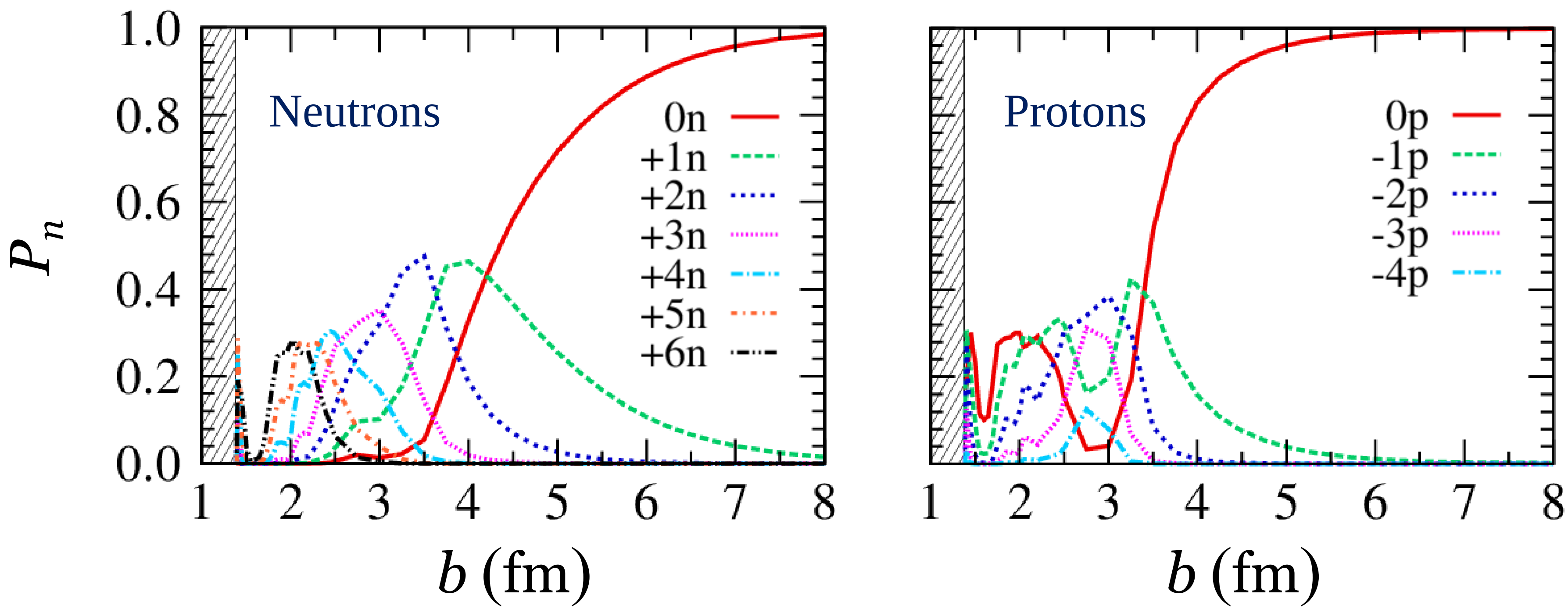
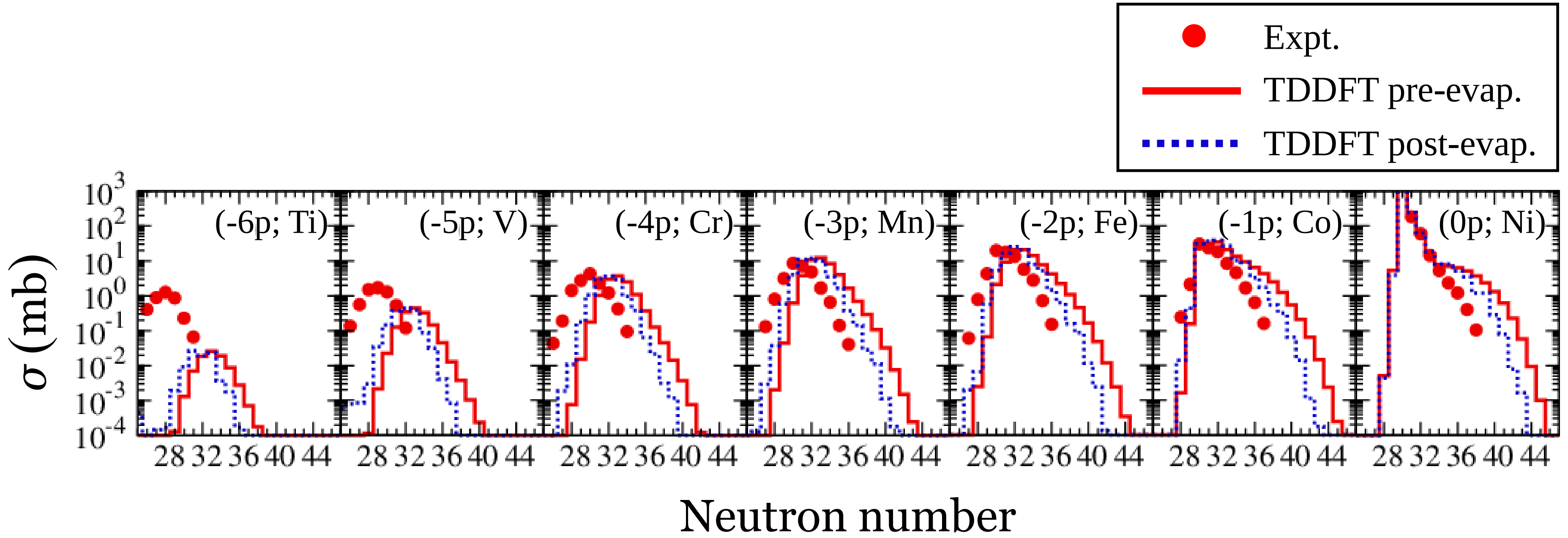


Transfer cross sections: TDDFT *vs.* Expt.

Comparable to measurements, disagreements for many-nucleon transfer

$$\sigma(N,Z) = 2\pi \int_0^\infty b\, P_N^{(n)}(b) P_Z^{(p)}(b)\, db$$

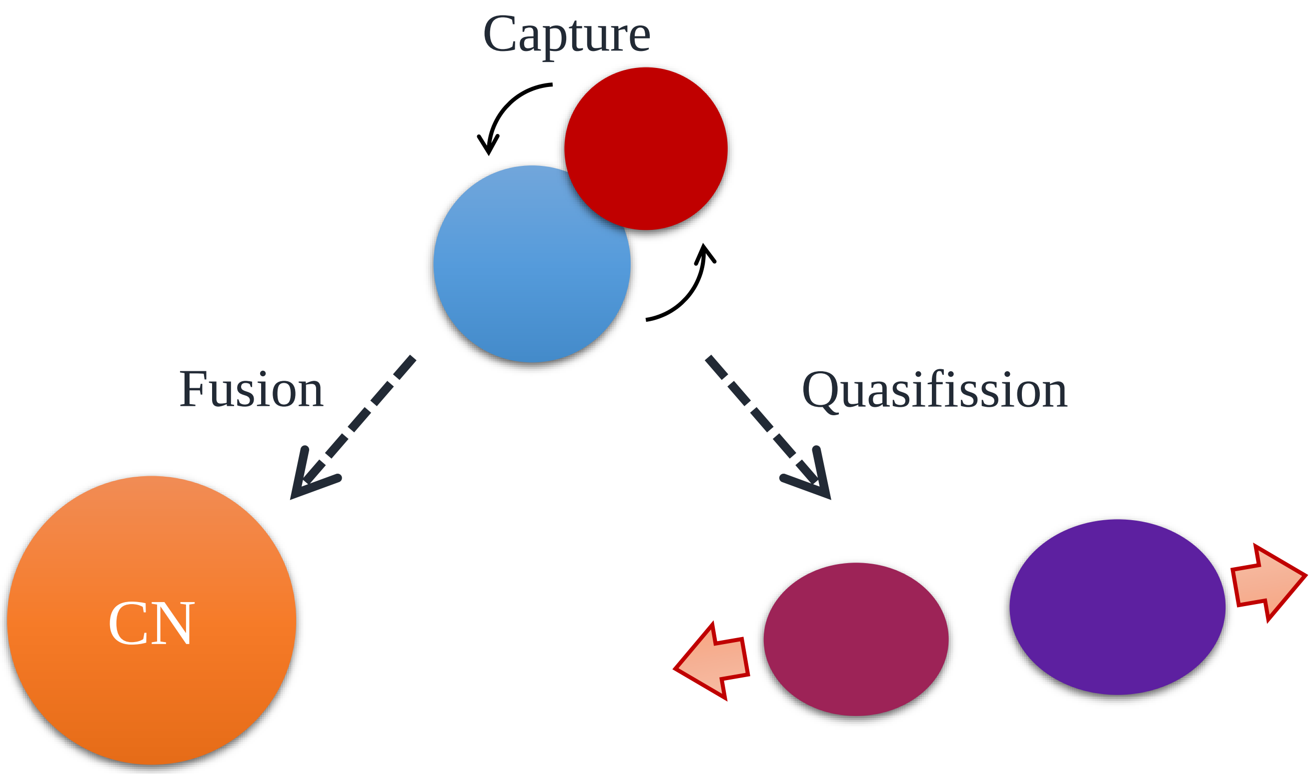


Expt.: L. Corradi *et al.*, PRC**66**(2002)024606

2. Quasifission processes

Quasifission process

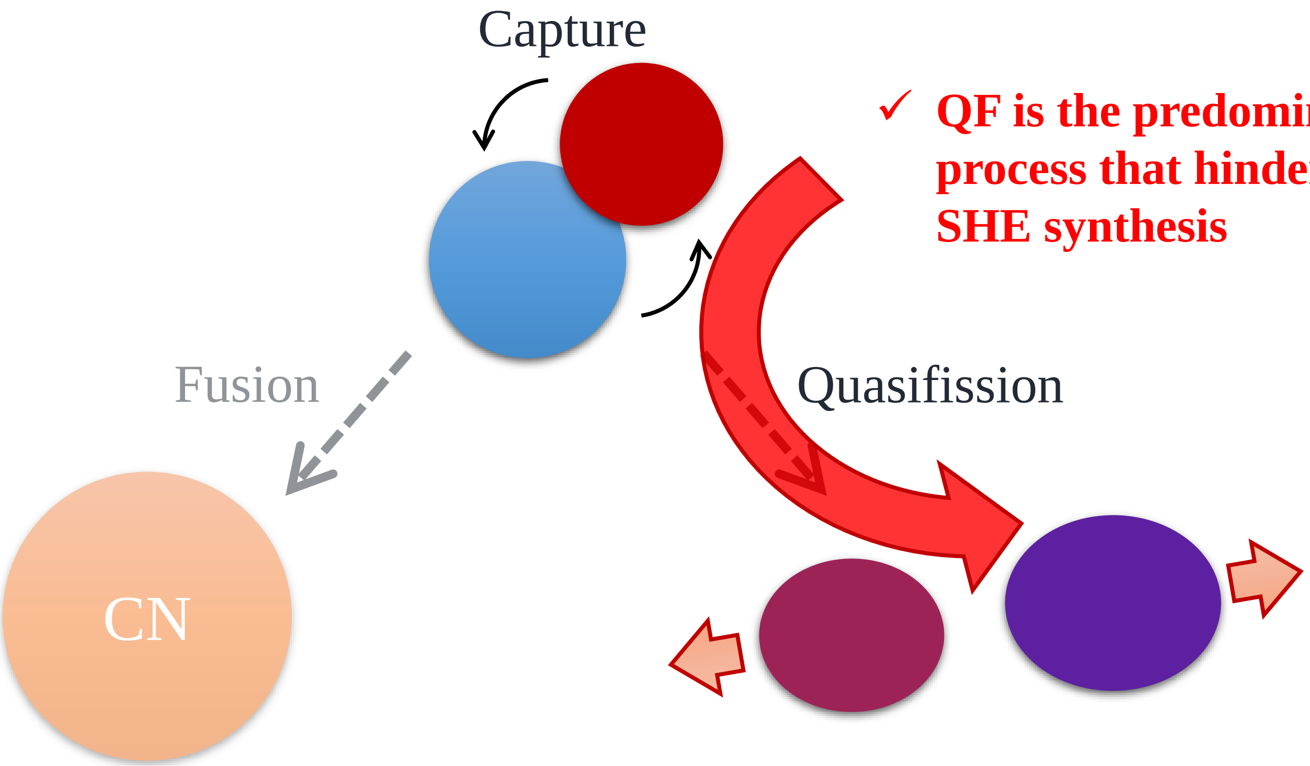
A fast (~10^{-21}-10^{-20} sec) fission process before compound nucleus formation (fusion)



$$\sigma_{\rm ER} \sim W_{\rm surv} * \sigma_{\rm cap} * P_{\rm CN}$$

Quasifission process

A fast (~10^{-21}-10^{-20} sec) fission process before compound nucleus formation (fusion)



✓ **QF is the predominant process that hinders SHE synthesis**

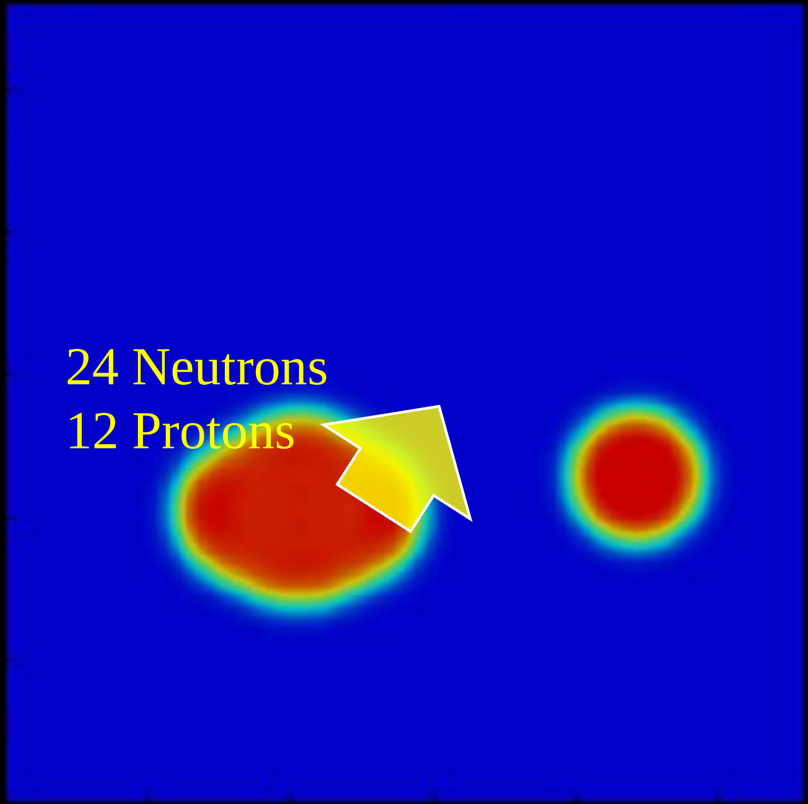
$$\sigma_{\rm ER} \sim W_{\rm surv} * \sigma_{\rm cap} * P_{\rm CN}$$

K.S. and K. Yabana, PRC**93**(2016)054616

Quasifission dynamics in TDDFT

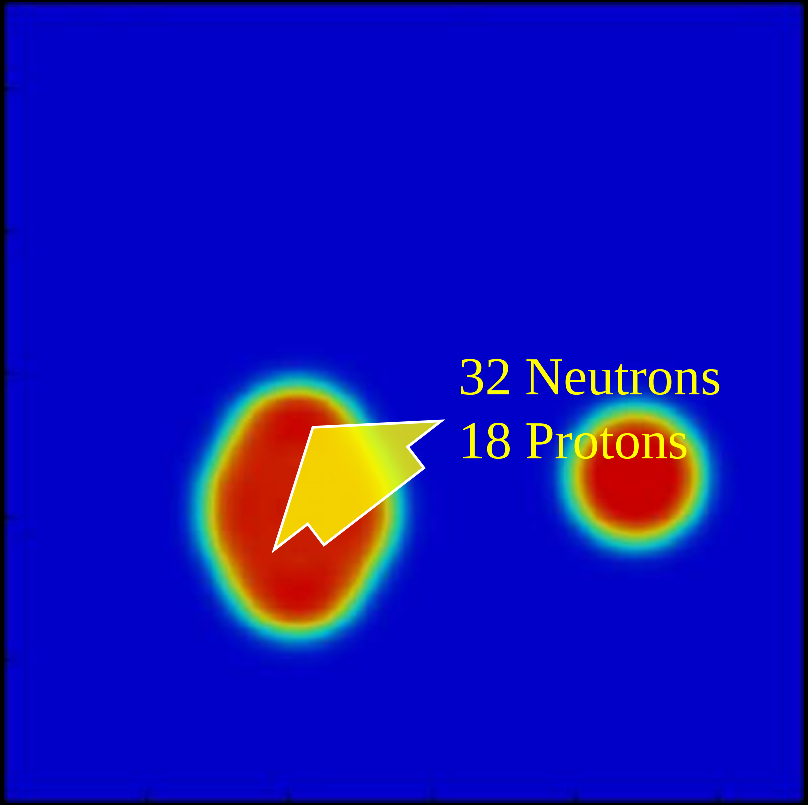
Tip collision

Shell effects of ^{208}Pb



Side collision

More mass-symmetric

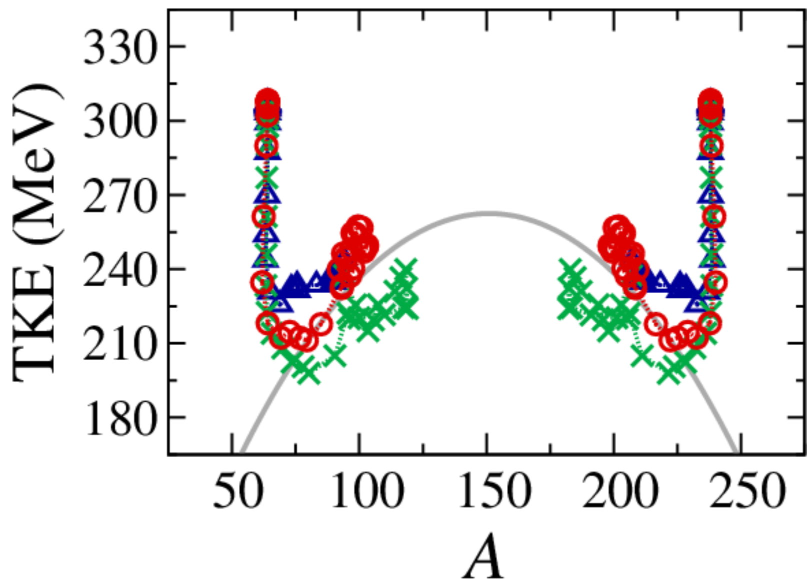


K.S. and K. Yabana, PRC**93**(2016)054616

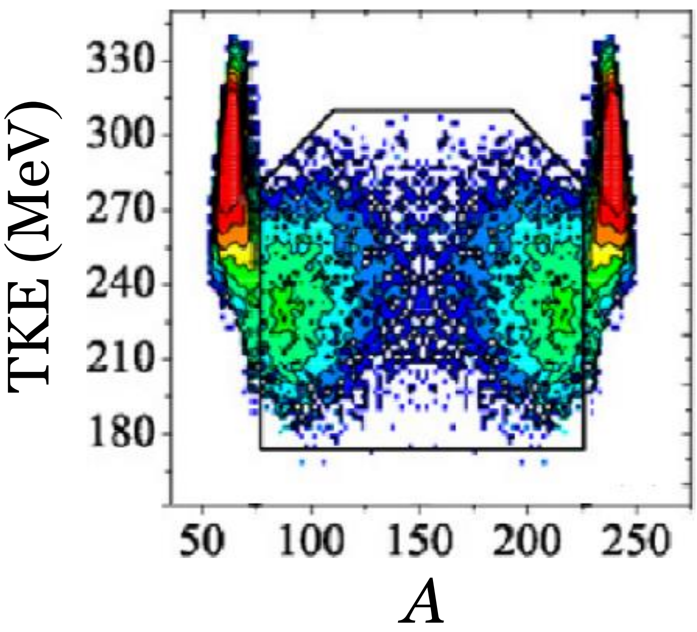
TDDFT provides quantitative description of quasifission dynamics

TKE-*A* distribution: Comparison with experimental data

TDDFT



Experiment

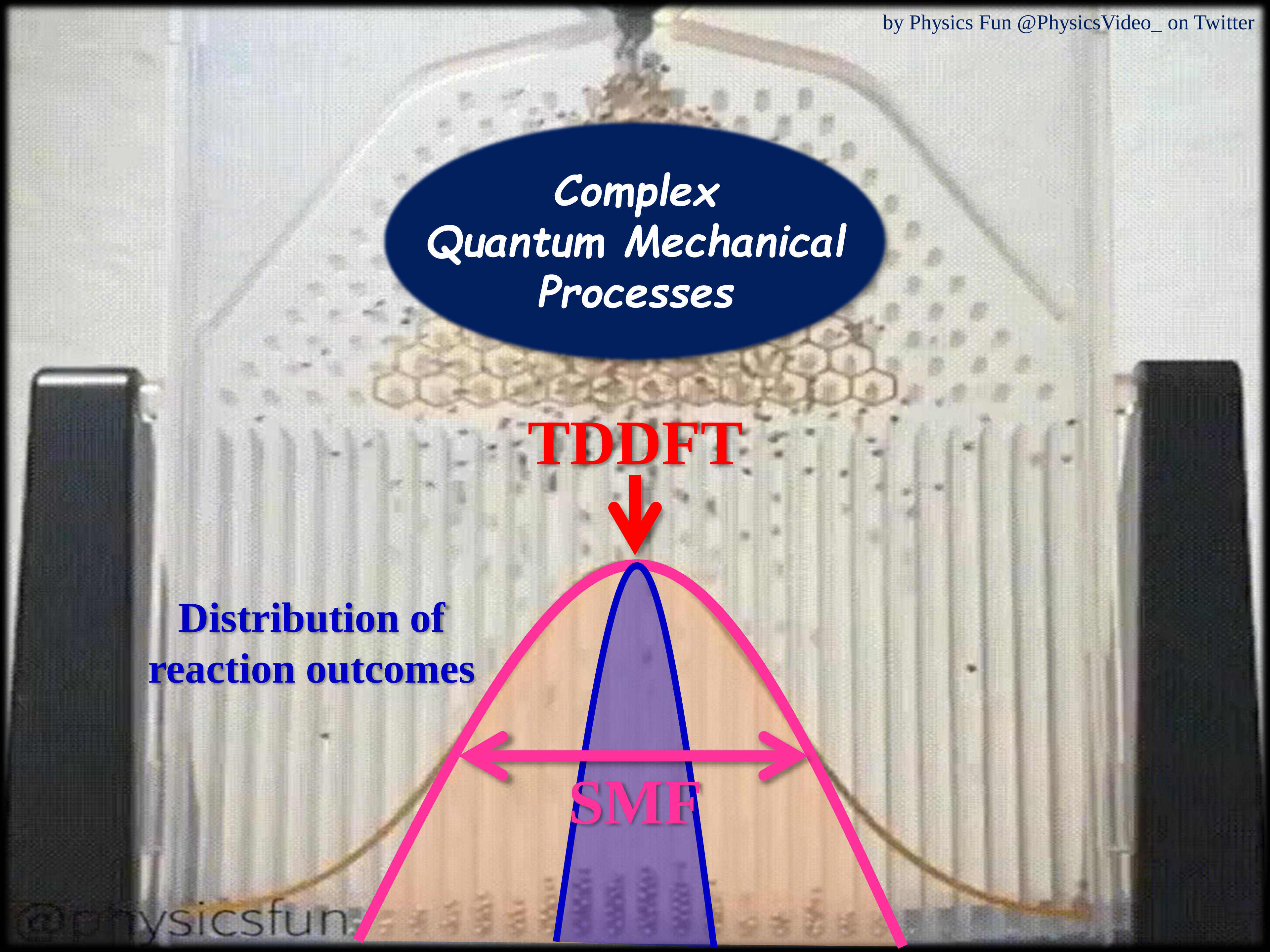


Expt.: E.M. Kozulin *et al.*, PLB**686**(2010)227

However, TDDFT can not properly describe the distribution of observables

⬇

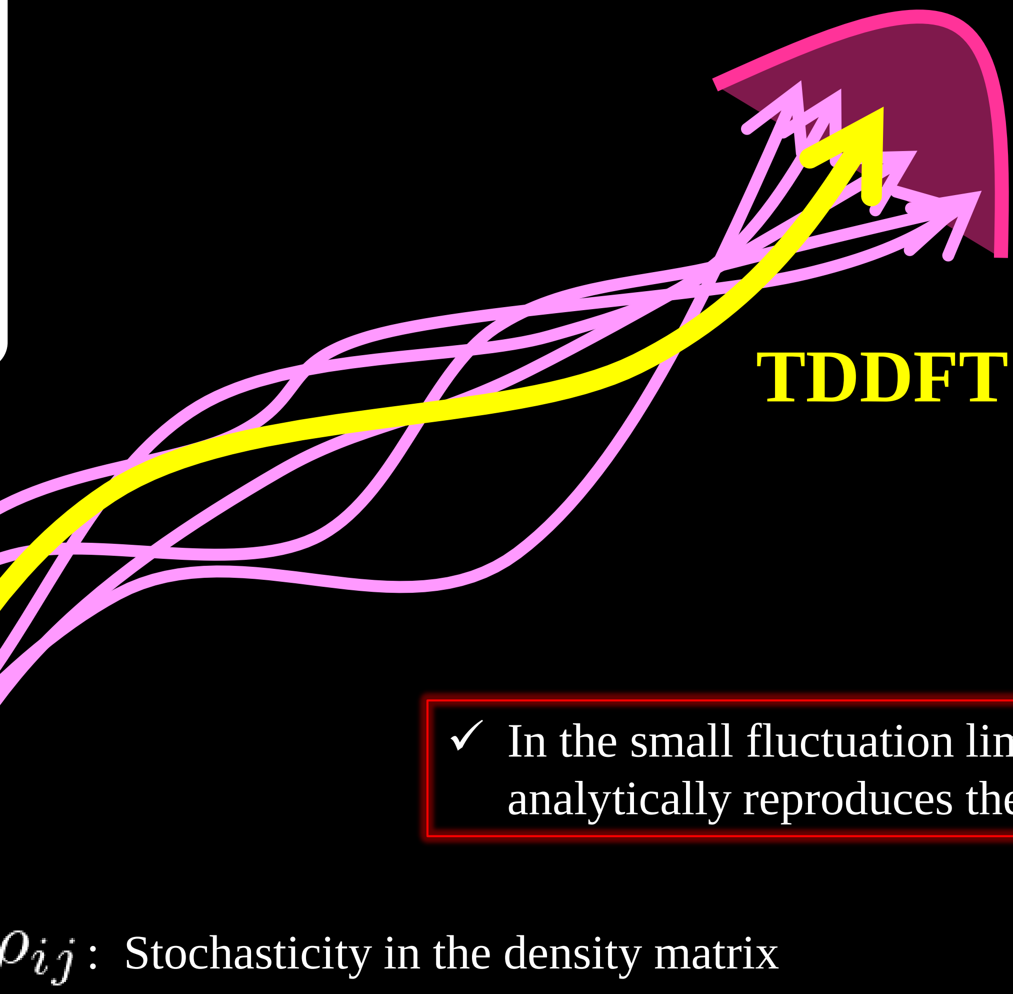
Stochastic extensions


by Physics Fun @PhysicsVideo_ on Twitter
Complex Quantum Mechanical Processes
TDDFT
Distribution of reaction outcomes
SMF
@physicsfun

Stochastic Mean-Field (SMF) approach

S. Ayik, Phys. Lett. **B658**, 174 (2008)
D. Lacroix and S. Ayik, Eur. Phys. J. A **50**, 95 (2014)

Sakir Ayik
(Tennessee Tech.)



Observables are evaluated by an ensemble average

- ✓ In the small fluctuation limit, SMF approach analytically reproduces the TDRPA formula

$\delta\rho_{ij}$: Stochasticity in the density matrix

SMF approach: Quantal diffusion description

K.S. and S. Ayik, PRC**102**(2020)014620

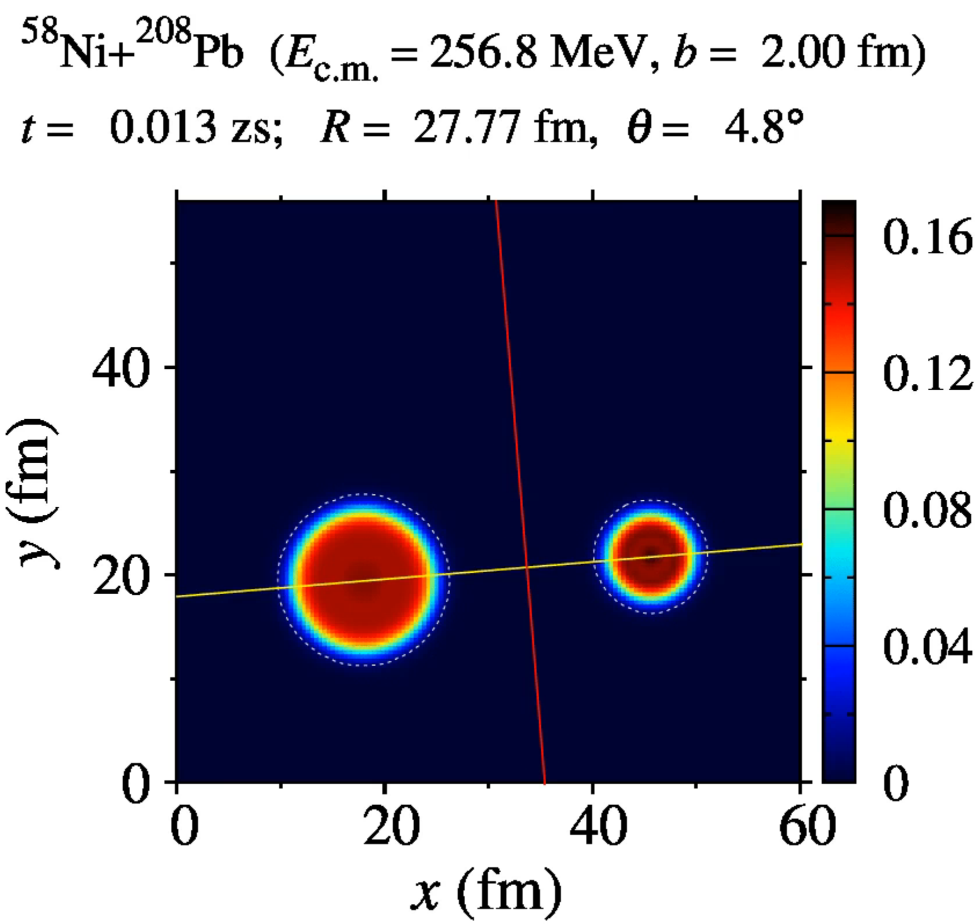
The widths develop in time by nucleon exchanges through the window

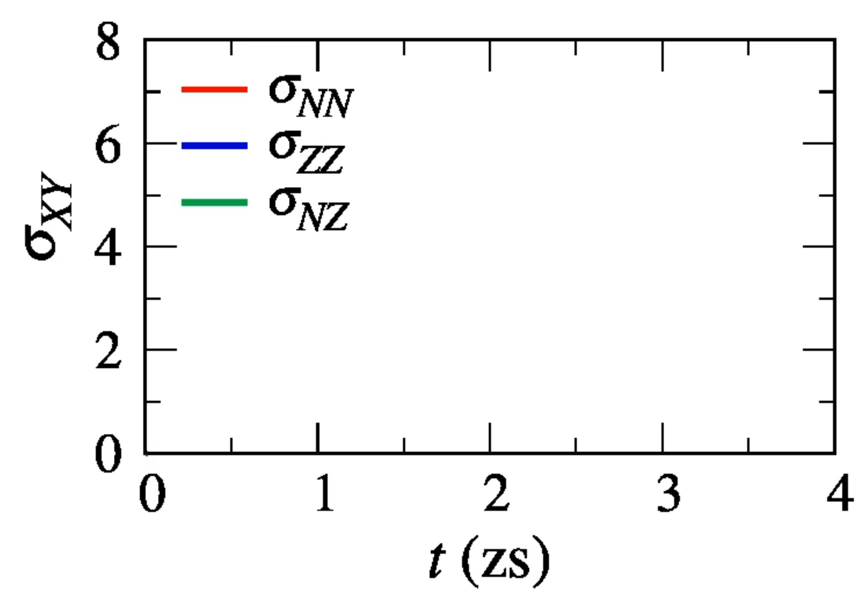
*Drift and diffusion coefficients (v & D) are determined by TDHF

$$\frac{\partial \sigma^2_{NN}}{\partial t} = 2\frac{\partial \nu_n}{\partial N_1}\sigma^2_{NN} + 2\frac{\partial \nu_n}{\partial Z_1}\sigma^2_{NZ} + 2D_{NN}$$

$$\frac{\partial \sigma^2_{ZZ}}{\partial t} = 2\frac{\partial \nu_p}{\partial Z_1}\sigma^2_{ZZ} + 2\frac{\partial \nu_p}{\partial N_1}\sigma^2_{NZ} + 2D_{ZZ}$$

$$\frac{\partial \sigma^2_{NZ}}{\partial t} = 2\frac{\partial \nu_p}{\partial N_1}\sigma^2_{NN} + 2\frac{\partial \nu_n}{\partial Z_1}\sigma^2_{ZZ} + \left(\frac{\partial \nu_n}{\partial N_1} + \frac{\partial \nu_p}{\partial Z_1}\right)\sigma^2_{NZ}$$



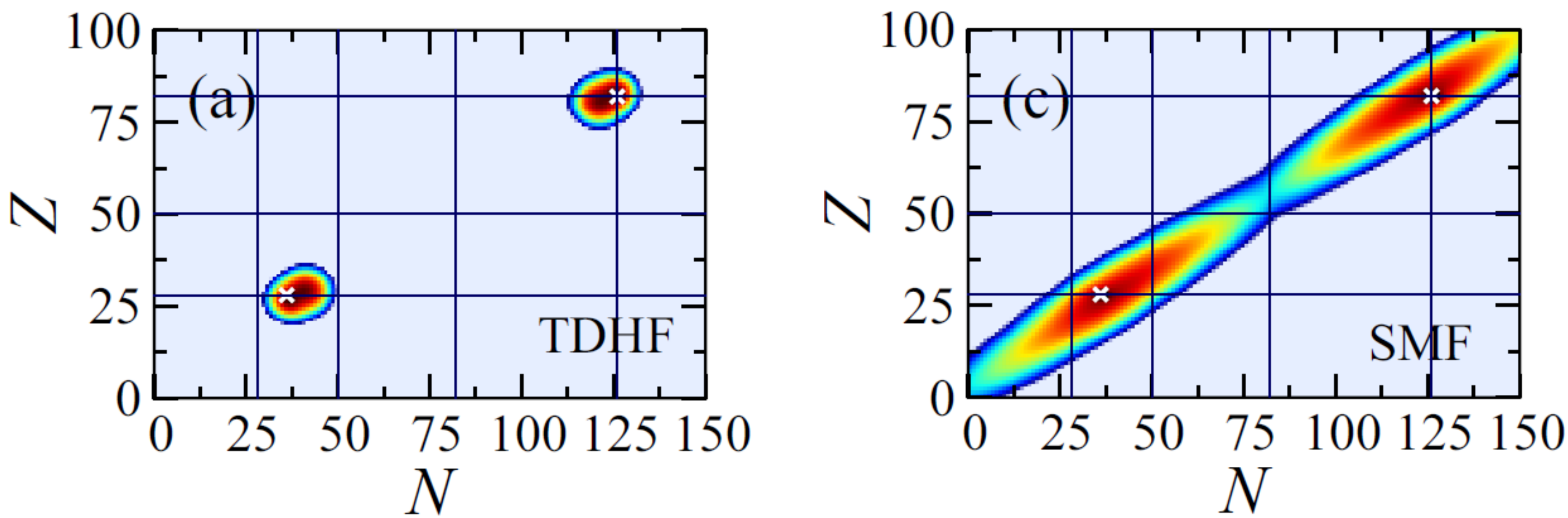


The SMF approach predicts a much wider distribution

$$\sigma(N,Z) = 2\pi \int_{b_{\min}}^{b_{\max}} b\, P_{N,Z}(b)\, db$$

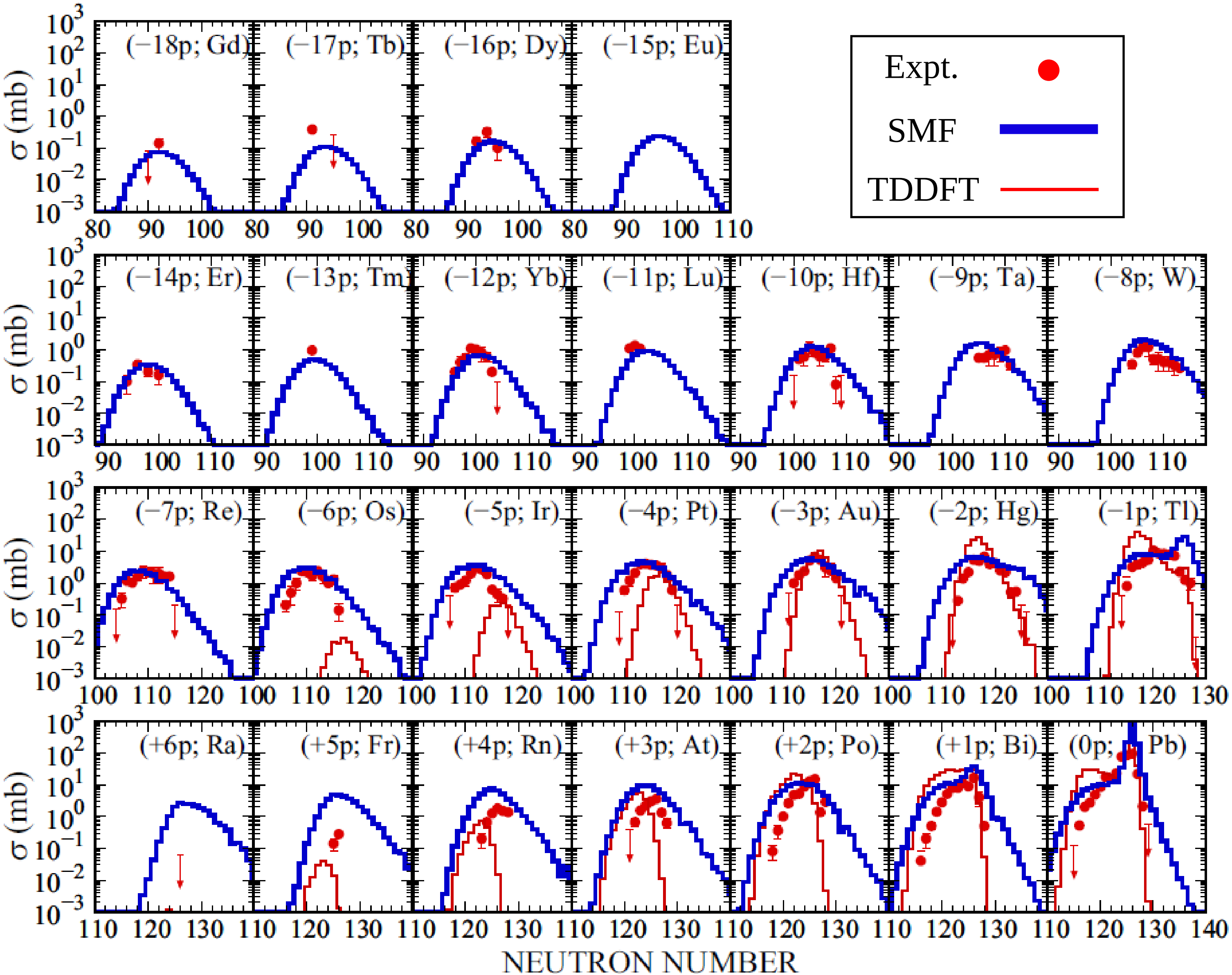
*$P_{N,Z}(b)$: transfer probability
Particle-number projection for TDHF
Correlated Gaussian for SMF

Primary production cross sections for lighter fragments



$$P_{N,Z}^{\mathrm{SMF}}(b) = \frac{1}{2\pi\sigma_{NN}(b)\sigma_{ZZ}(b)\sqrt{1-\rho^2(b)}}$$
$$\times \exp\left\{-\frac{1}{2(1-\rho^2(b))}\left[\left(\frac{N-\bar{N}(b)}{\sigma_{NN}(b)}\right)^2 + \left(\frac{Z-\bar{Z}(b)}{\sigma_{ZZ}(b)}\right)^2 + 2\rho(b)\left(\frac{N-\bar{N}(b)}{\sigma_{NN}(b)}\right)\left(\frac{Z-\bar{Z}(b)}{\sigma_{ZZ}(b)}\right)\right]\right\} \qquad \rho(b) = \frac{\sigma_{NZ}^2(b)}{\sigma_{NN}(b)\sigma_{ZZ}(b)}$$

Secondary production cross sections for heavier fragments



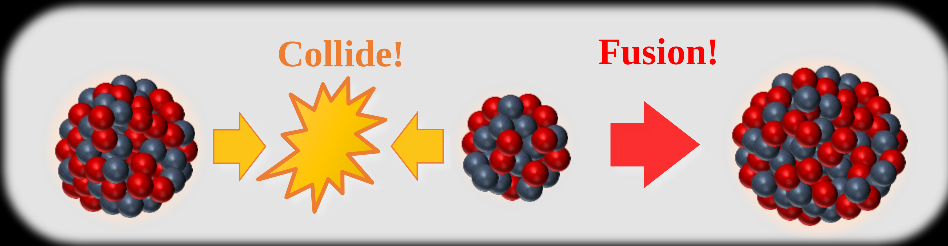
Expt.: W. Królas *et al.*, Nucl. Phys. A **724**, 289 (2010)

At the frontiers in nuclear physics:

3. Synthesis of superheavy elements

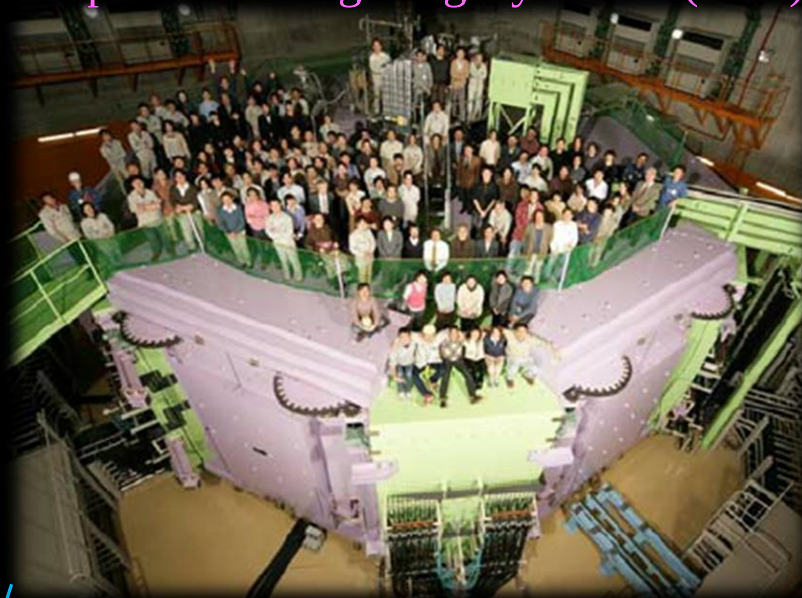
→ **also relevant to chemistry**

Nucleosynthesis at accelerator facilities

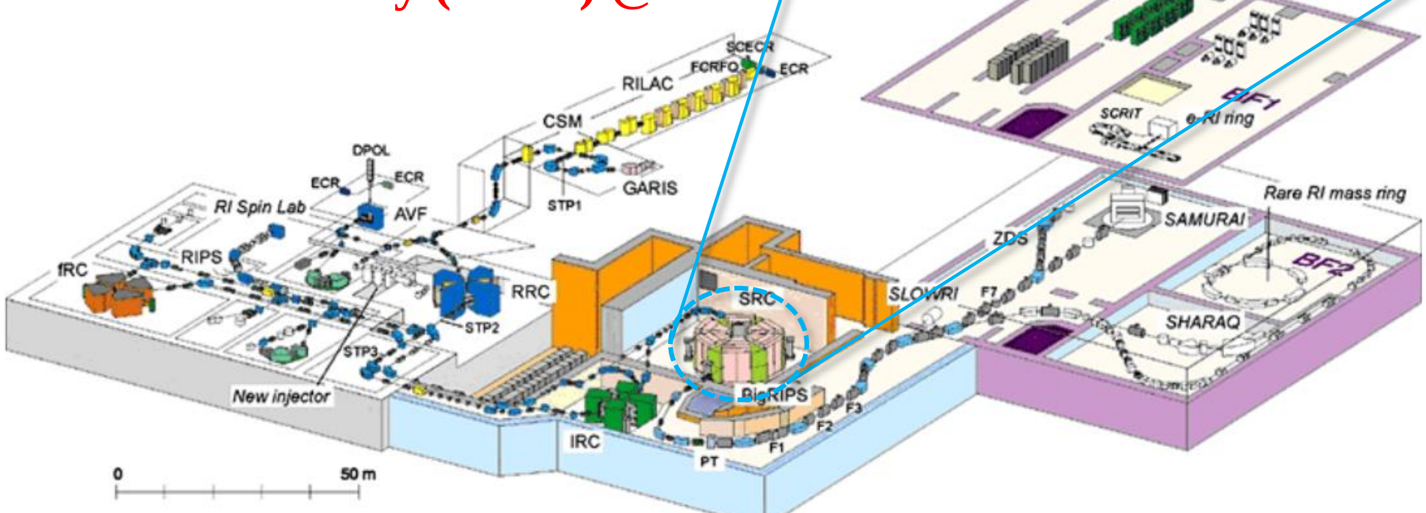


The world-leading factory of unstable nuclei!

Superconducting Ring Cyclotron (SRC)

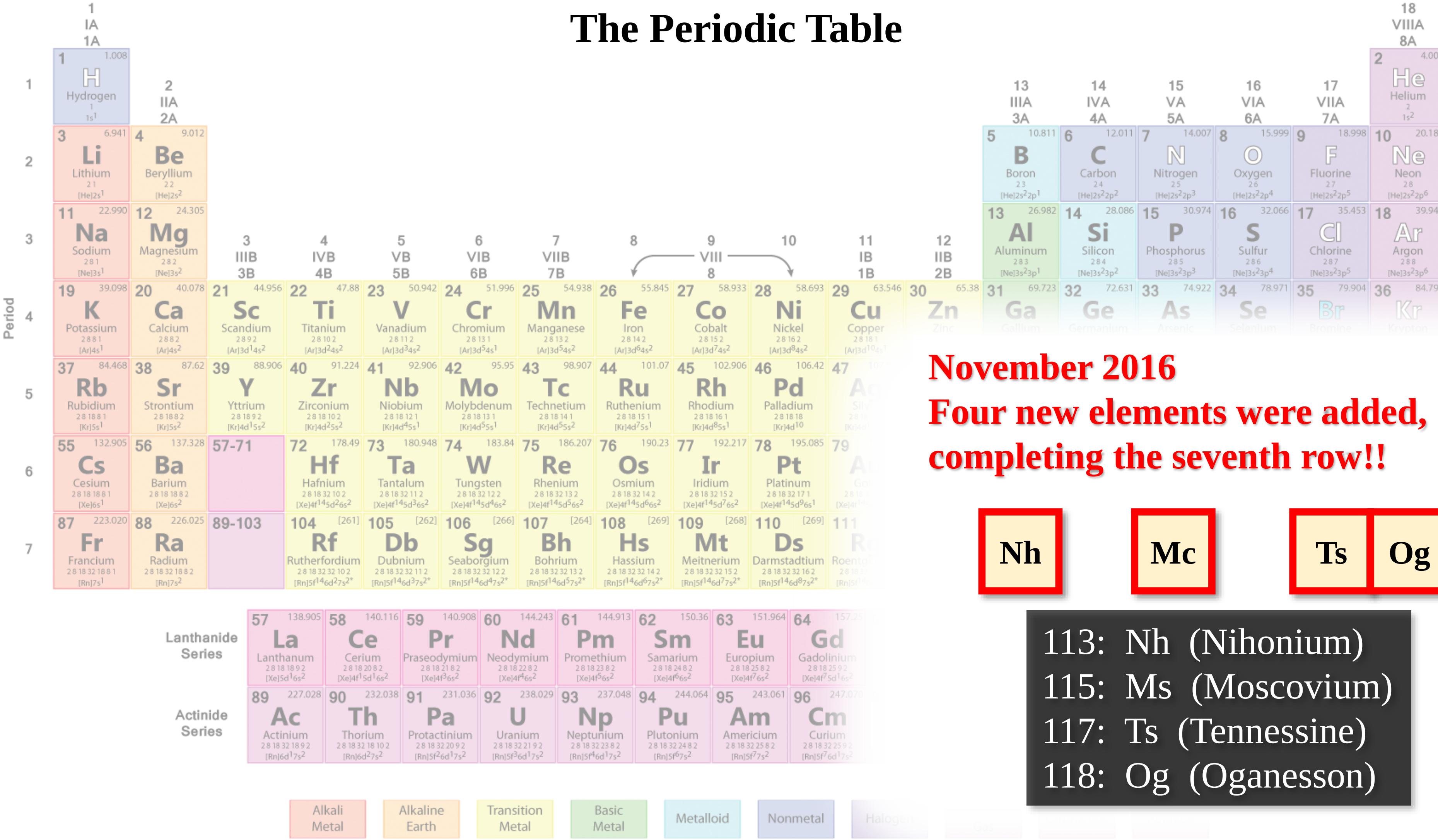


RI Beam Factory (RIBF) @RIKEN



The periodic table is growing!

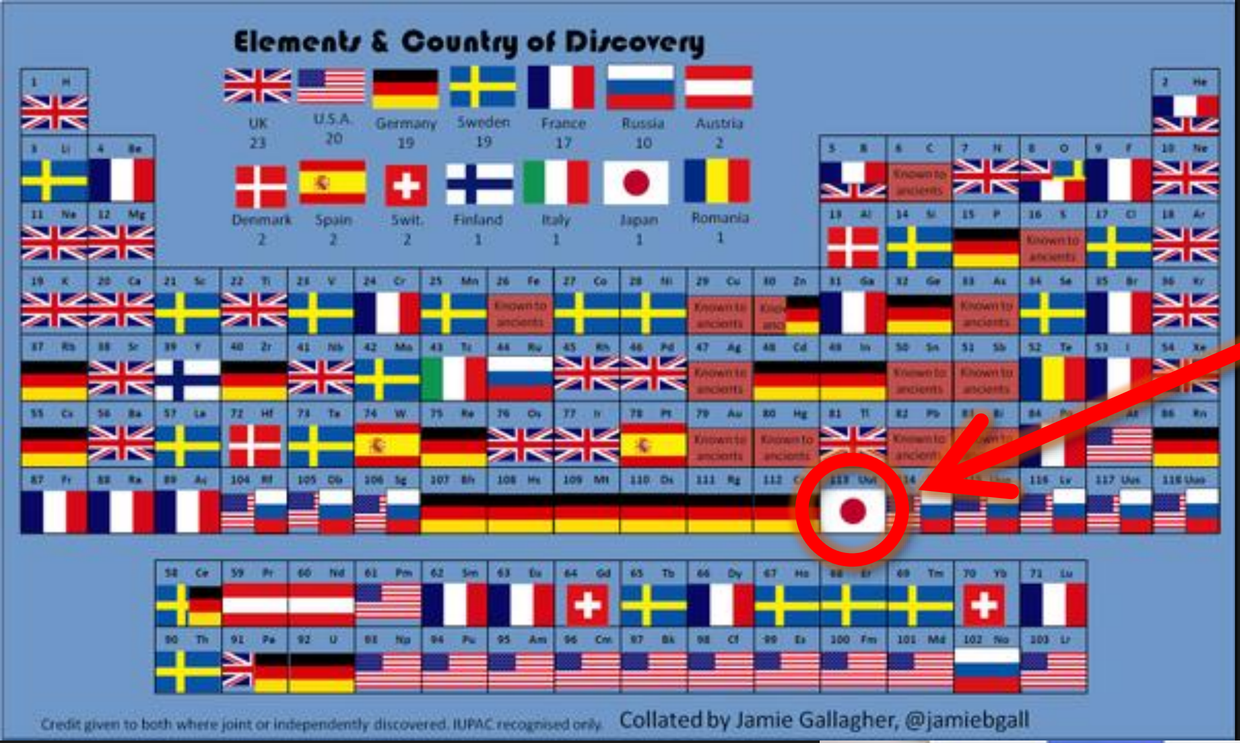
Synthesis of "superheavy element" is the most challenging subject in nuclear physics



November 2016
Four new elements were added, completing the seventh row!!

Nh **Mc** **Ts** **Og**

113: Nh (Nihonium)
115: Ms (Moscovium)
117: Ts (Tennessine)
118: Og (Oganesson)



Nihonium is the only one discovered by Asian country:

The element 113

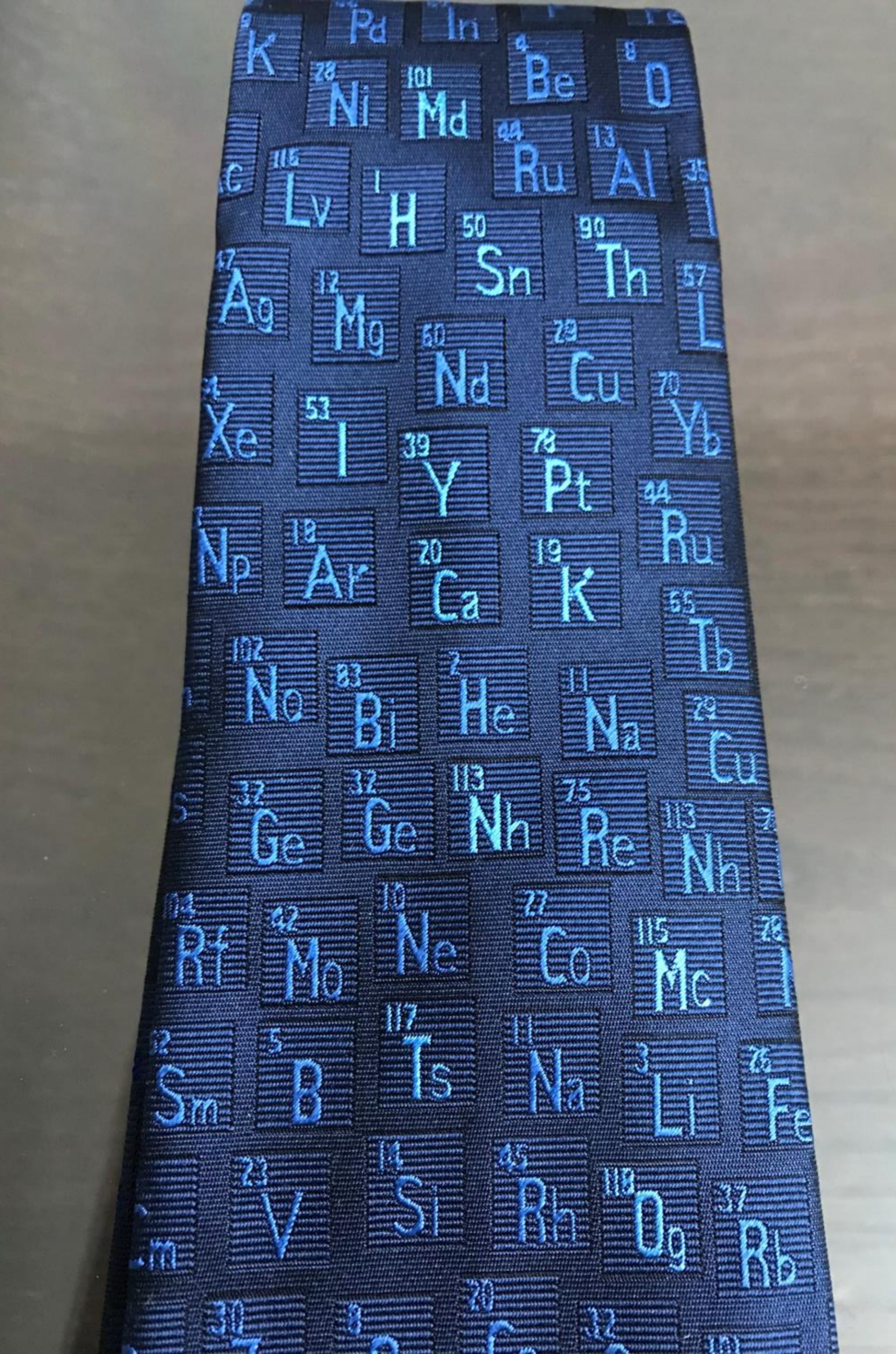
Nov. 30, 2016: Name confirmed

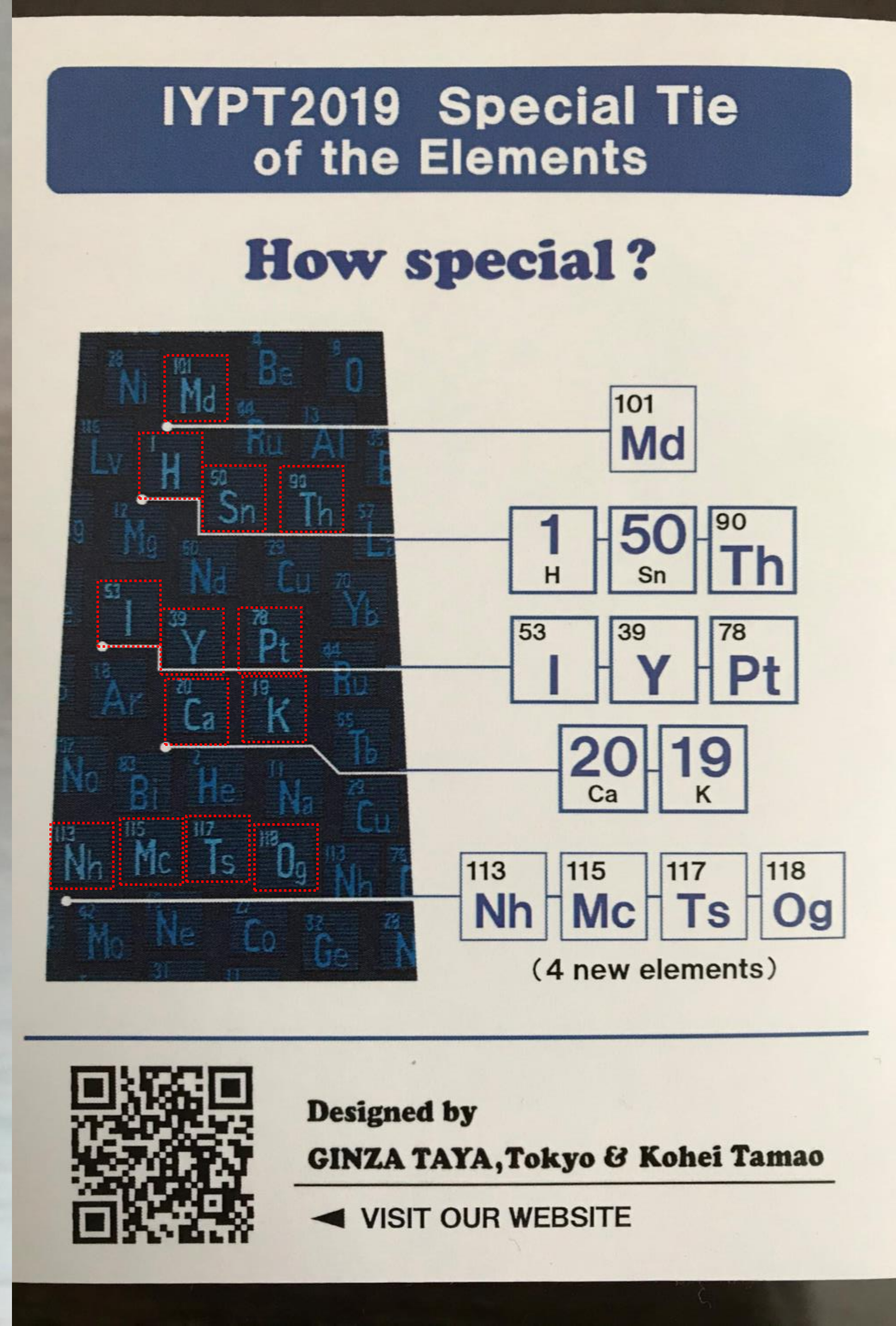
June 8, 2016: Name announced

Dec. 31, 2015: Naming rights given

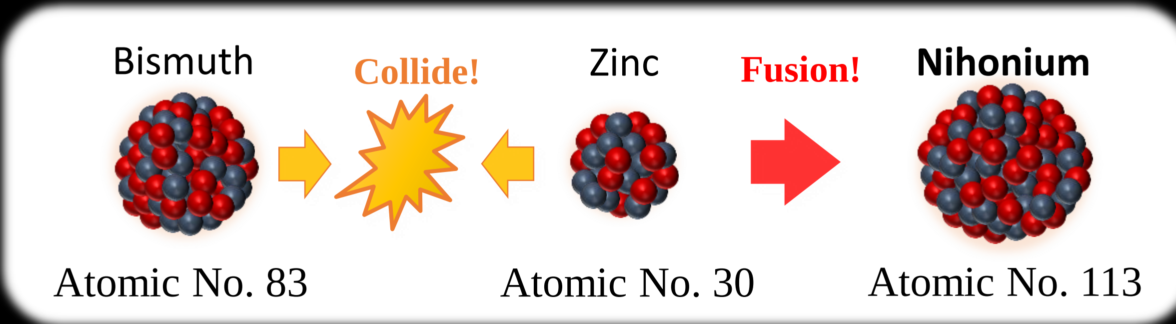
2019 was the 150th anniversary of the Periodic Table!

Dec. 5, 2019@Tokyo Prince Hotel




IYPT2019 Special Tie of the Elements
How special ?
101 Md
1 H
50 Sn
90 Th
53 I
39 Y
78 Pt
20 Ca
19 K
113 Nh
115 Mc
117 Ts
118 Og
(4 new elements)
Designed by
GINZA TAYA, Tokyo & Kohei Tamao
◀ VISIT OUR WEBSITE

A long way to synthesize Nihonium



Sep. 2003 expt. started --> ~100 days irradiation --> ~100 days irradiation --> ~360 days irradiation

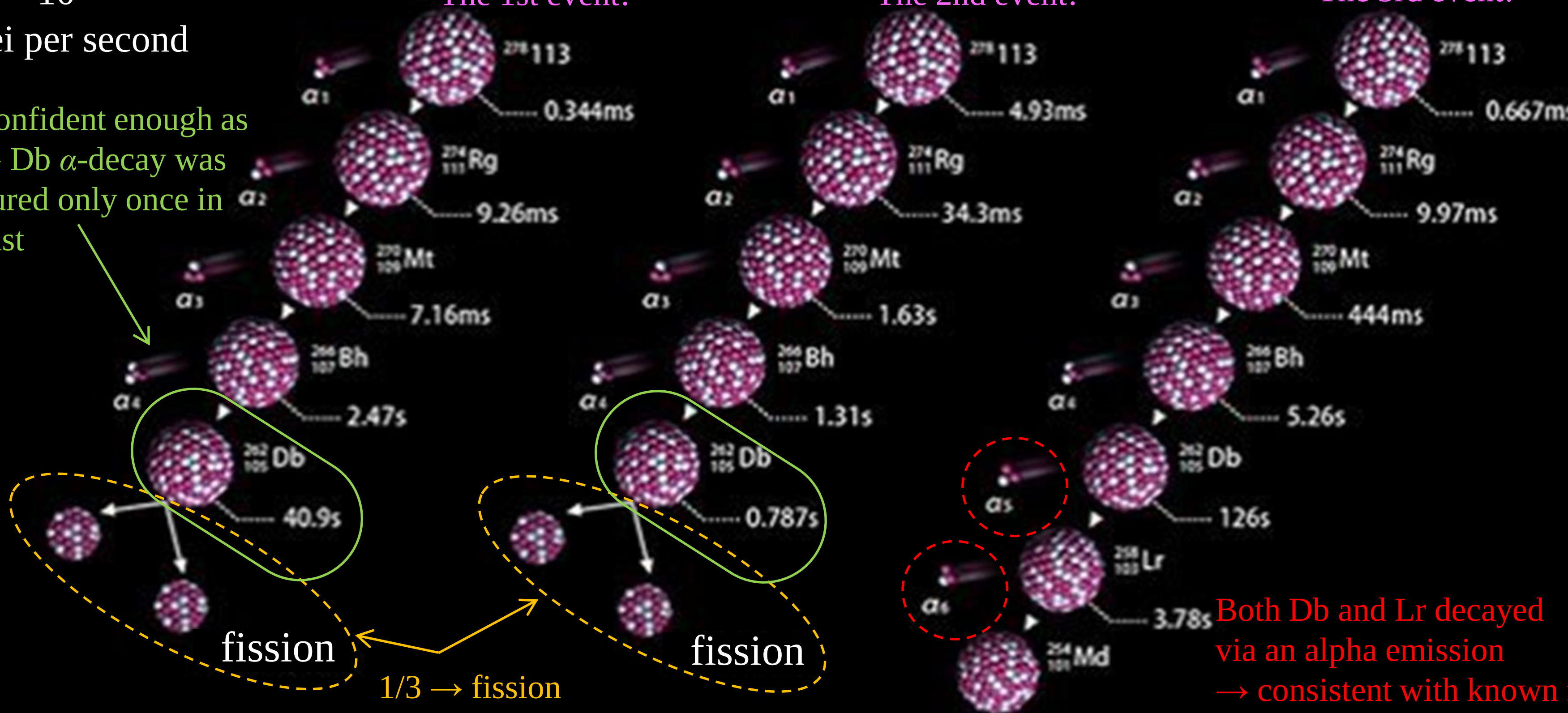
July 23, 2004 — The 1st event!

April 2, 2005 — The 2nd event!

Aug. 12, 2012 — The 3rd event!

~ 2.4×10^{12} nuclei per second

Not confident enough as Bh → Db α-decay was measured only once in the past

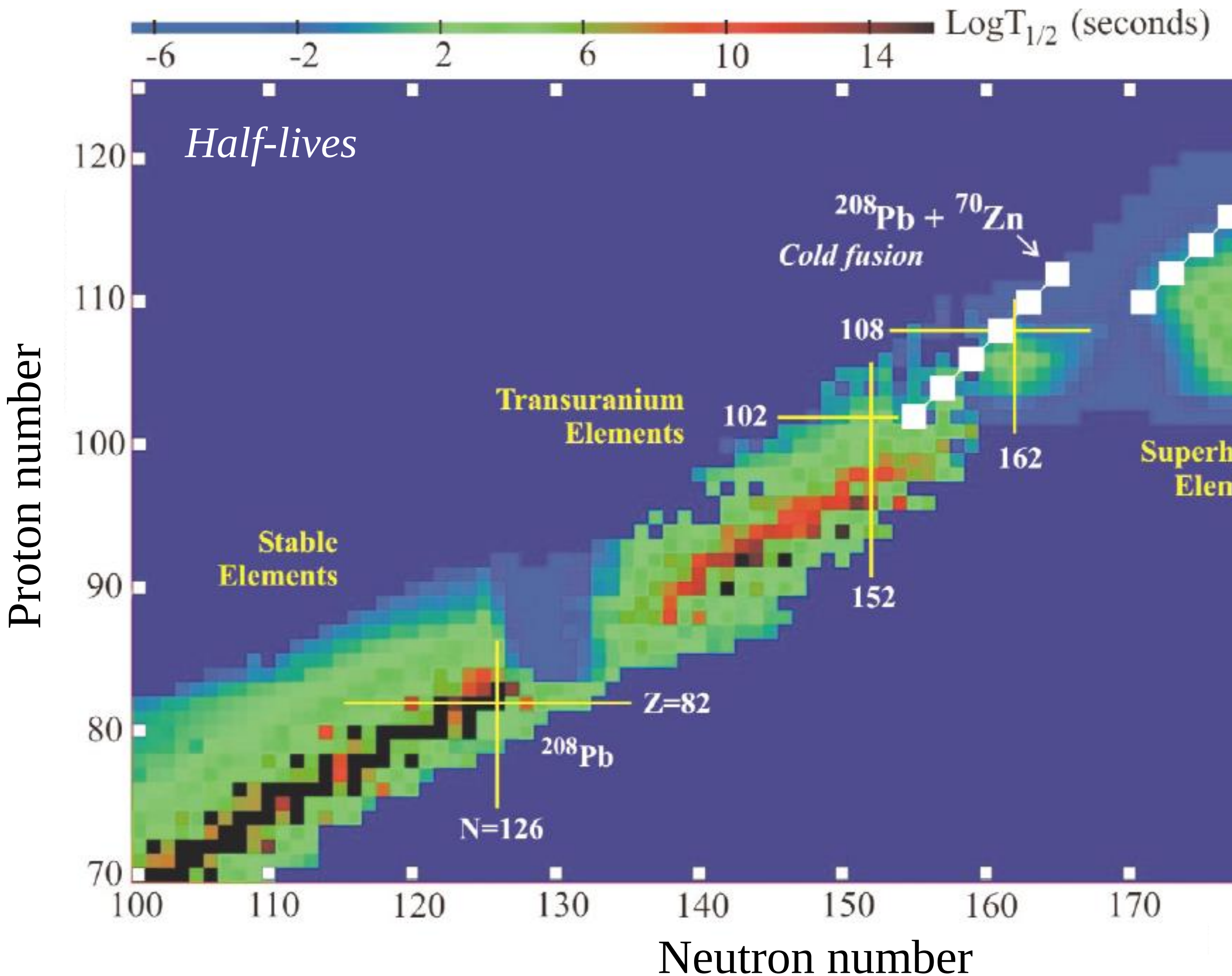


1/3 → fission
2/3 → α-decay

Both Db and Lr decayed via an alpha emission → consistent with known fact

The north-east part of the nuclear map

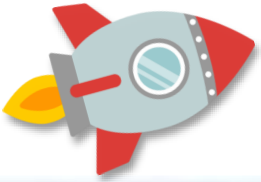
*10^8 sec ~ 3 years



Yuri Oganessian, Pure Appl. Chem. **78**, 889 (2006)

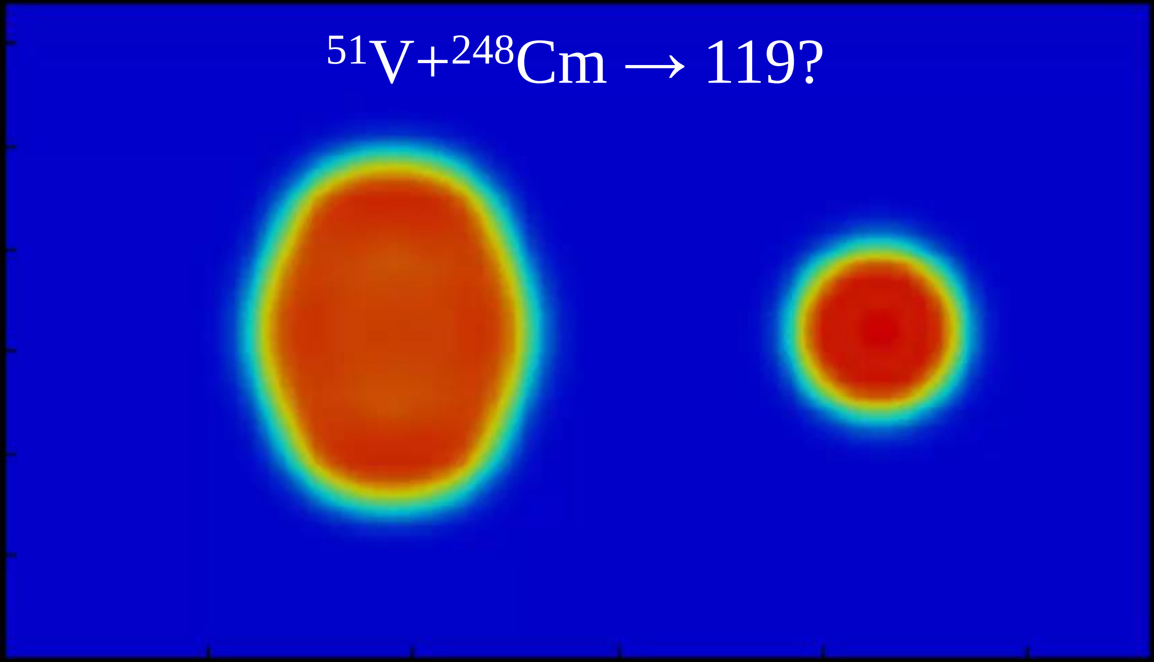
The north-east part of the nuclear map

We do need theoretical predictions!



The next is: 119 or 120

TDDFT simulation for SHE synthesis on a supercomputer

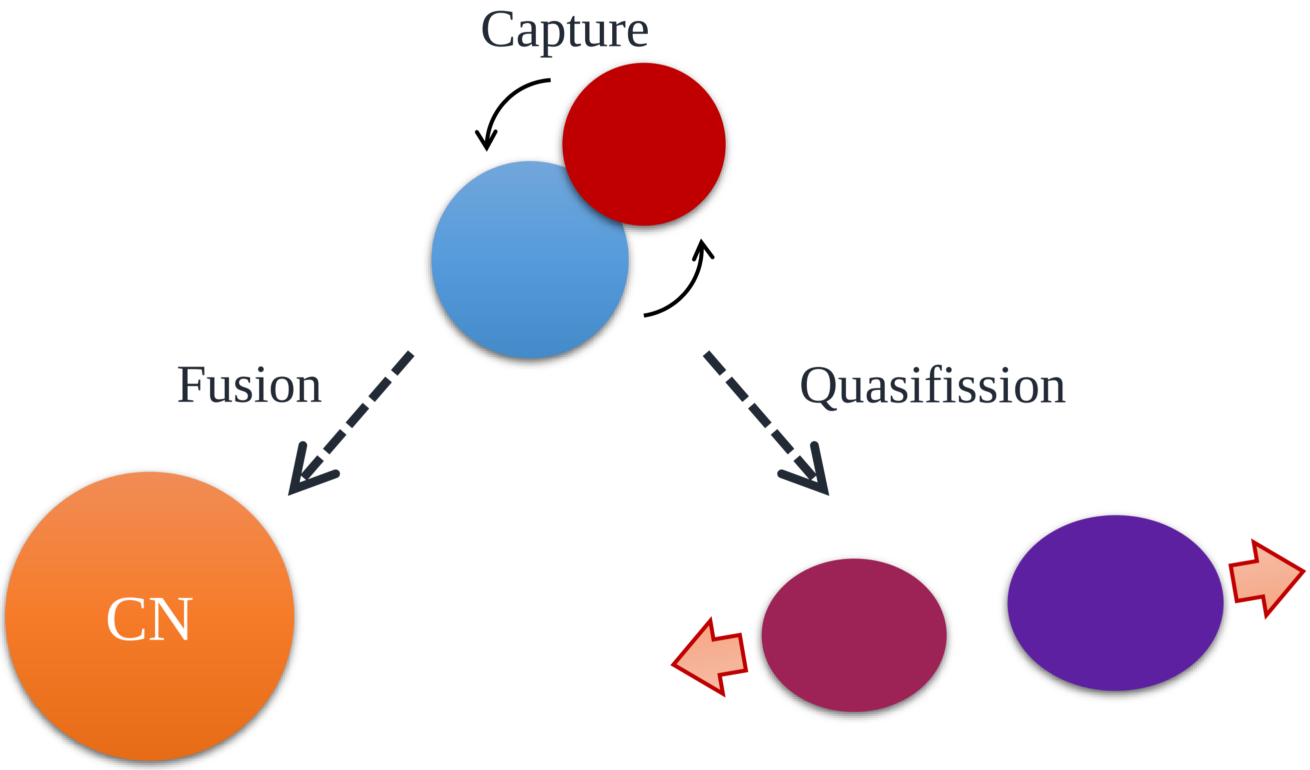


Collaborative works are in progress with Kyoto U., Kindai U., and Kyushu U.

cf. K.S. and K. Hagino, Phys. Rev. C **99**, 051602(R) (2019)

Quasifission process

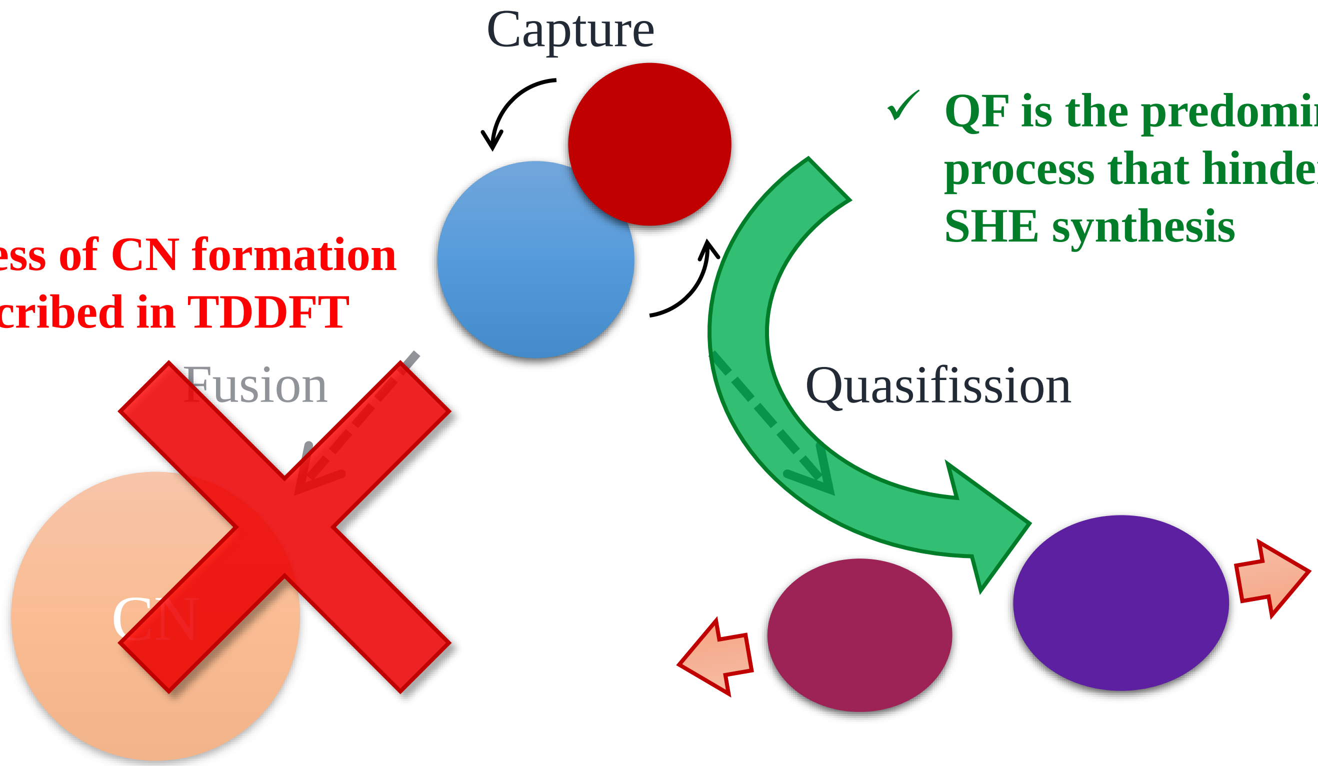
A fast (~10^{-21}-10^{-20} sec) fission process before compound nucleus formation (fusion)



$$\sigma_{\rm ER} \sim W_{\rm surv} * \sigma_{\rm cap} * P_{\rm CN}$$

Quasifission process

A fast (~10^{-21}-10^{-20} sec) fission process before compound nucleus formation (fusion)



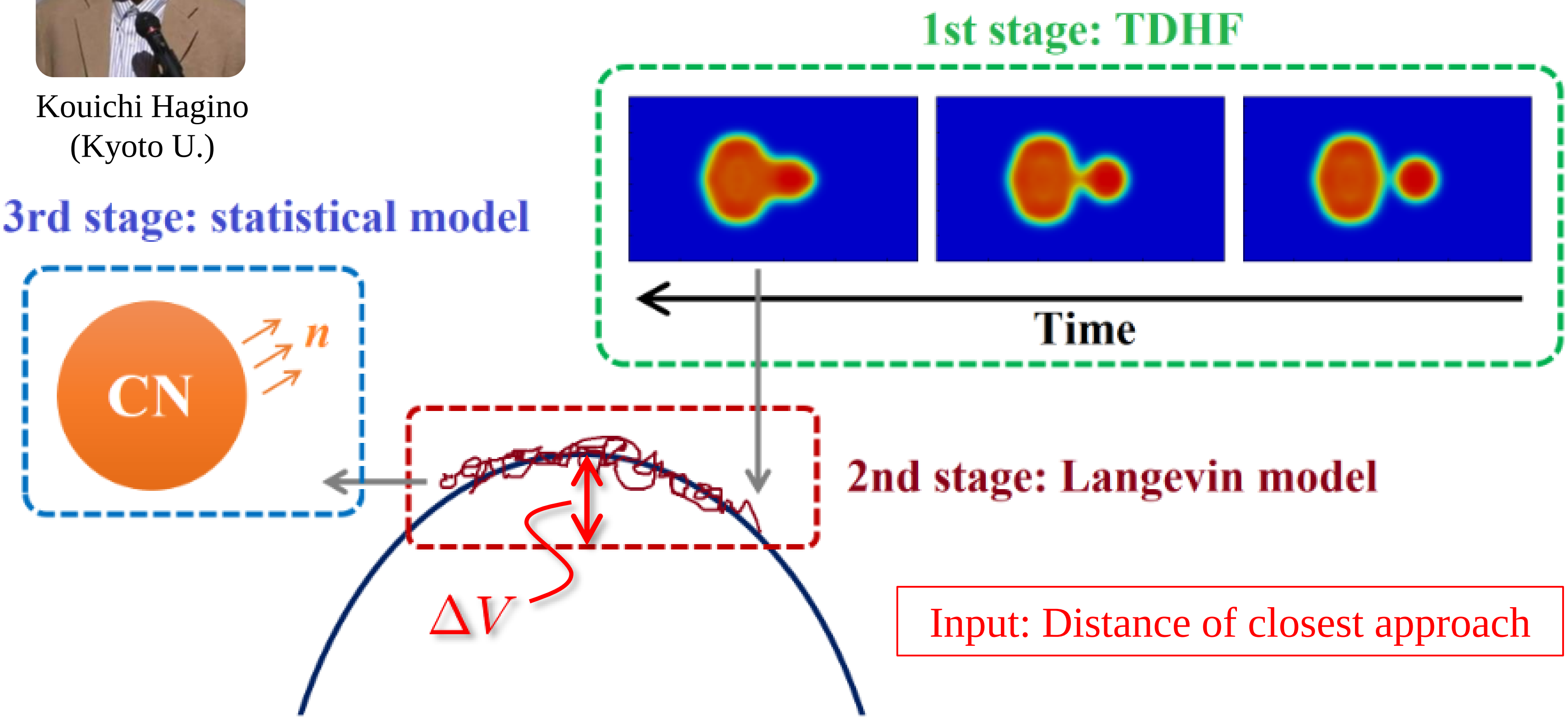
- ✓ **The rare process of CN formation can not be described in TDDFT**
- ✓ **QF is the predominant process that hinders SHE synthesis**

$$\sigma_{\rm ER} \sim W_{\rm surv} * \sigma_{\rm cap} * P_{\rm CN}$$

K.S. and K. Hagino, Phys. Rev. C **99**, 051602(R) (2019)
Rapid Comm. with Editors' Suggestion

Kouichi Hagino
(Kyoto U.)

TDDFT + Langevin approach: Idea



We use fusion-by-diffusion model to describe the "up-hill diffusion" over the inner barrier

- **Analytical formula can be derived:**

$$P_{\rm CN} = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{\Delta V}{T}\right)\right]$$

Fusion-by-diffusion model:

W.J. Świątecki, K. Siwek-Wilczyńska, and J. Wilczyński,
Acta Phys. Pol. B **34**(2003)2049; PRC**71**(2005)014602
K. Hagino, PRC**98**(2018)014607

K.S. and K. Hagino, Phys. Rev. C **99**, 051602(R) (2019)

Magicity of ^{48}Ca affects the survival probability via the lower excitation energy

System	CN	E^* (MeV)	TDDFT: $R_{\min}$ (fm)	FBD: $P_{\rm CN}$ ($\times10^4$)	$W_{\rm sur}$ ($\times10^9$)	$P_{\rm CN}\,W_{\rm sur}$ ($\times10^{13}$)
^{48}Ca+^{254}Fm	^{302}120	29.0	12.93	1.72	176	302
^{54}Cr+^{248}Cm	^{302}120	33.2	13.09	1.89	1.31	2.47
^{51}V+^{249}Bk	^{300}120	37.0	12.94	3.95	0.117	0.461
^{48}Ca+^{257}Fm	^{305}120	30.5	12.94	2.49	0.729	1.82

Very similar for all systems

Thus, $P_{\rm CN}$ is also similar (higher E^*, larger $P_{\rm CN}$)

Note:
Survival probability also depends on the fission barrier height!

How much does pairing affect the reaction dynamics?

4. Solitonic excitations in heavy-ion reactions

TDSLDA: TDDFT with local treatment of pairing

Kohn-Sham scheme is extended for non-interacting quasiparticles

➢ TDSLDA equations (formally equivalent to TDHFB or TD-BdG equations)

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} u_{k,\uparrow}(\boldsymbol{r},t) \\ u_{k,\downarrow}(\boldsymbol{r},t) \\ v_{k,\uparrow}(\boldsymbol{r},t) \\ v_{k,\downarrow}(\boldsymbol{r},t) \end{pmatrix} = \begin{pmatrix} h_{\uparrow\uparrow}(\boldsymbol{r},t) & h_{\uparrow\downarrow}(\boldsymbol{r},t) & 0 & \Delta(\boldsymbol{r},t) \\ h_{\downarrow\uparrow}(\boldsymbol{r},t) & h_{\downarrow\downarrow}(\boldsymbol{r},t) & -\Delta(\boldsymbol{r},t) & 0 \\ 0 & -\Delta^*(\boldsymbol{r},t) & -h^*_{\uparrow\uparrow}(\boldsymbol{r},t) & -h^*_{\uparrow\downarrow}(\boldsymbol{r},t) \\ \Delta^*(\boldsymbol{r},t) & 0 & -h^*_{\downarrow\uparrow}(\boldsymbol{r},t) & -h^*_{\downarrow\downarrow}(\boldsymbol{r},t) \end{pmatrix}\begin{pmatrix} u_{k,\uparrow}(\boldsymbol{r},t) \\ u_{k,\downarrow}(\boldsymbol{r},t) \\ v_{k,\uparrow}(\boldsymbol{r},t) \\ v_{k,\downarrow}(\boldsymbol{r},t) \end{pmatrix}$$

Supercomputing!!

$h_\sigma = \dfrac{\delta E}{\delta n_\sigma}$: s.p. Hamiltonian

$\Delta = -\dfrac{\delta E}{\delta \nu^*}$: pairing field

$n_\sigma(\boldsymbol{r},t) = \sum_{E_k<E_c} |v_{k,\sigma}(\boldsymbol{r},t)|^2$: number density

$\nu(\boldsymbol{r},t) = \sum_{E_k<E_c} u_{k,\uparrow}(\boldsymbol{r},t)v^*_{k,\downarrow}(\boldsymbol{r},t)$: anomalous density

$\boldsymbol{j}_\sigma(\boldsymbol{r},t) = \hbar\sum_{E_k<E_c} \mathrm{Im}[v^*_{k,\sigma}(\boldsymbol{r},t)\boldsymbol{\nabla}v_{k,\sigma}(\boldsymbol{r},t)]$: current

A large number (10^4-10^6) of 3D coupled non-linear PDEs have to be solved!!

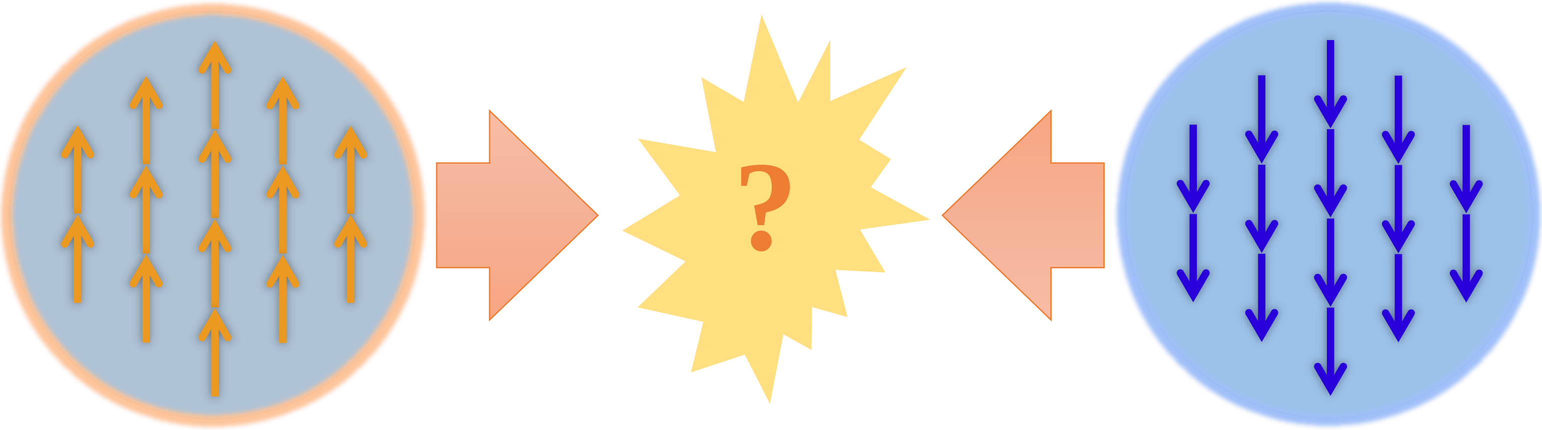
# of qp orbitals ~ # of grid points

3D, TDSLDA calculations (Fayans w/o LS) predicts novel phenomena associated with solitonic excitations!!

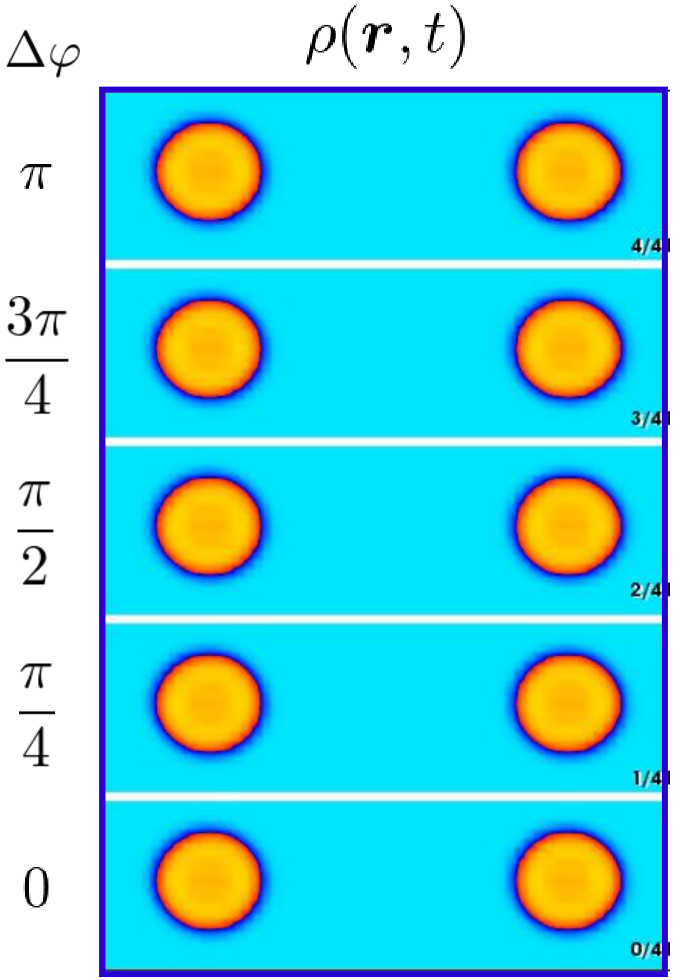
Q. What happens when two **superfluid** nuclei with different **phases** collide??

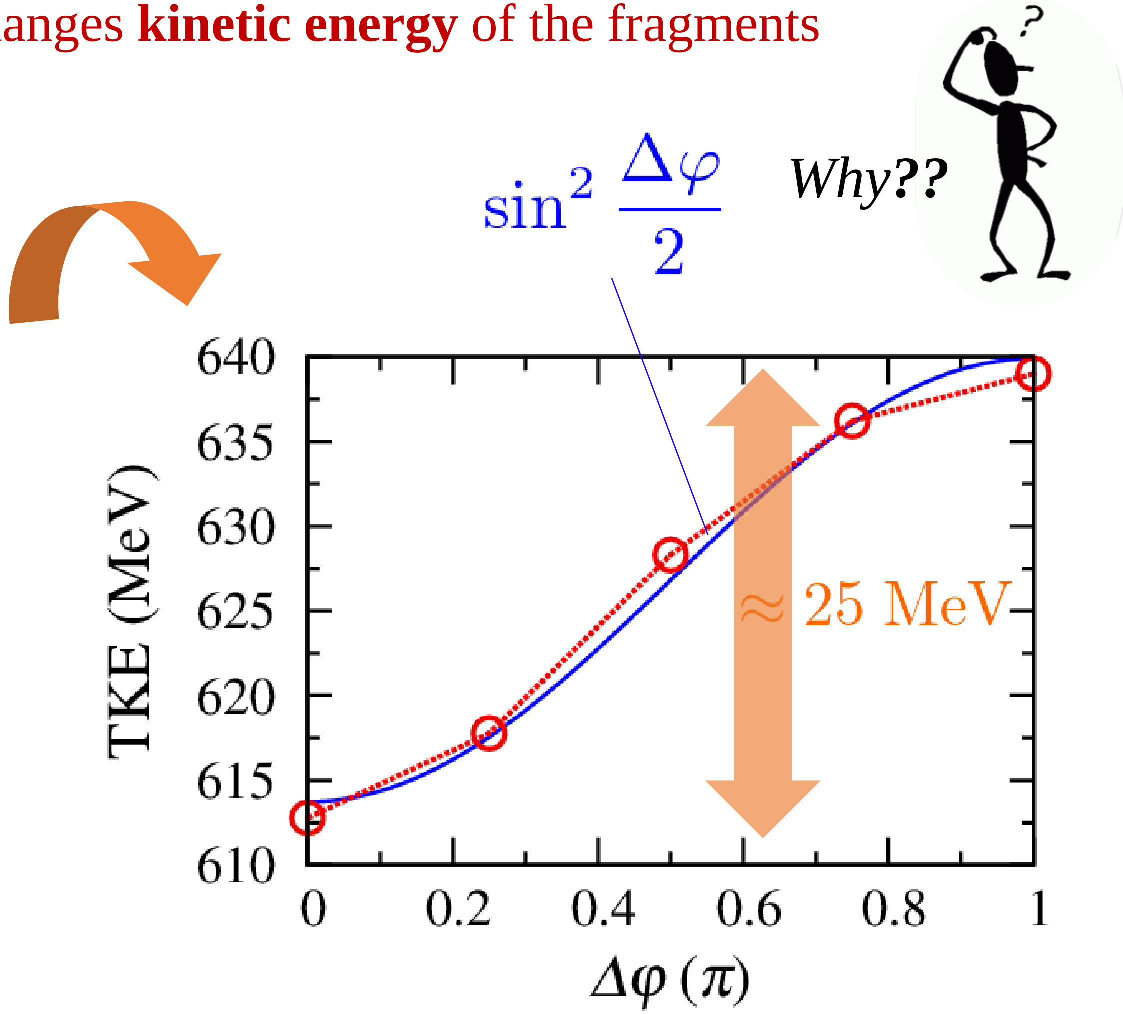
$$\Delta\varphi \ (\equiv \varphi_1 - \varphi_2)$$

$|\Delta_1(\boldsymbol{r},t)|e^{\mathrm{i}\varphi_1(\boldsymbol{r},t)}$ $|\Delta_2(\boldsymbol{r},t)|e^{\mathrm{i}\varphi_2(\boldsymbol{r},t)}$



The phase difference changes **kinetic energy** of the fragments

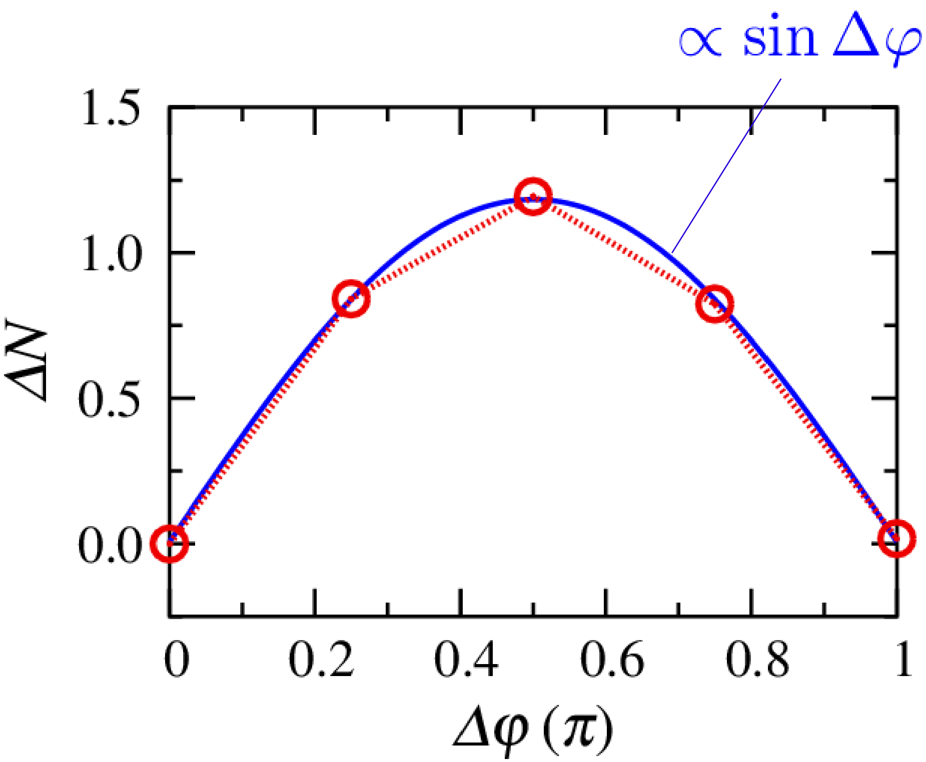


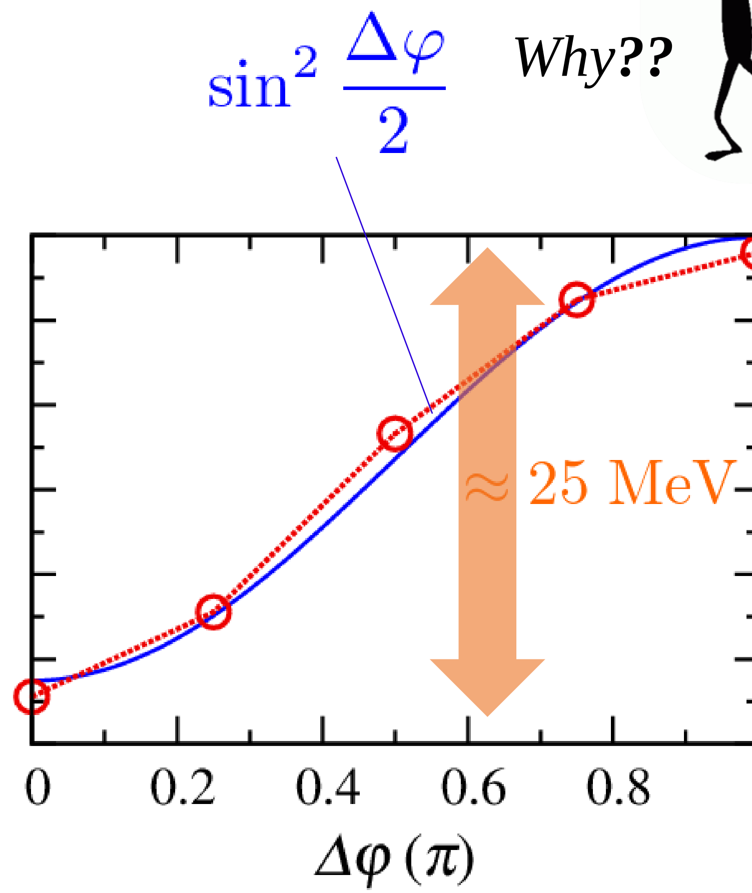


P. Magierski, K.S., G. Wlazłowski, Phys. Rev. Lett. **119**, 042501 (2017)

The phase difference changes **kinetic energy** of the fragments

Note:
It cannot be explained by Josephson effect!





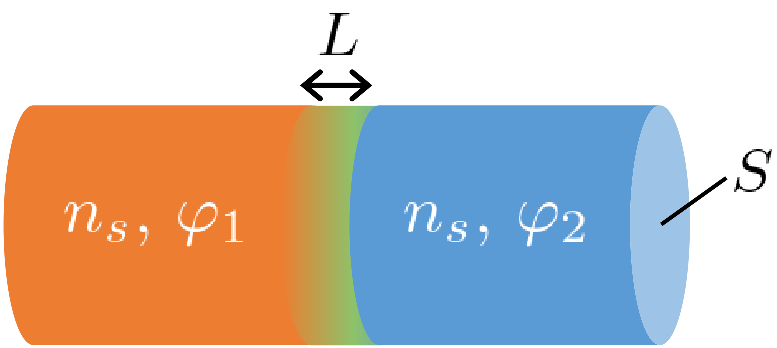
Why??

P. Magierski, K.S., G. Wlazłowski, Phys. Rev. Lett. **119**, 042501 (2017)

Additional energy is required to attach two superfluids with different phases

- The additional energy (derived from Ginzburg-Landau theory)

$$E = \frac{S}{L}\frac{\hbar^2}{2m} n_s \sin^2 \frac{\Delta\varphi}{2}$$



$\Delta\varphi\ (\equiv \varphi_1 - \varphi_2)$

*It does not depend on the absolute value of the pairing!

e.g.) S=πR^2, L~R=6 fm, n_s=0.08 fm^{-3} → E~30 MeV

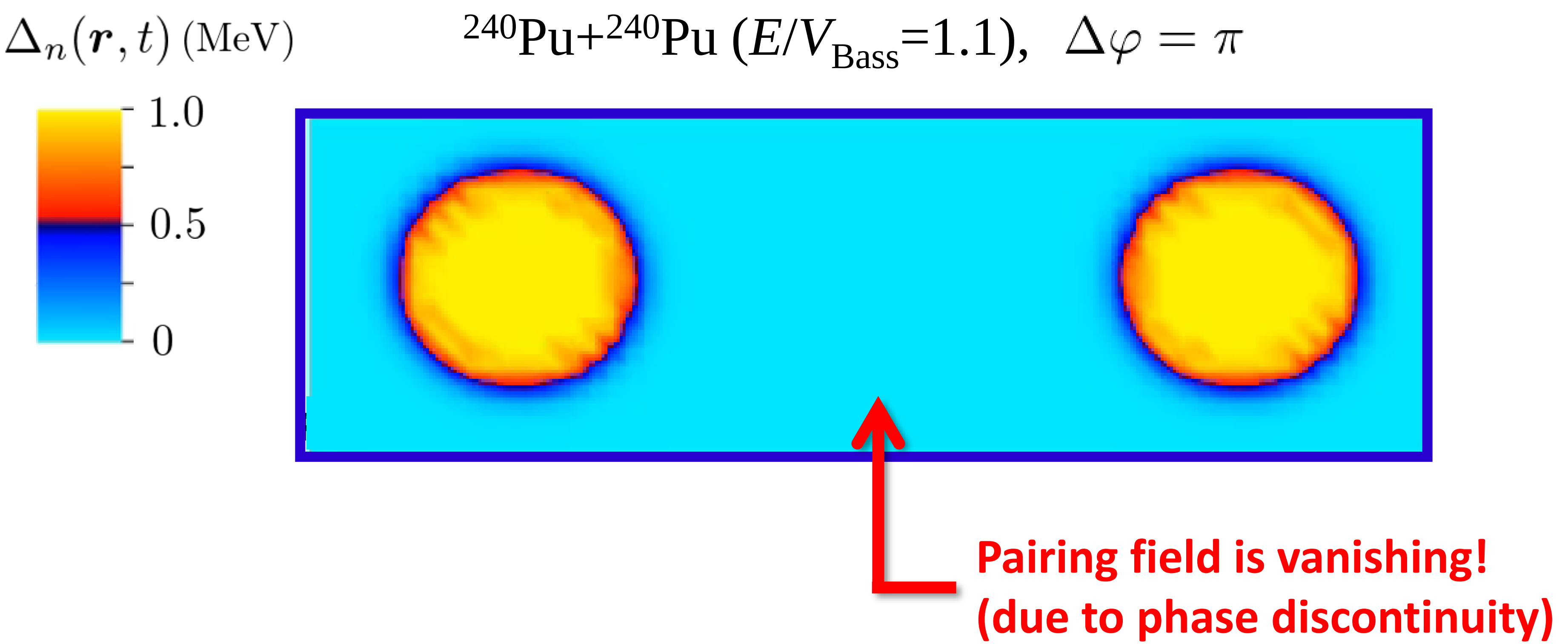
S: Attaching area

L: Length scale over which the phase varies

n_s: Superfluid density

P. Magierski, K.S., G. Wlazłowski, Phys. Rev. Lett. **119**, 042501 (2017)

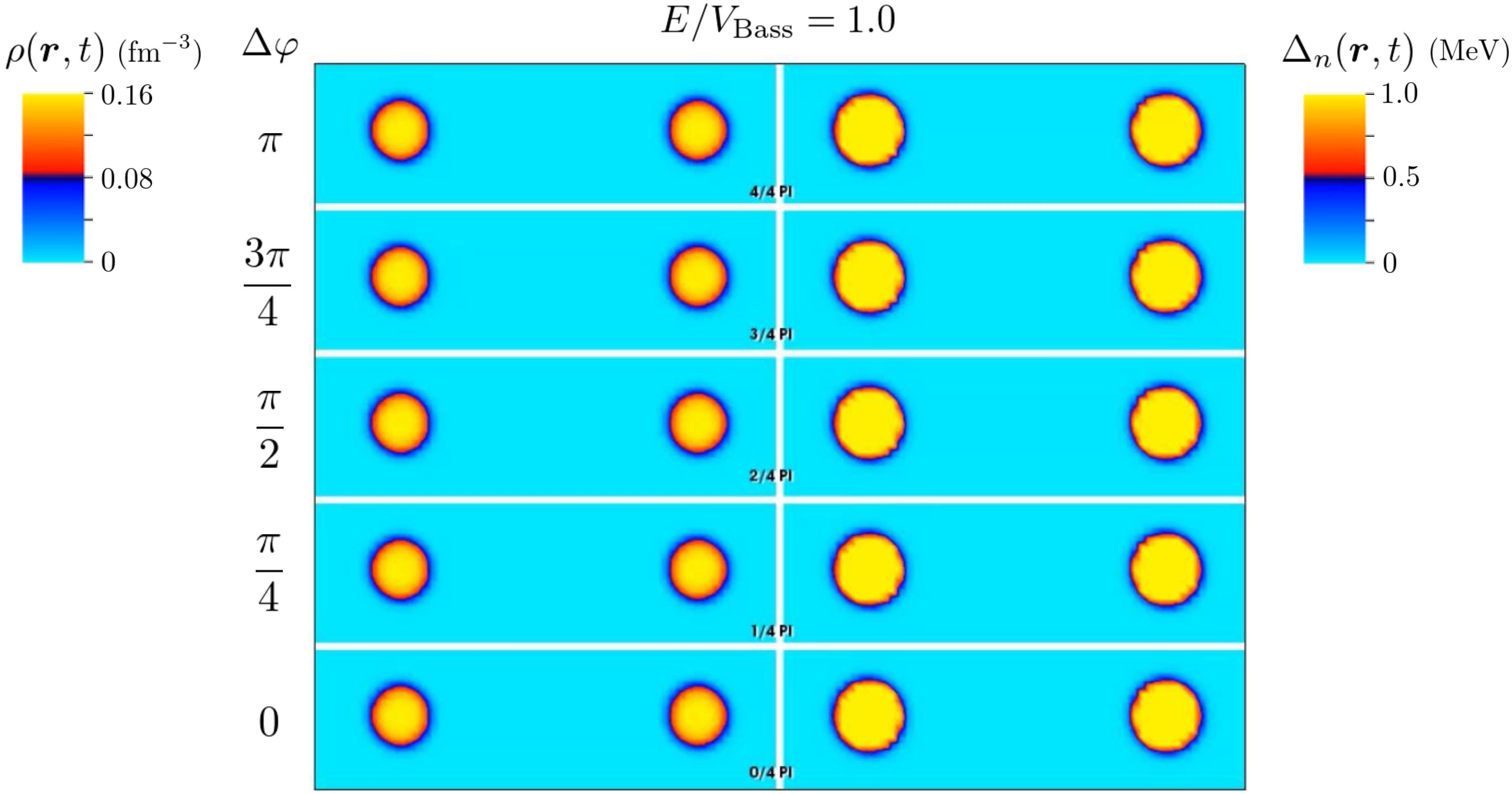
Additional energy is required to attach two superfluids with different phases



P. Magierski, K.S., G. Wlazłowski, Phys. Rev. Lett. **119**, 042501 (2017)

TDSLDA results: $^{90}Zr+^{90}Zr$ head-on collisions

Fusion reaction is suppressed by the phase difference



P. Magierski, K.S., G. Wlazłowski, Phys. Rev. Lett. **119**, 042501 (2017)

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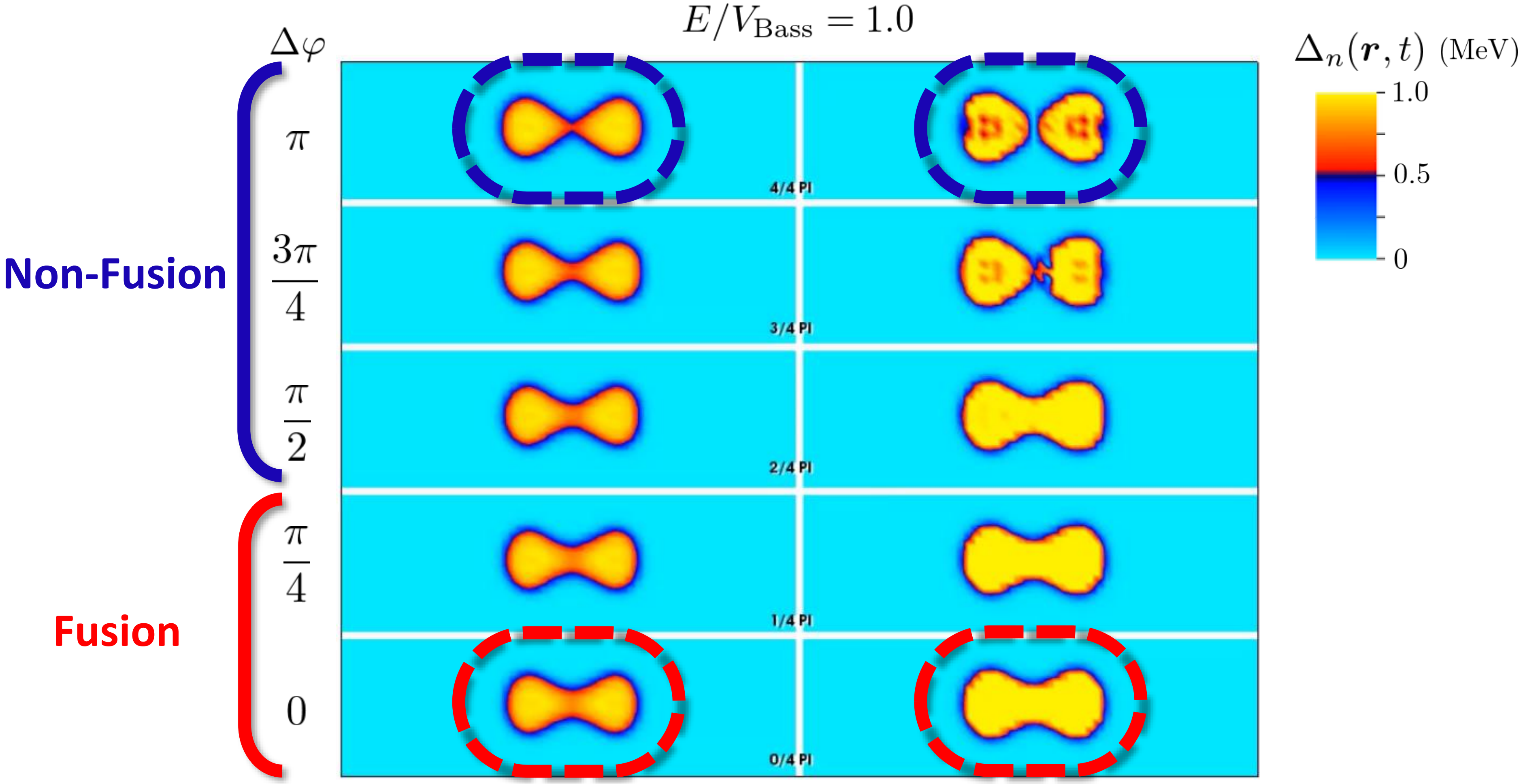
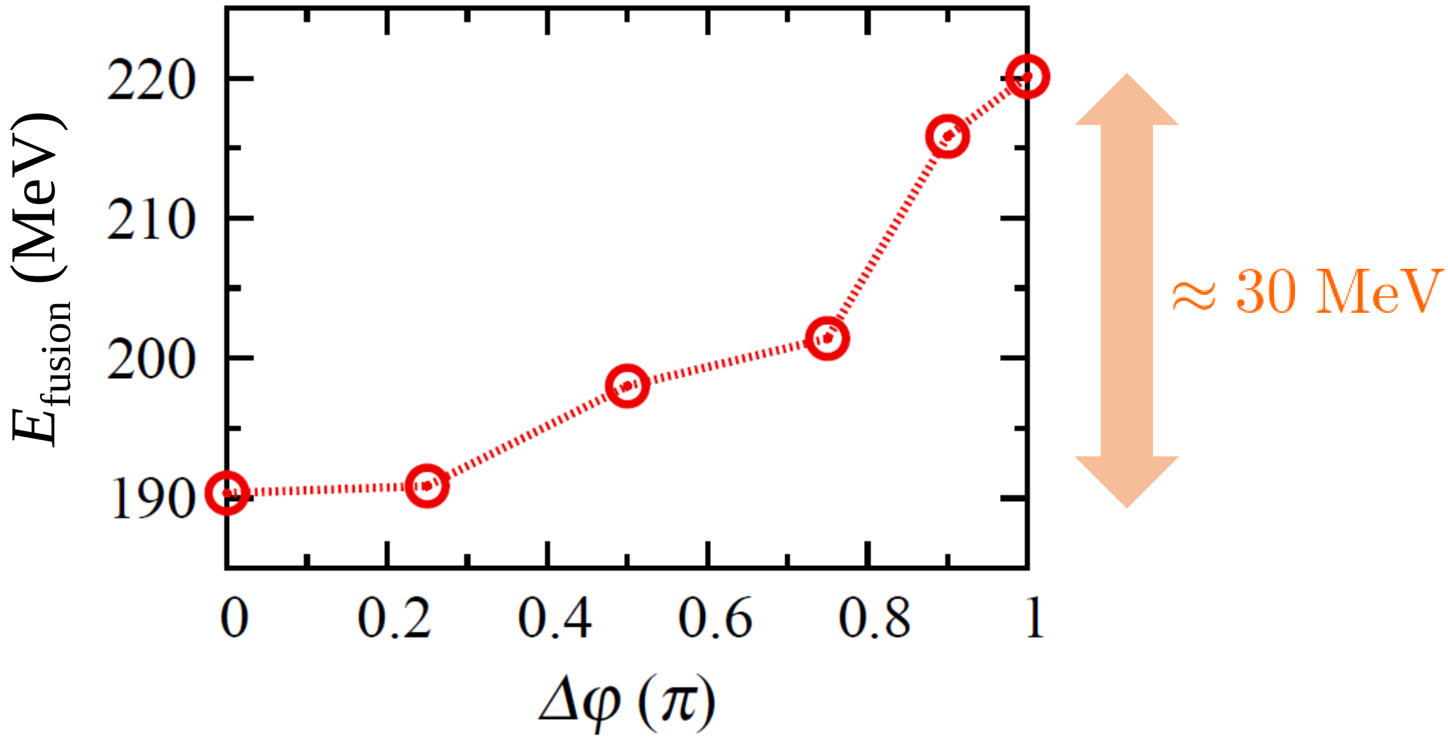


P. Magierski, K.S., G. Wlazłowski, Phys. Rev. Lett. **119**, 042501 (2017)

Fusion reaction is suppressed by the phase difference

*$\boldsymbol{E}_{\mathbf{fusion}}$: the lowest energy at which fusion reaction is observed



P. Magierski, K.S., G. Wlazłowski, Phys. Rev. Lett. **119**, 042501 (2017)

When two superfluid nuclei with different phases collide
solitonic excitations might be induced

$$\Delta\varphi \; (\equiv \varphi_1 - \varphi_2)$$

$|\Delta_1(\boldsymbol{r},t)|e^{\mathrm{i}\varphi_1(\boldsymbol{r},t)}$ $|\Delta_2(\boldsymbol{r},t)|e^{\mathrm{i}\varphi_2(\boldsymbol{r},t)}$

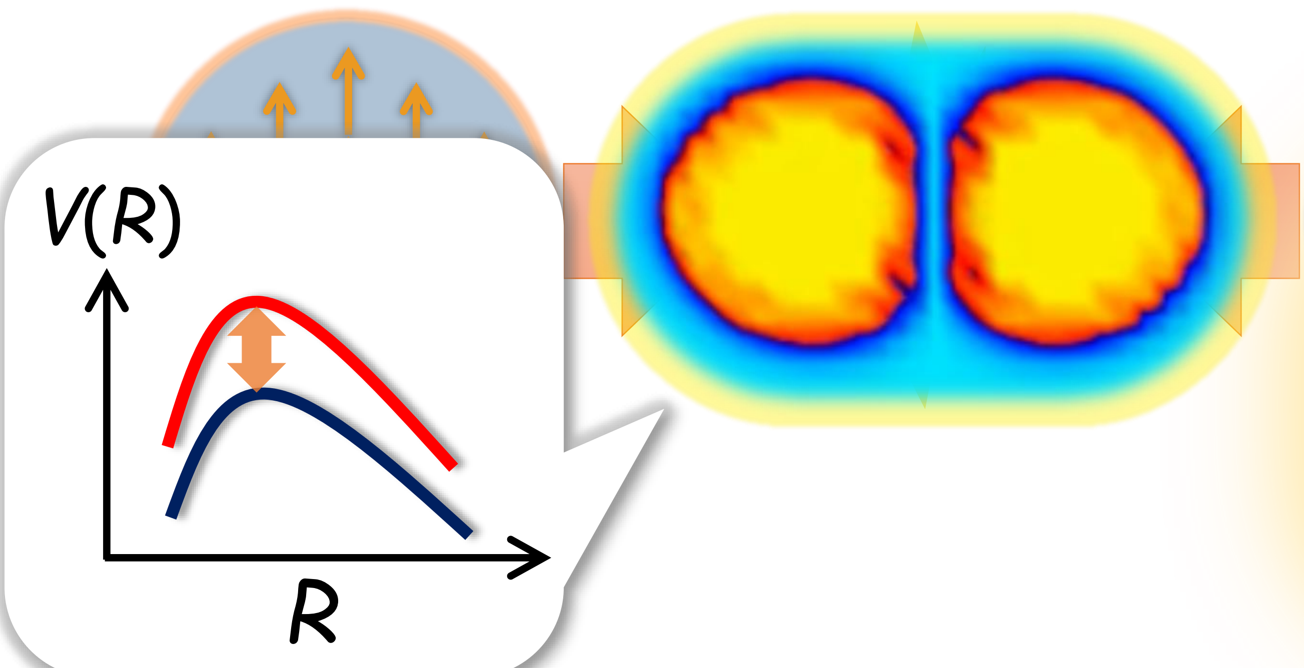
P. Magierski, K.S., G. Wlazłowski, Phys. Rev. Lett. **119**, 042501 (2017)

Summary of the findings

When two superfluid nuclei with different phases collide
solitonic excitations might be induced

$$\Delta\varphi\ (\equiv \varphi_1 - \varphi_2)$$

$|\Delta_1(\boldsymbol{r},t)|e^{\mathrm{i}\varphi_1(\boldsymbol{r},t)}$ $|\Delta_2(\boldsymbol{r},t)|e^{\mathrm{i}\varphi_2(\boldsymbol{r},t)}$



It may affect:

- ☐ TKE (~10-30 MeV)
- ☐ Fusion dynamics
- ☐ Neck formation
- ☐ Contact time
- ☐ Scattering angle

P. Magierski, K.S., G. Wlazłowski, Phys. Rev. Lett. **119**, 042501 (2017)

Summary

Takeaway message

✓ TDDFT can properly describe the main reaction outcomes in low-energy heavy-ion reactions, and may be further improved with extended techniques

Main reaction outcomes

TDDFT

Average number of nucleons,
TKE, scattering angles,
contact times, ...

Fluctuations/correlations

SMF (or TDRPA)

Width of mass, charge distributions,
correlation between *n*/*p* transfers,
...

Further extensions

e.g. TDDFT+Langevin

Providing input information for
other theoretical approaches

Lecture Plan

Theory (8/7 10:00-11:30)

#1. An introduction to microscopic mean-field approaches and (TD)DFT

Nuclear reactions (8/7 13:00-14:30)

#2. Recent advances in microscopic approaches for heavy-ion reactions

Superheavy element synthesis & deep-inelastic collisions

Neutron stars (8/8 10:00-11:30)

#3. Neutron-star “glitch” and neutron superfluid

Dynamics of quantized vortices in the inner crust of neutron stars

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2-12-1 O-Okayama, Meguro, Tokyo 152-8551, Japan
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http://sekizawa.fizyka.pw.edu.pl/english/