Purpose of today's presentation

- ✔ To clarify what is interesting to study low-energy heavy ion reactions

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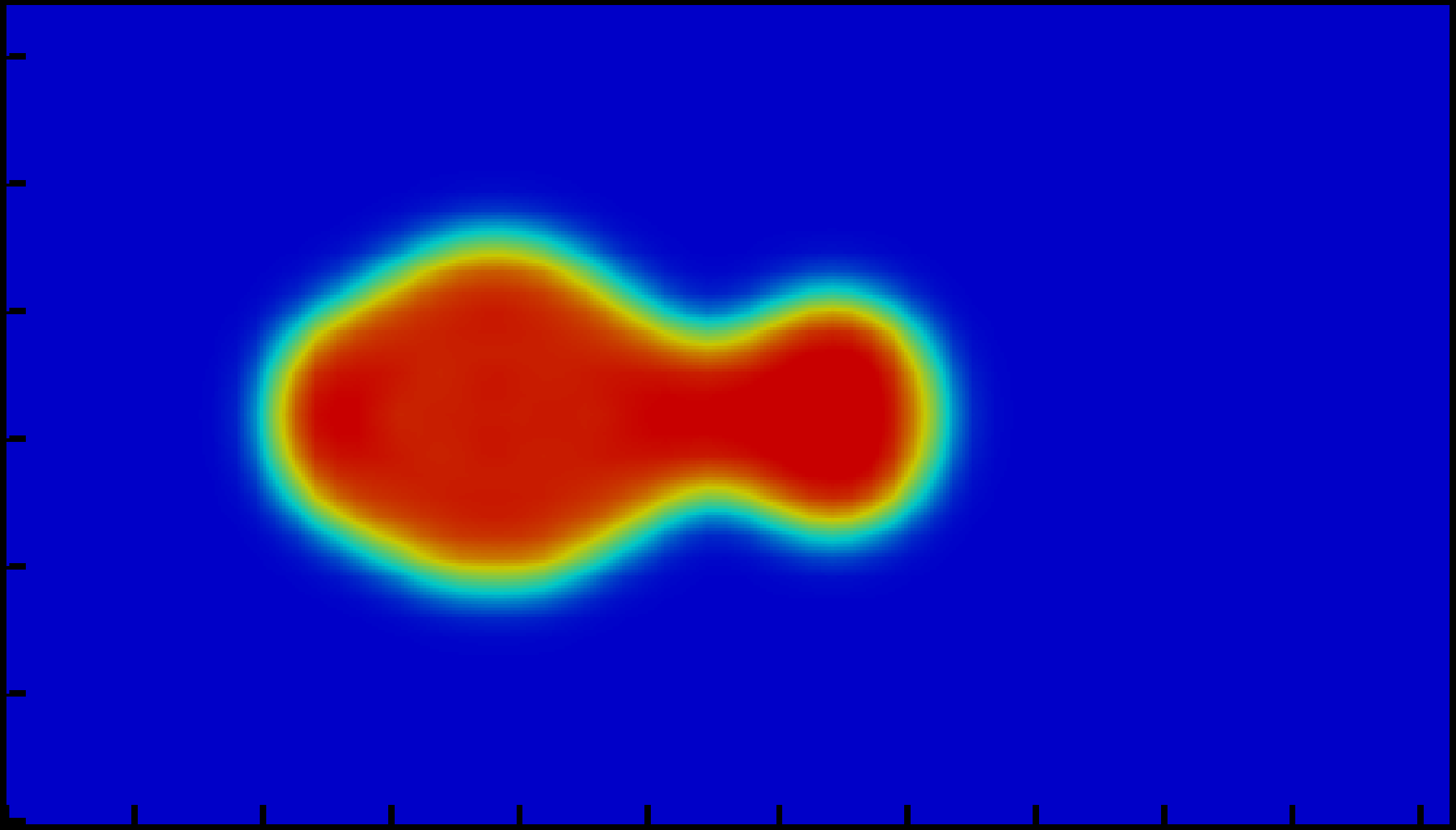
My short answer:

Quantum many-body dynamics!!



Time-dependent density functional theory for low-energy heavy ion reactions

Kazuyuki Sekizawa

(Warsaw University of Technology, Poland)

In collaboration with

Kazuhiro Yabana

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

Outline

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What I would like to tell you today

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1. Introduction: Our interests for low-energy heavy ion reactions
2. Method: Time-dependent density functional theory (TDDFT)
3. Example: ^{238}U+^{124}Sn reaction
4. Proposal and conclusion

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What is a low-energy heavy ion reaction?

What is a low-energy heavy ion reaction?

Not “high-energy” !!

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Not "high-energy" !!

RHIC

Relativistic Heavy Ion Collider

Taken from Brookhaven National Laboratory Website (http://www.bnl.gov/rhic/)

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✔ a "*gentle*" collision at around the Coulomb barrier

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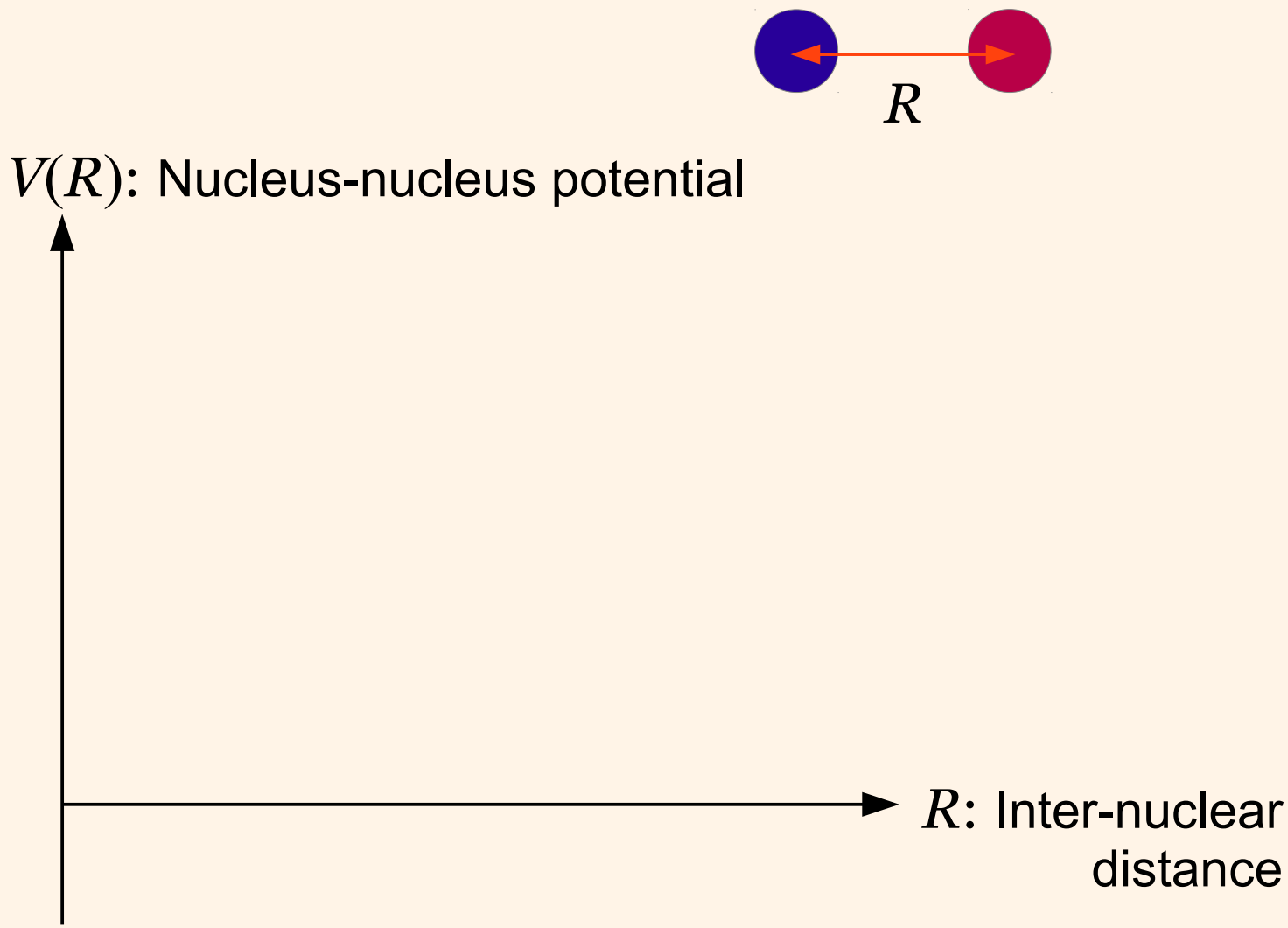

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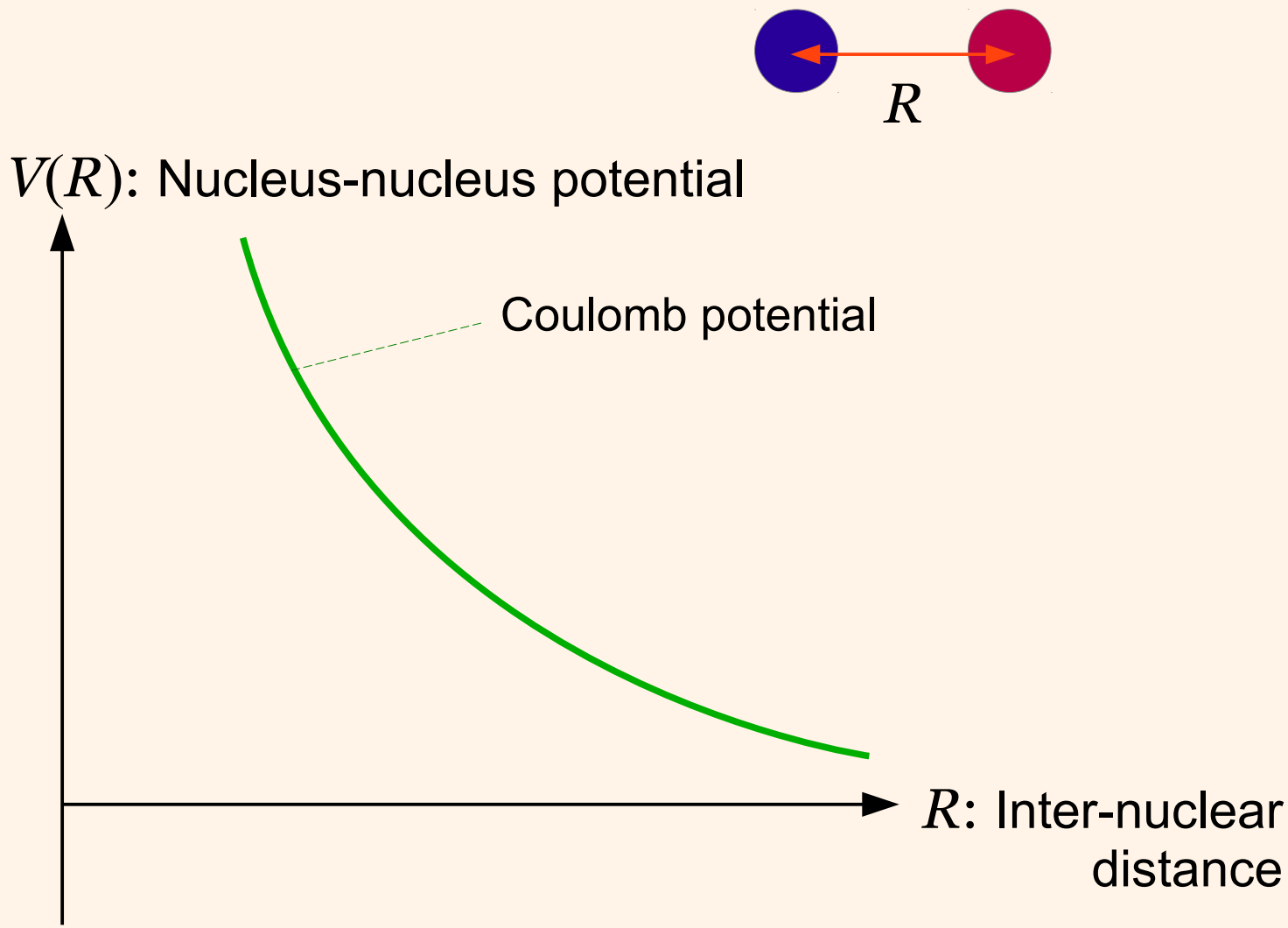

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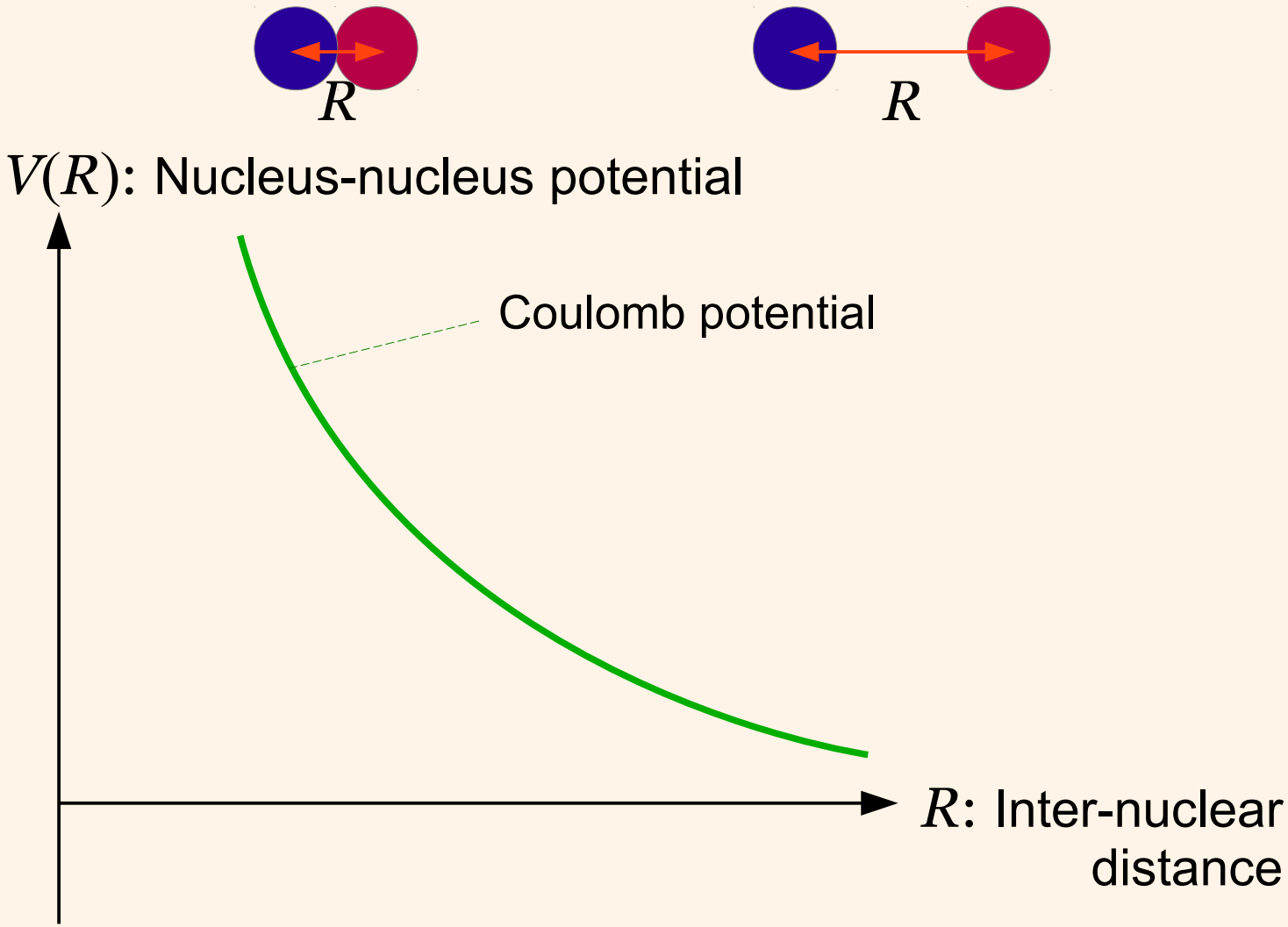

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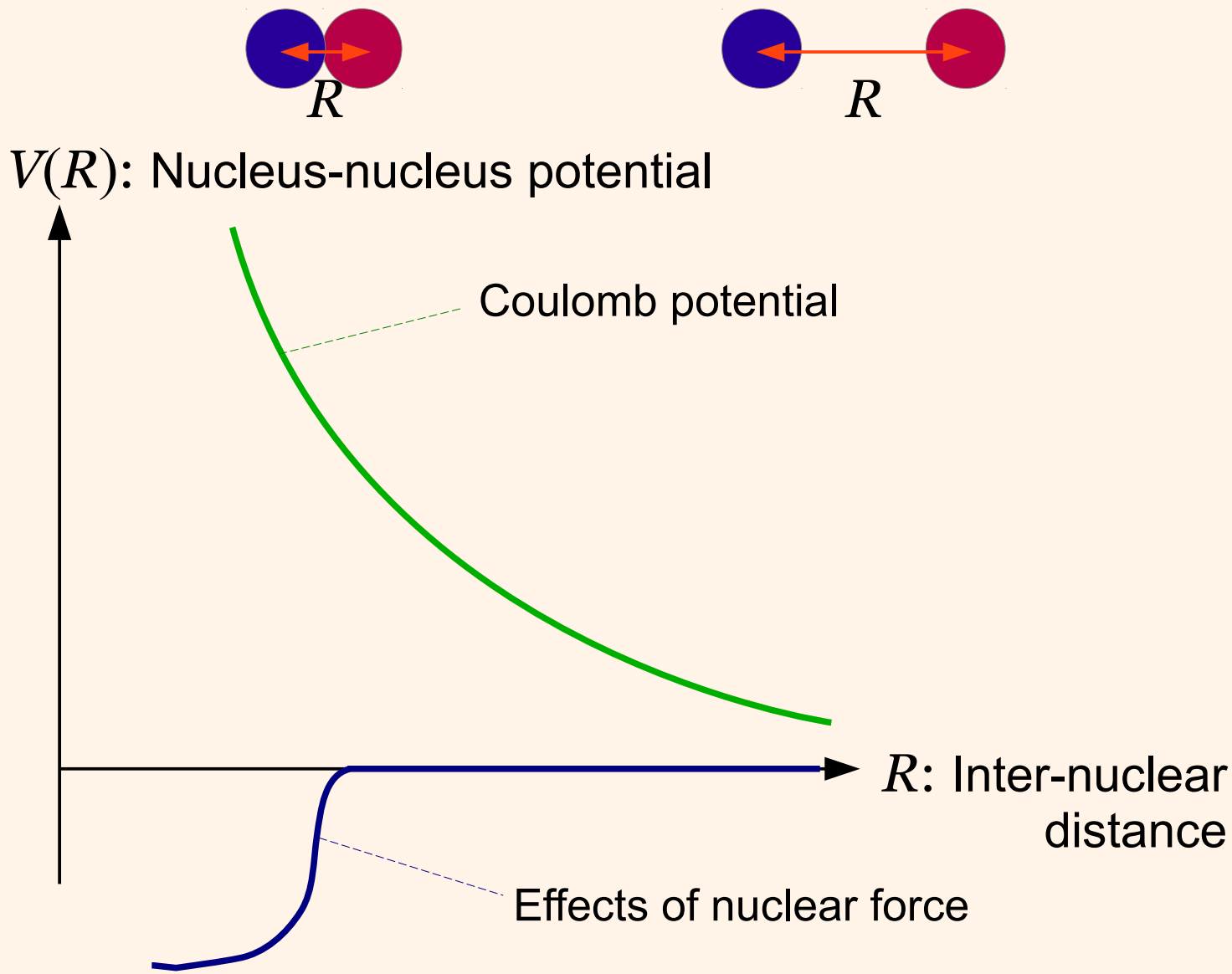

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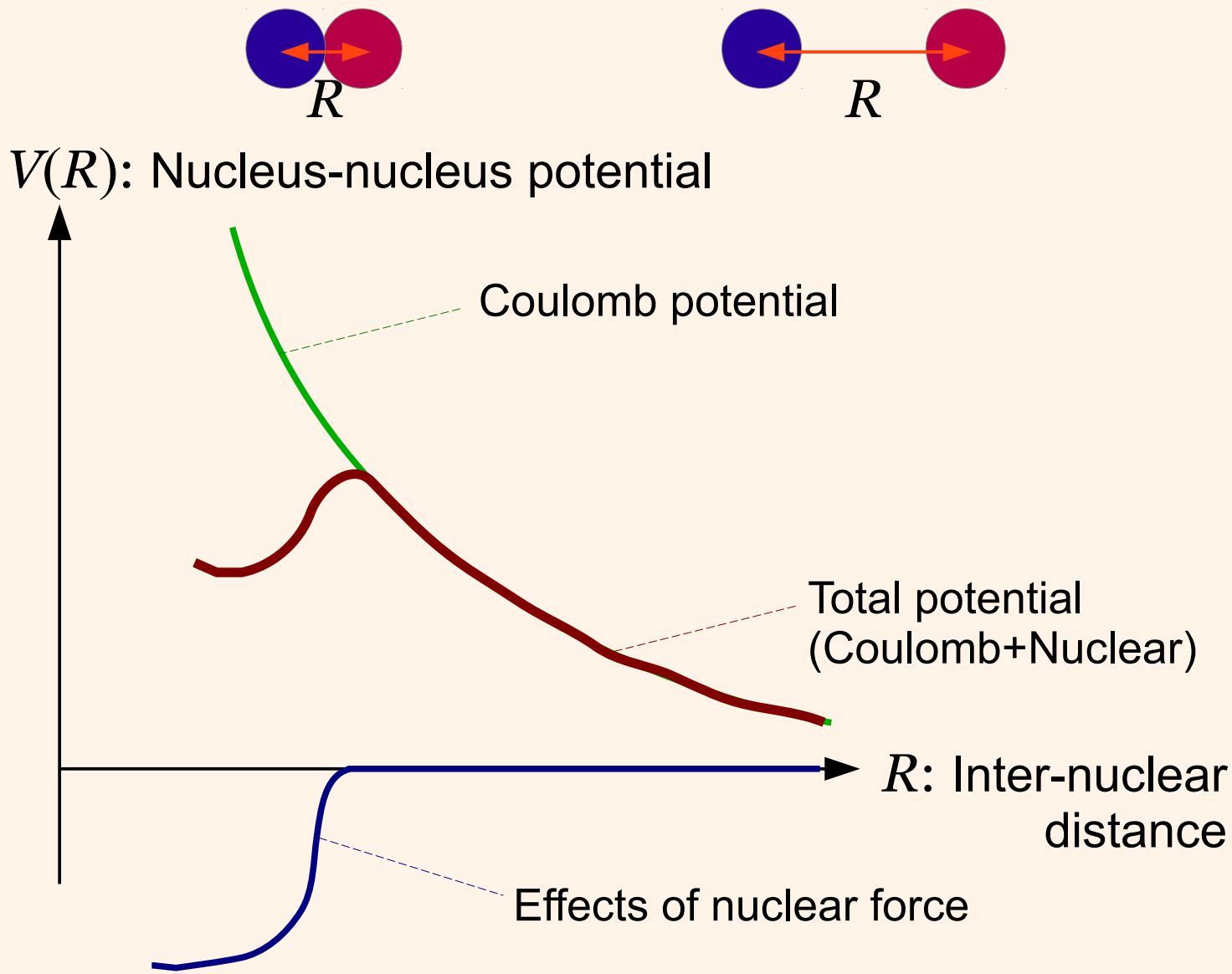

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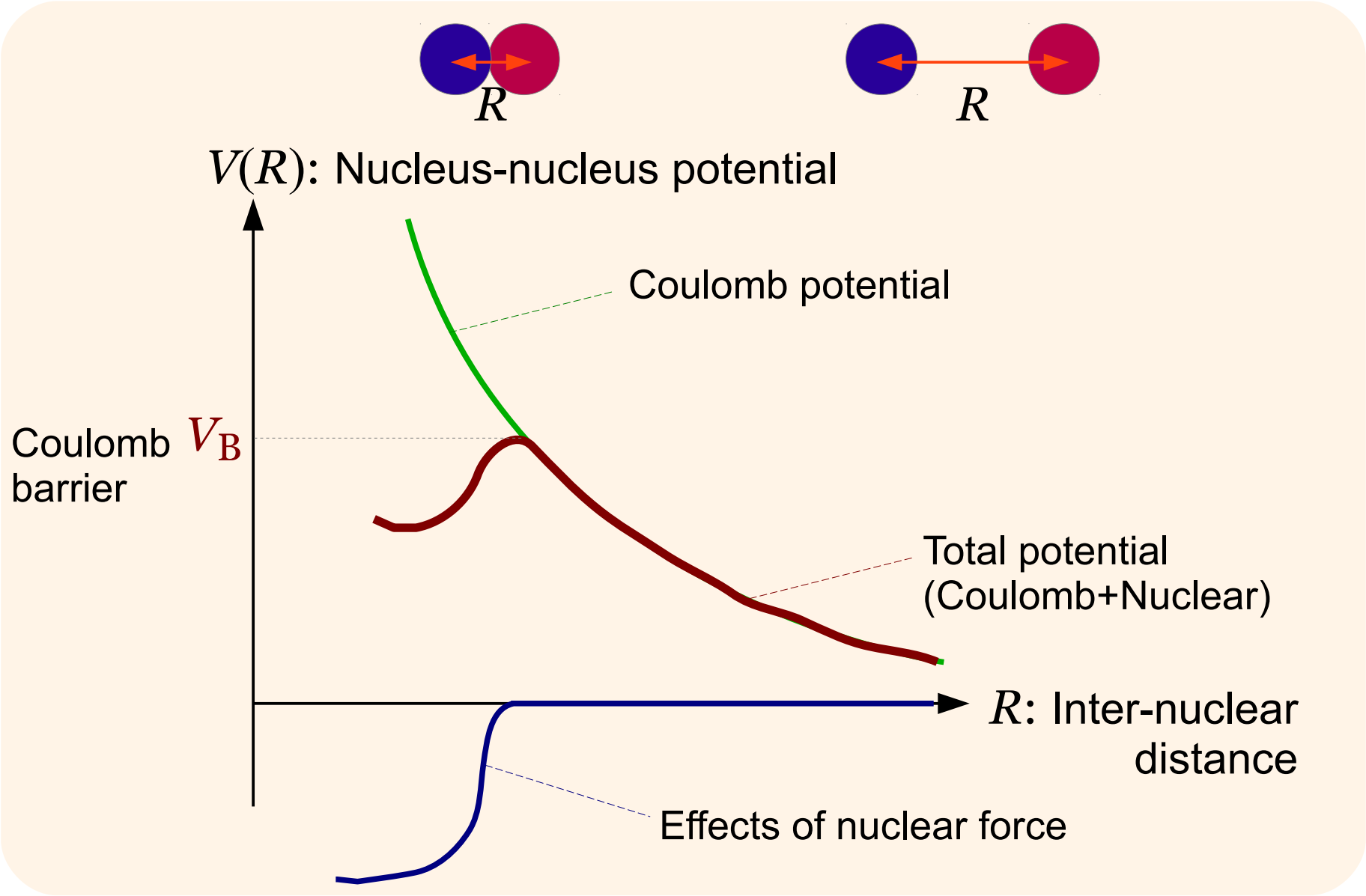

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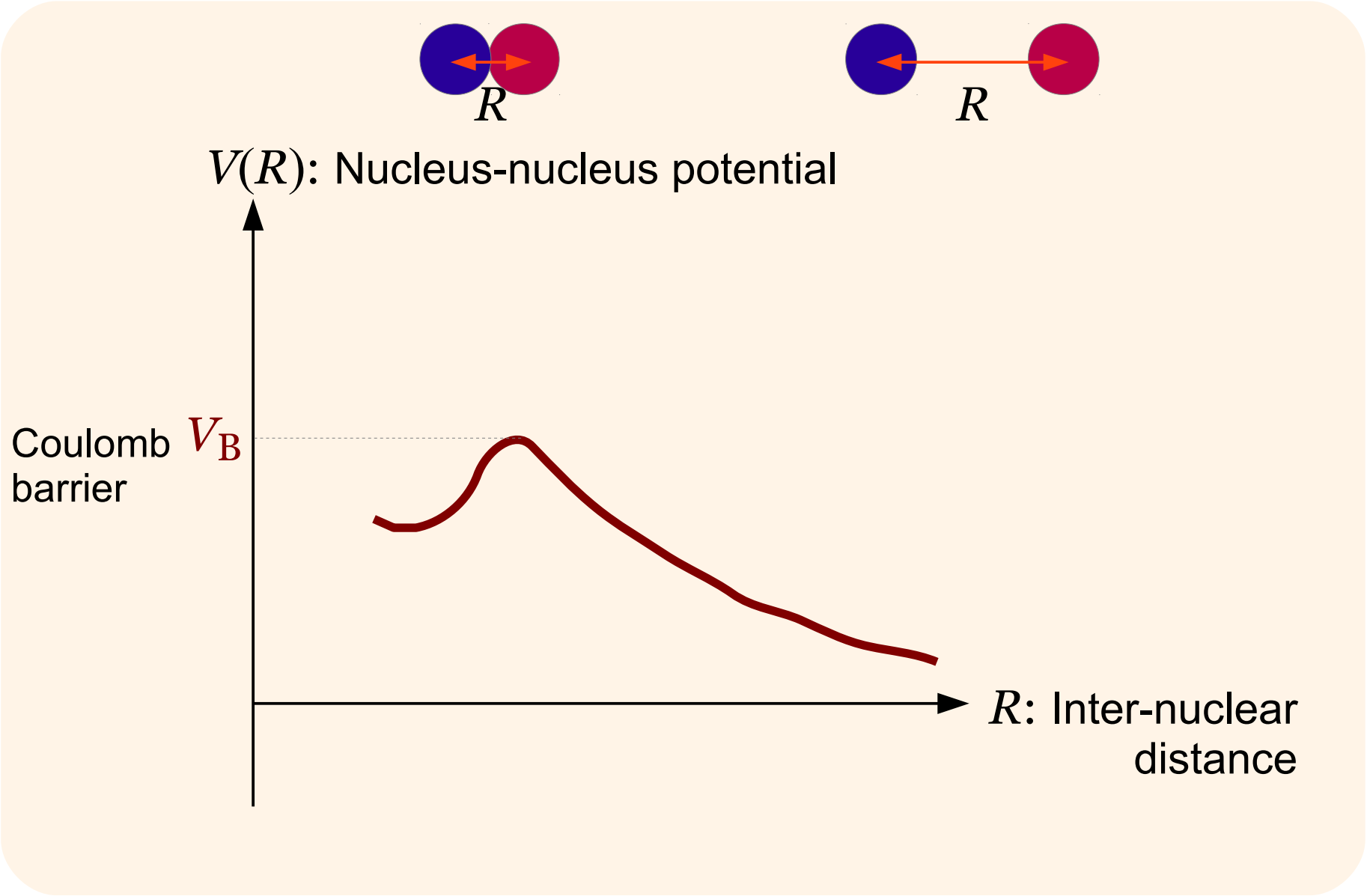

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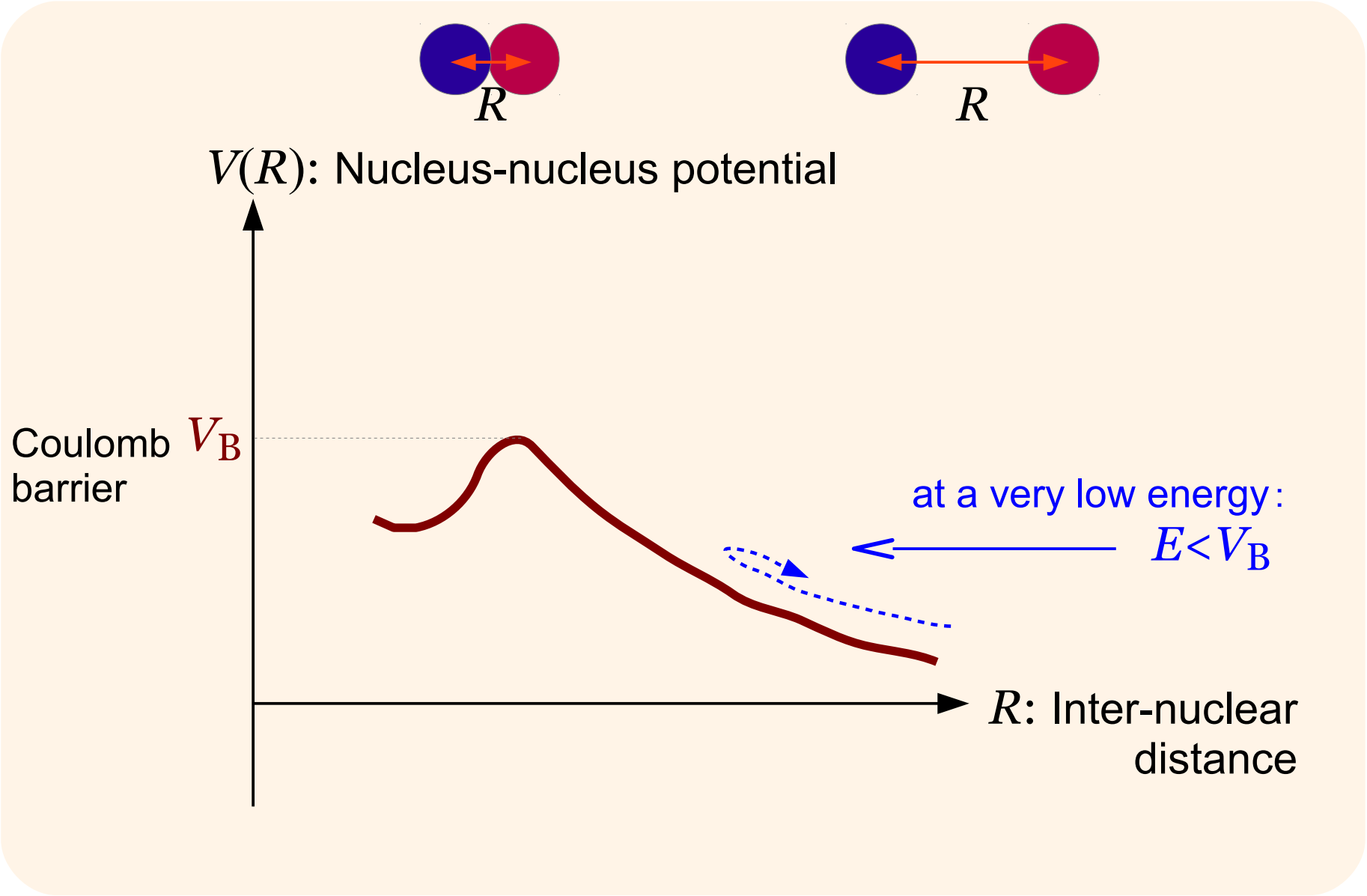

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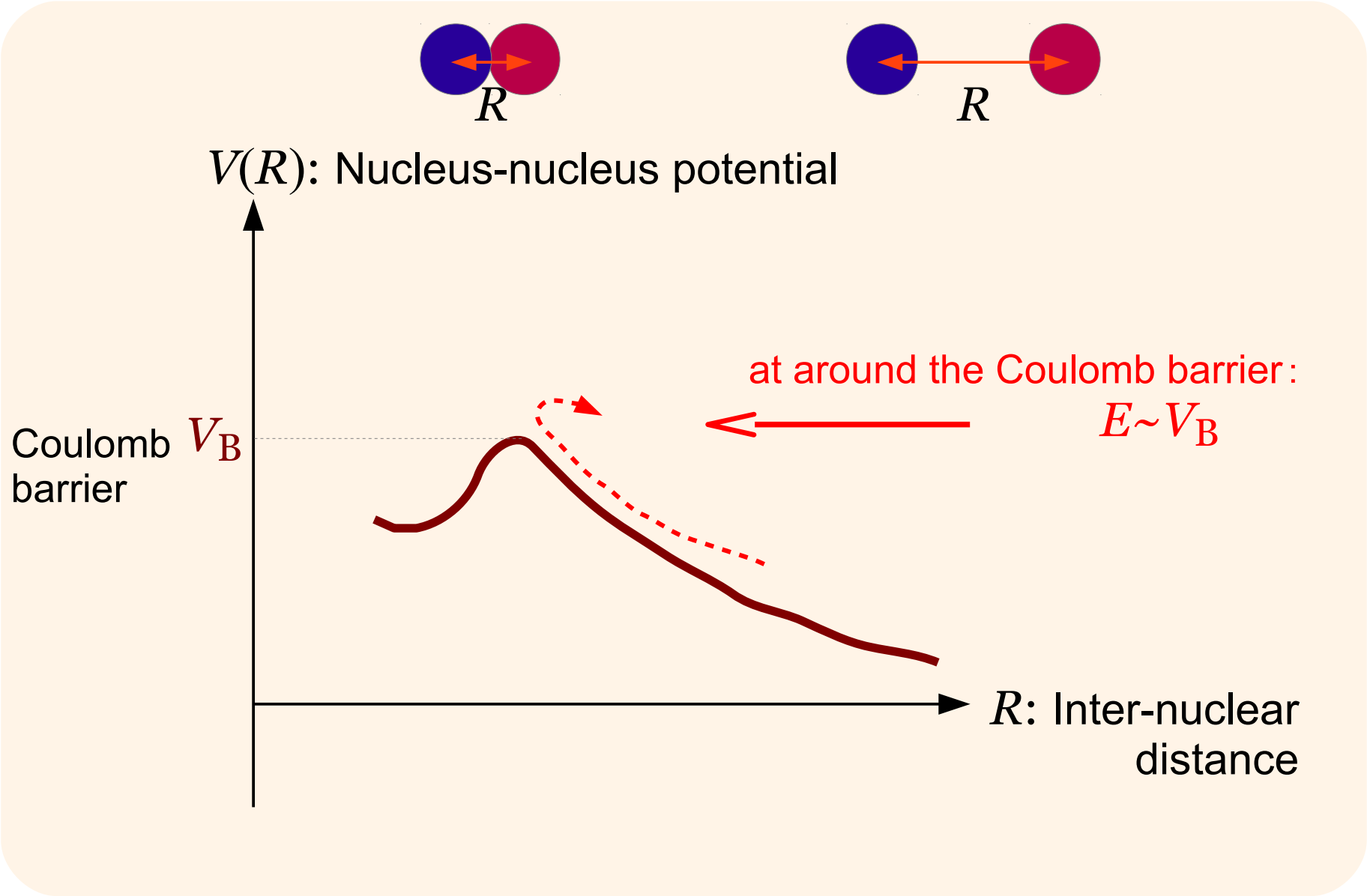

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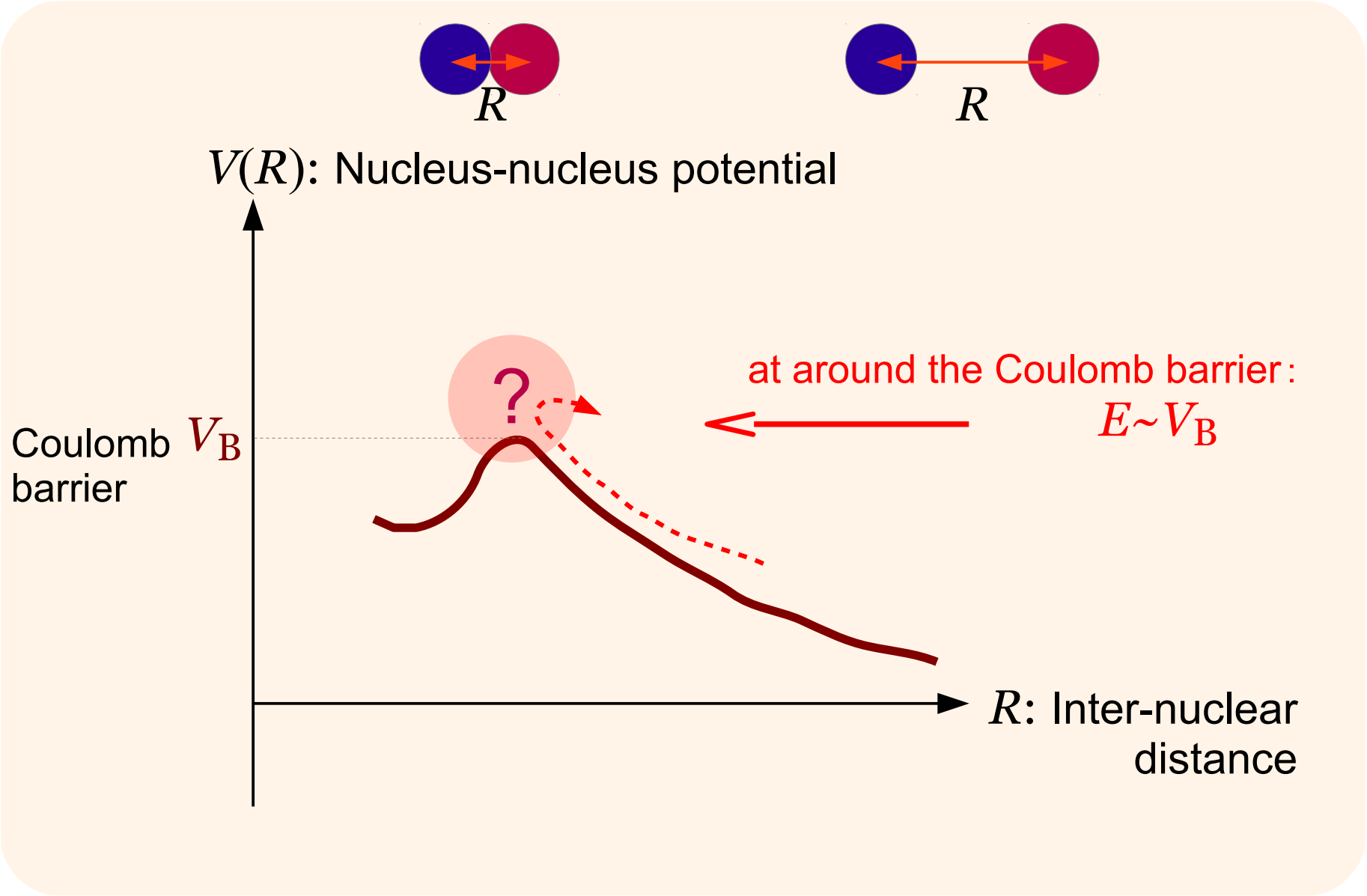

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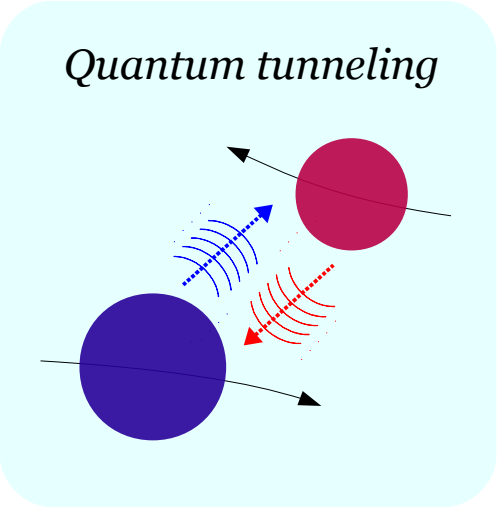

Transfer of few nucleons

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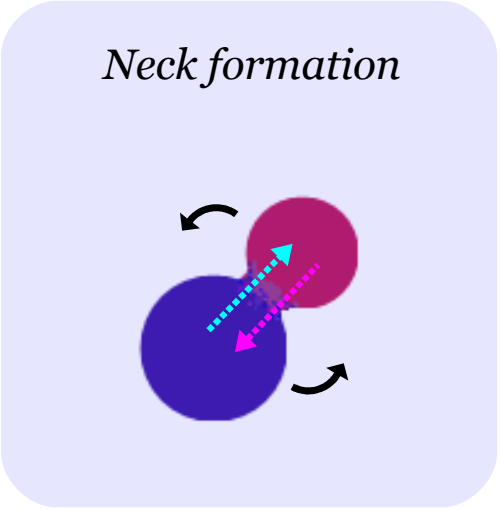
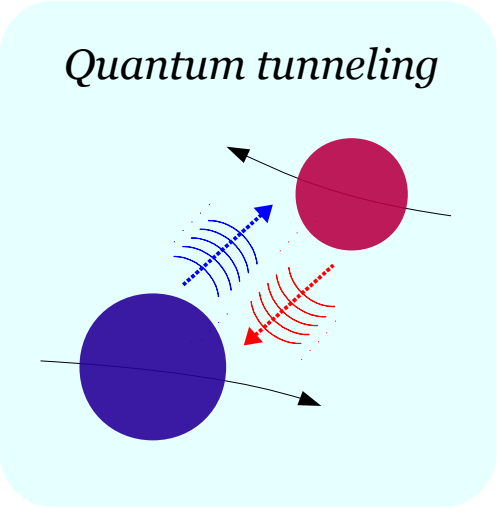


Multinucleon transfer



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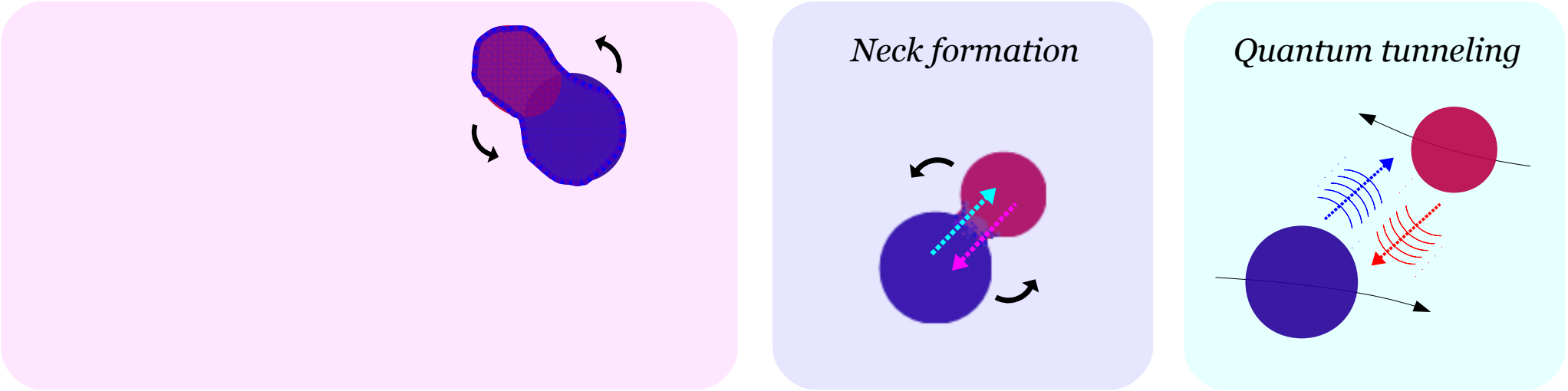

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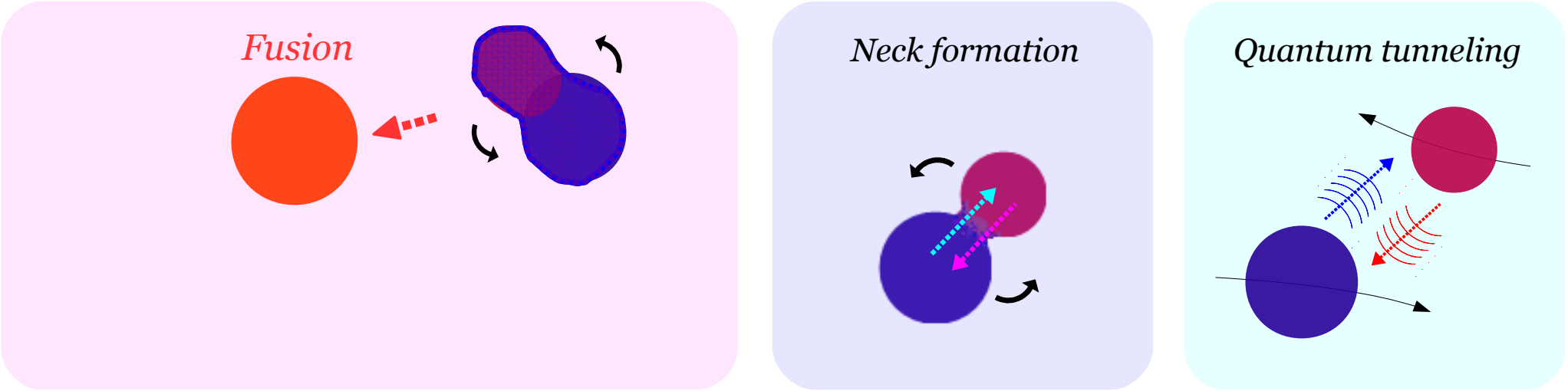

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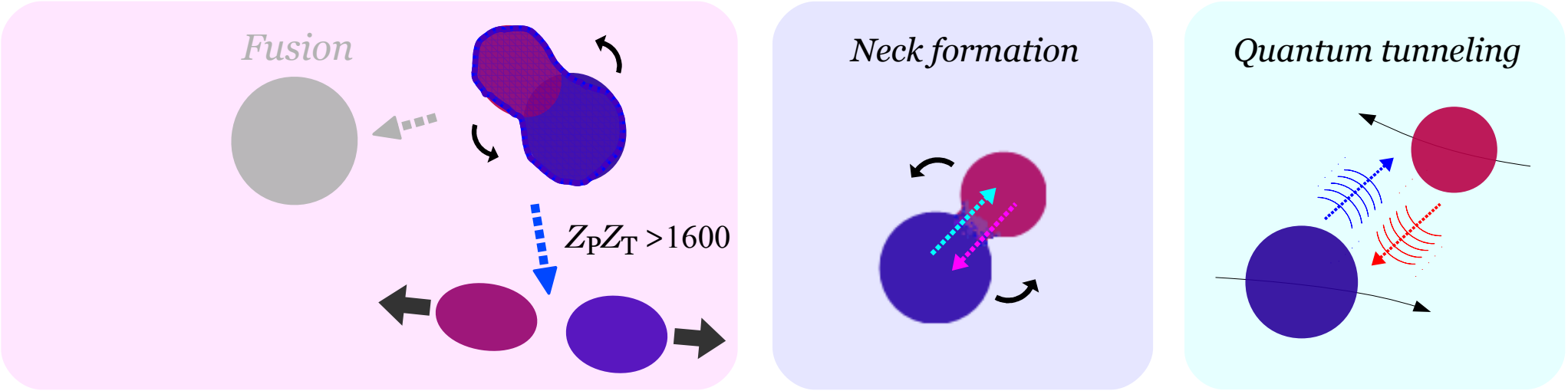

Quasifission | Multinucleon transfer | Transfer of few nucleons

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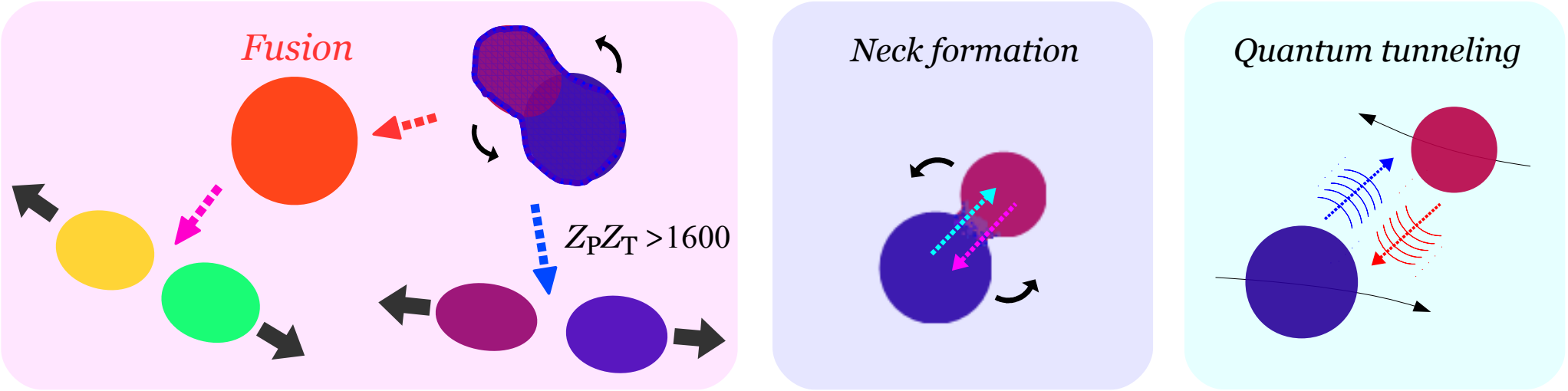

Fusion-fission | Quasifission | Multinucleon transfer | Transfer of few nucleons

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Aim: To predict how to produce unstable nuclei

- ✔ Each box represents an atomic nucleus (with different N and Z)
- ✔ To study unstable nuclei, we need to produce them experimentally

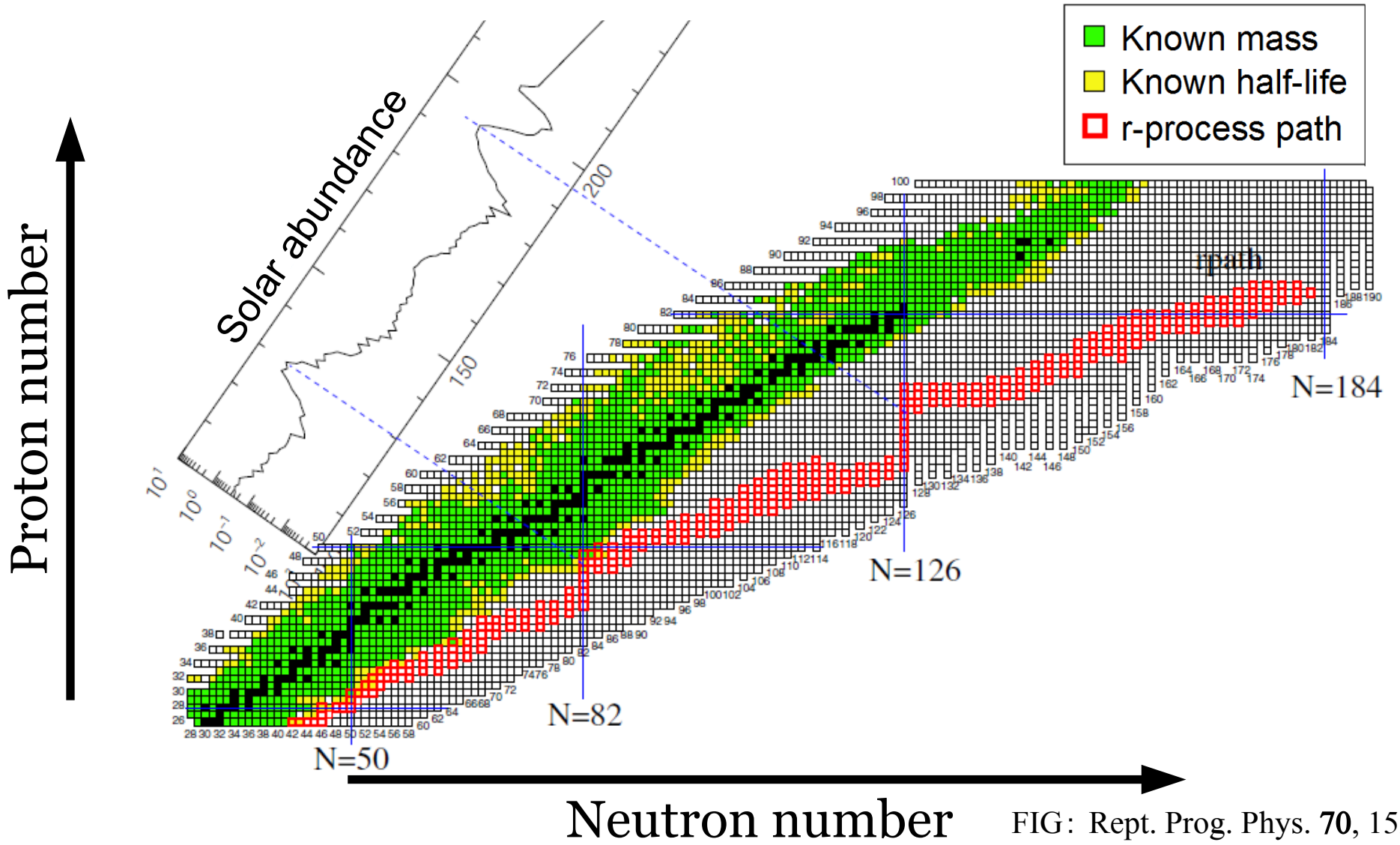

FIG: Rept. Prog. Phys. **70**, 1525 (2007)

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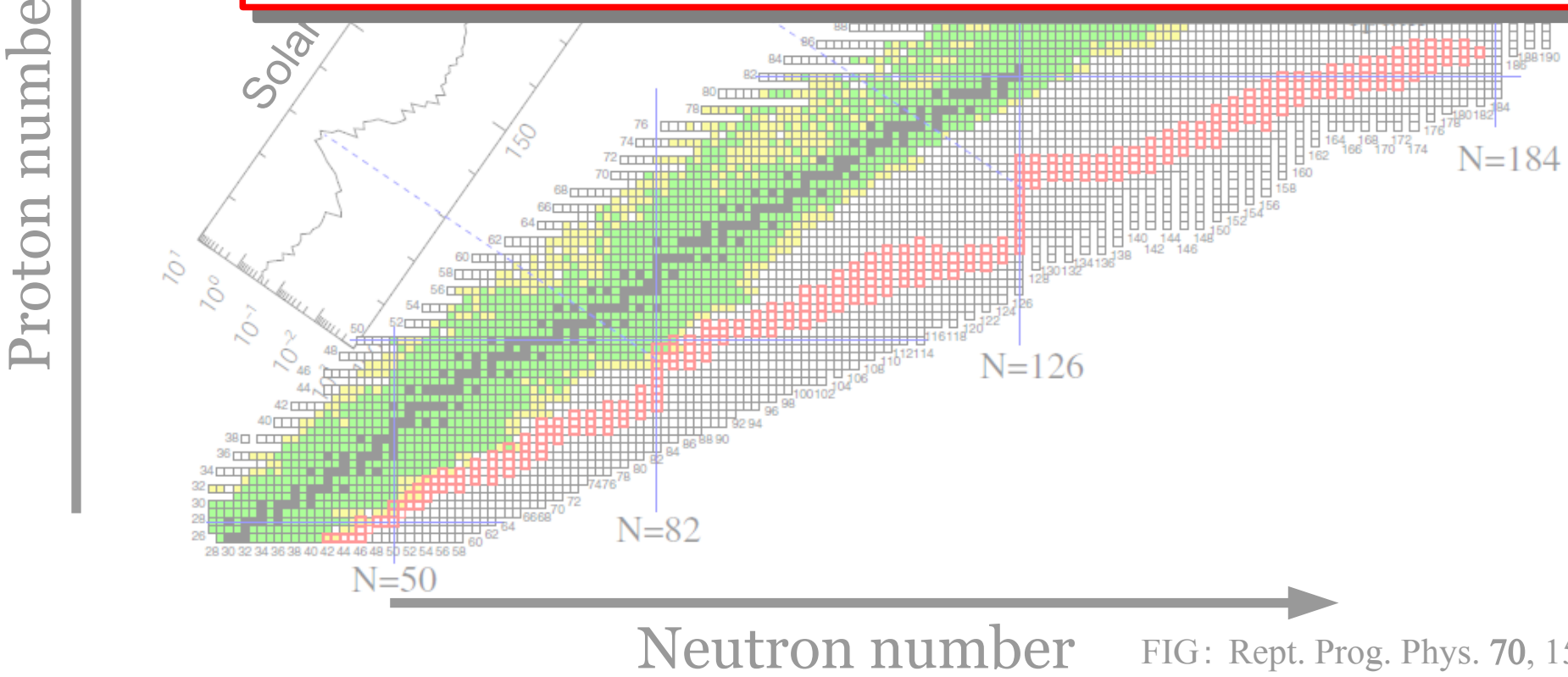
To produce objective unstable nuclei, what is the best projectile-target combination and incident energy?

We have conducted microscopic simulations based on TDDFT



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Hohenberg-Kohn (HK) theorem

$\hat{H} = \hat{T} + \hat{V}_{\rm int} + \hat{V}_{\rm ext}$: interacting system of interest

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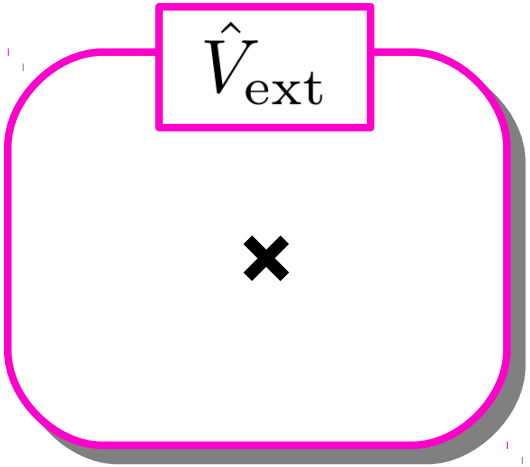

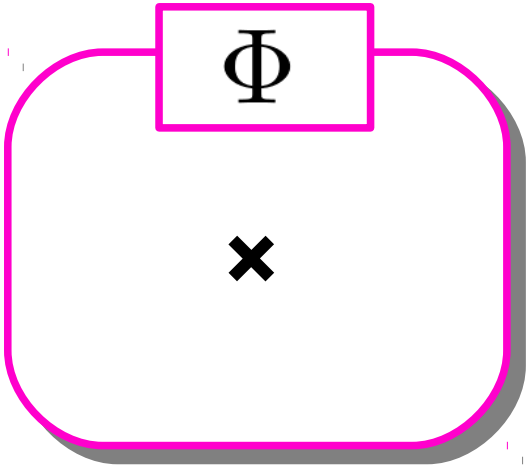

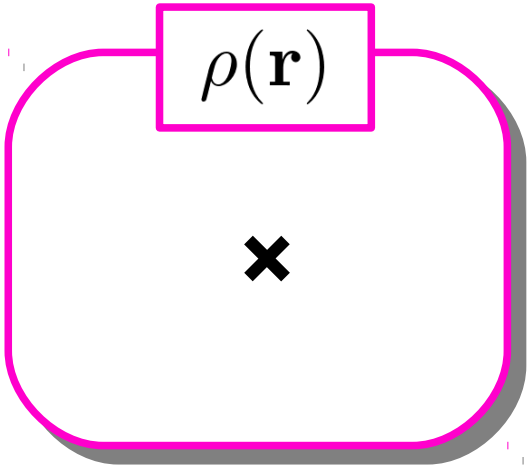

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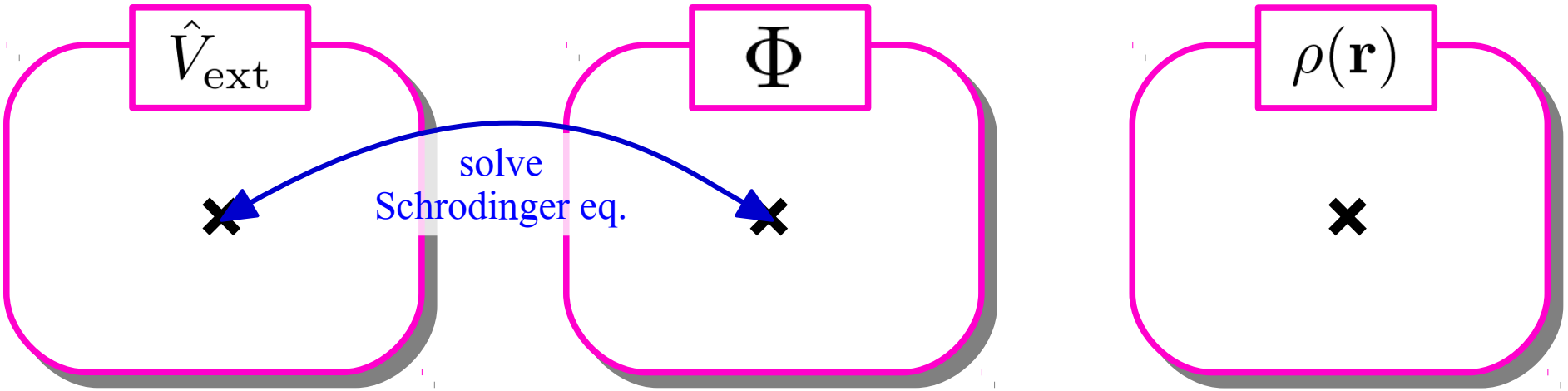

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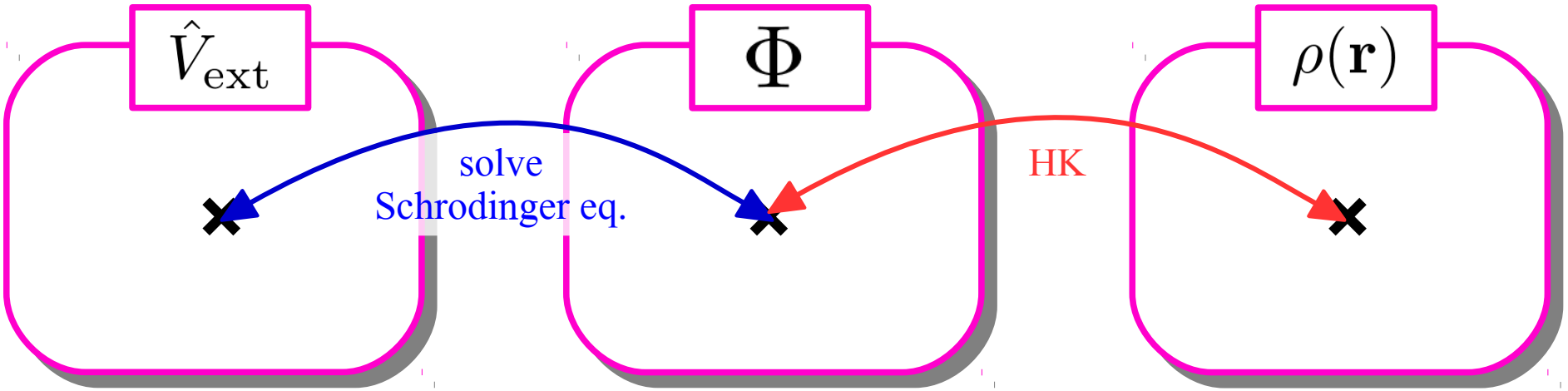

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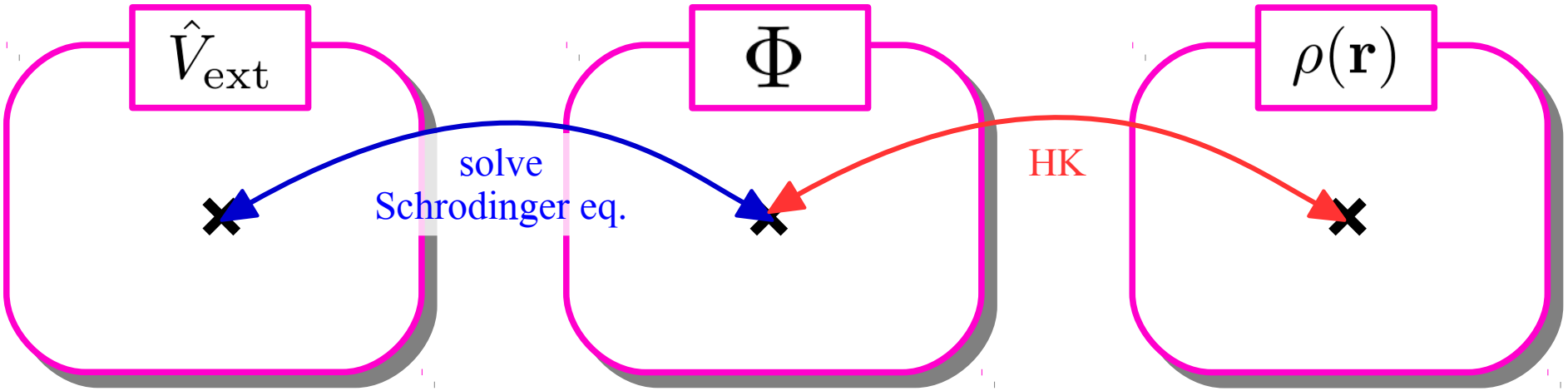

HK theorem states: $\hat{V}_{\rm ext} \Leftrightarrow \Phi \Leftrightarrow \rho(\mathbf{r})$

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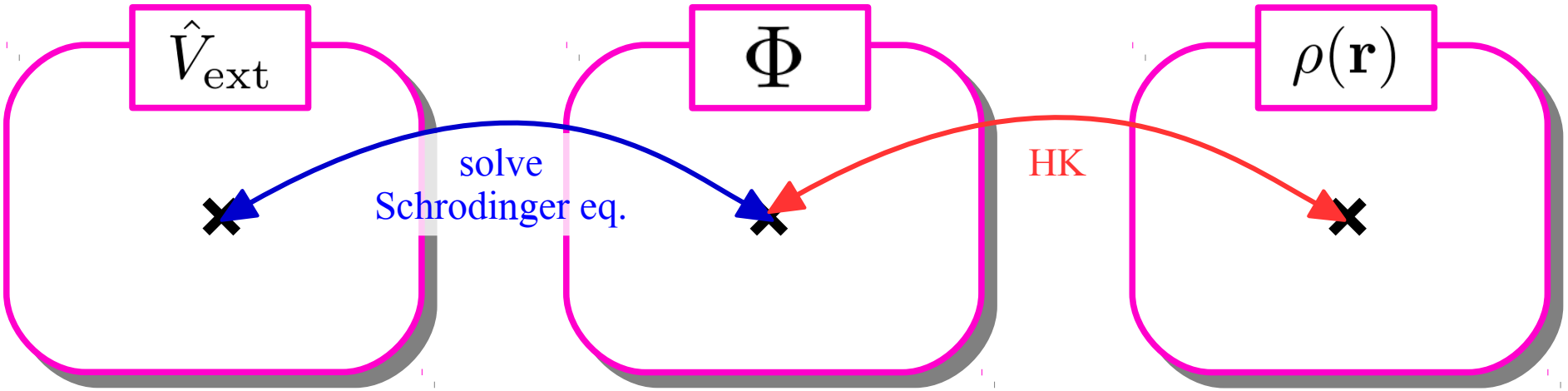

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$$E_{\rm g.s.} = E[\rho_{\rm g.s.}] = \min_{\rho} E[\rho]$$

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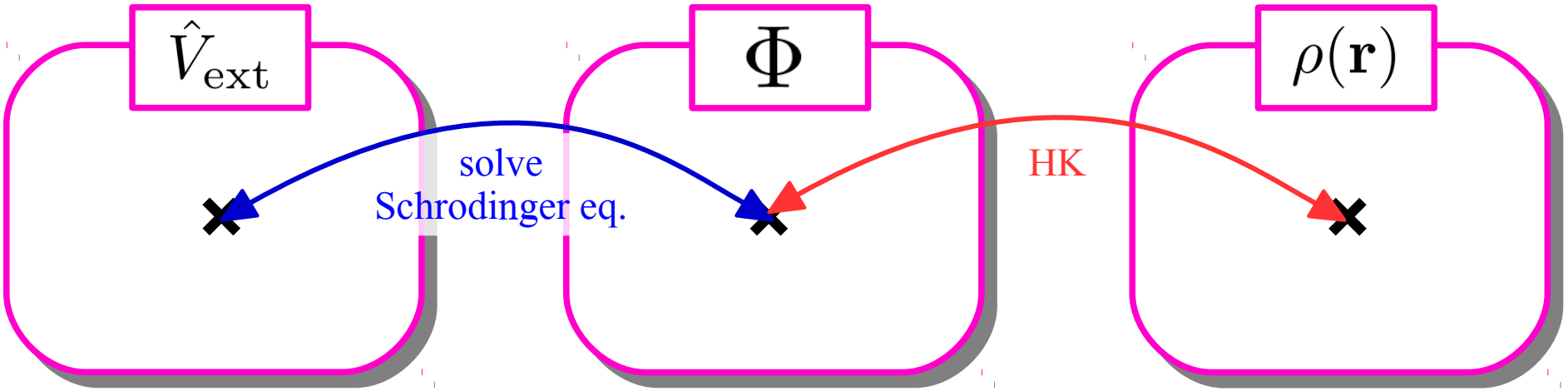

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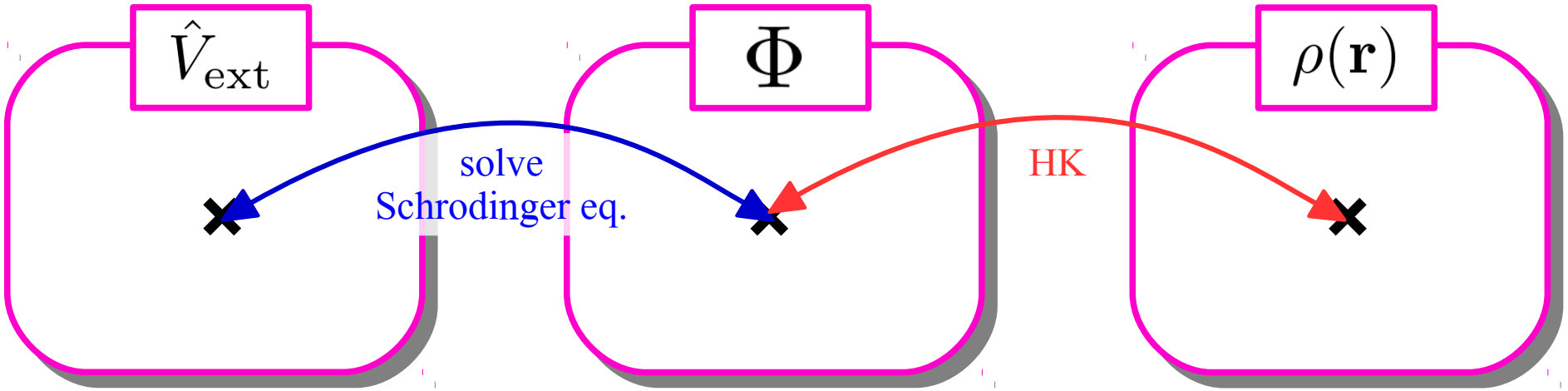

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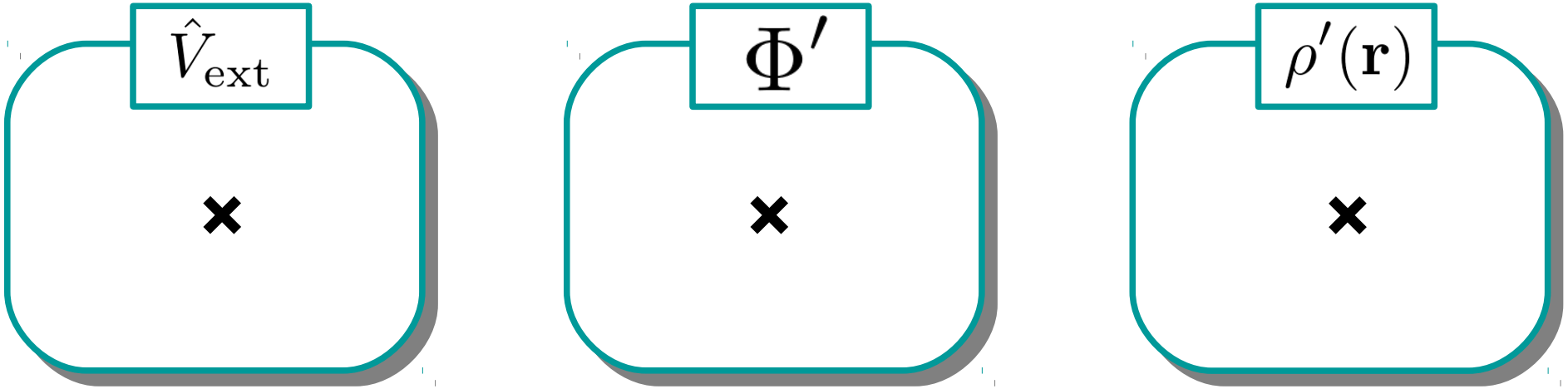

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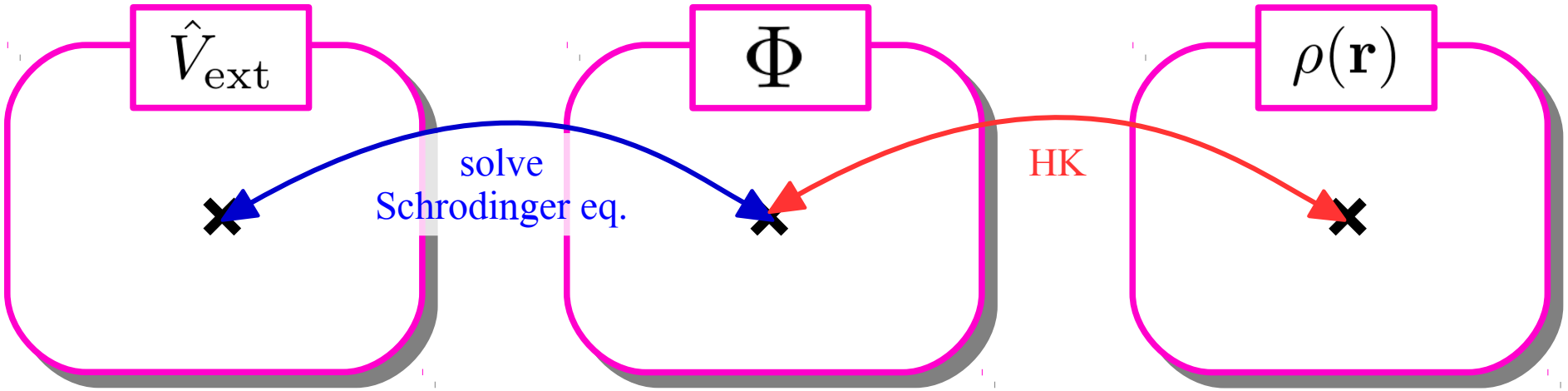

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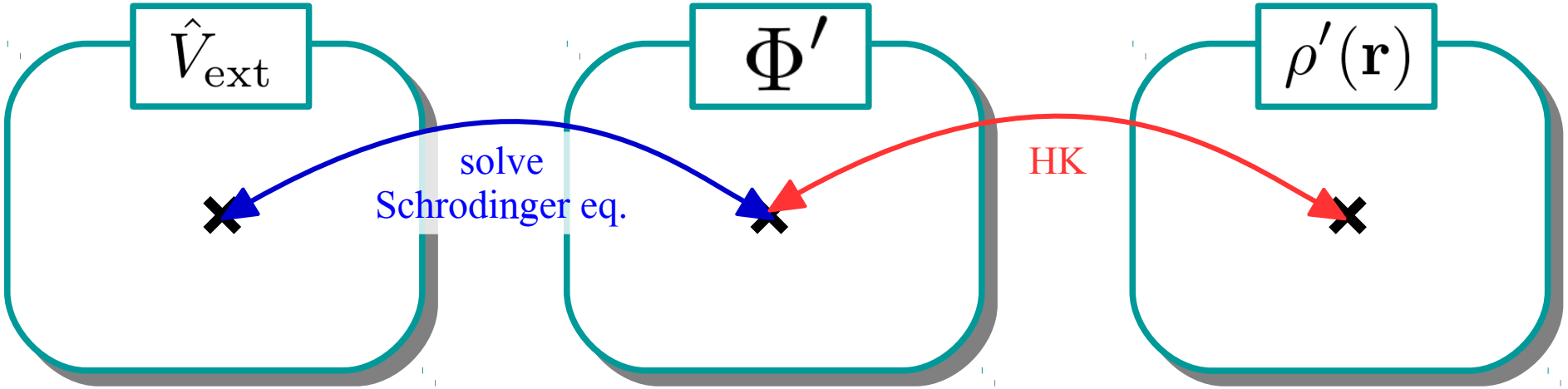

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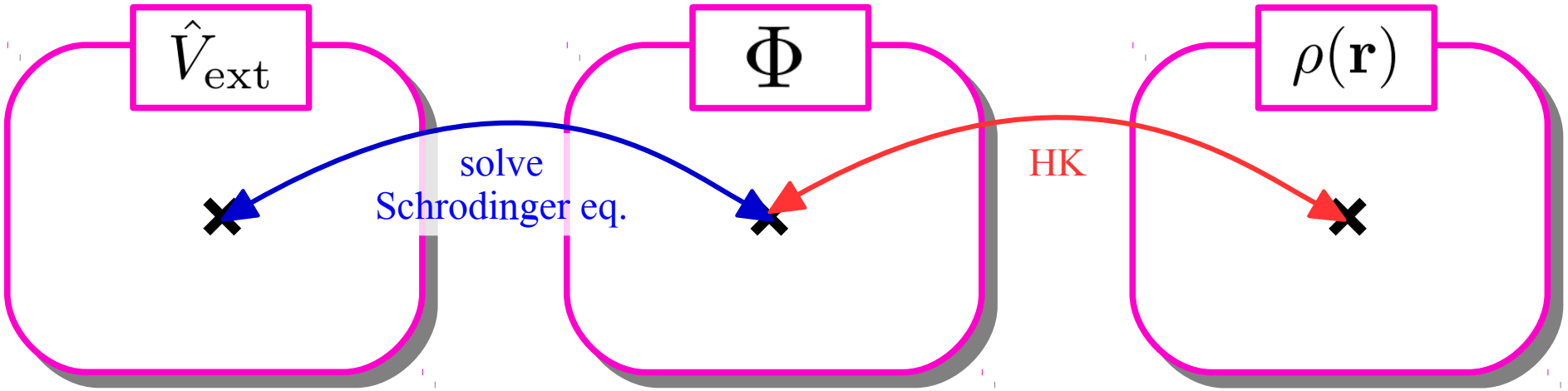

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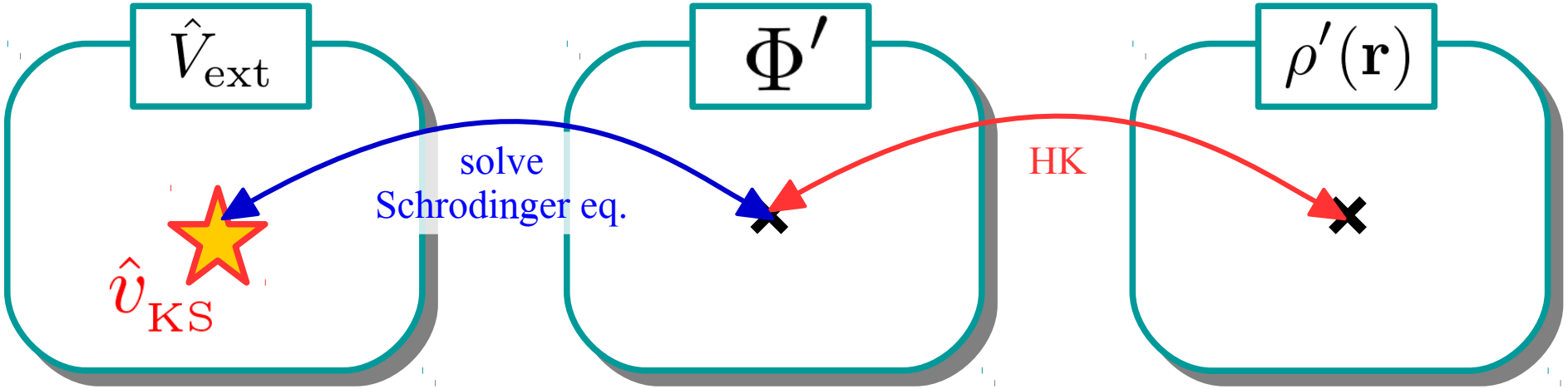

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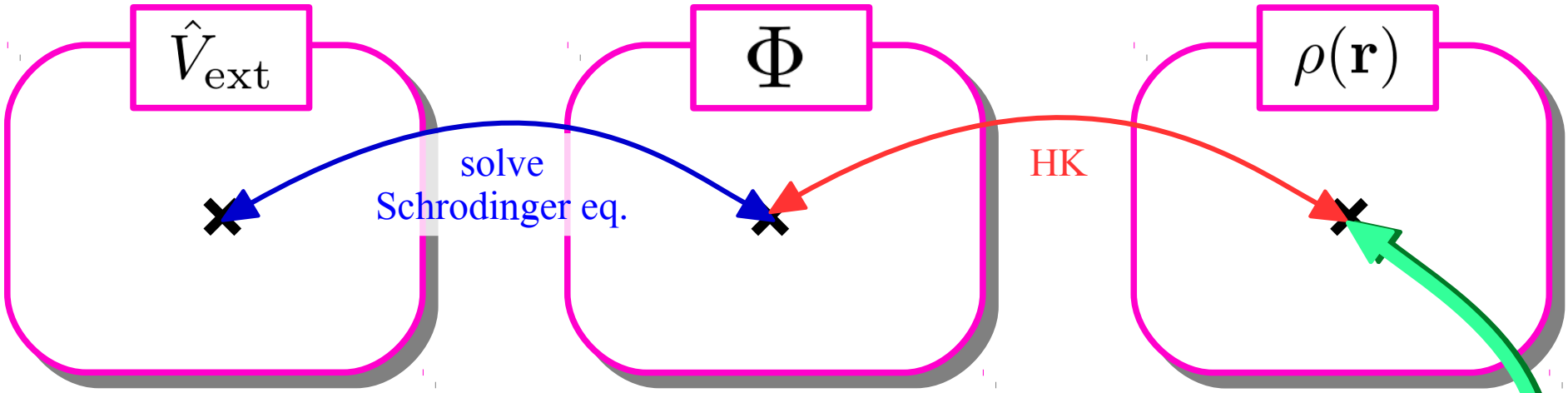

$\rho'(\mathbf{r}) = \rho(\mathbf{r})$

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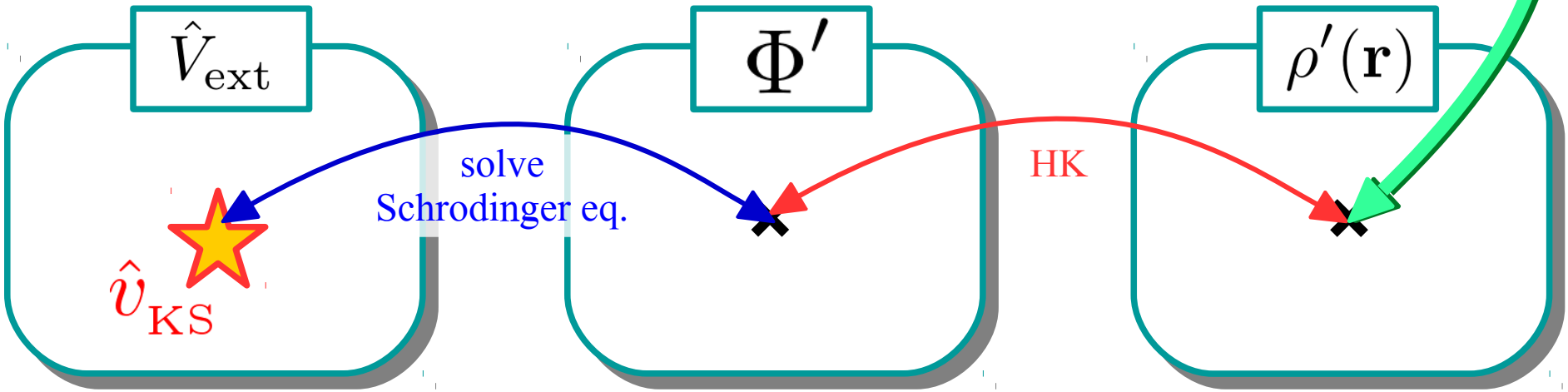

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✔ By solving the KS equation for the non-interacting system, we can get exact solution for the interacting system

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Kohn-Sham equation

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

$$\rho(\mathbf{r}) = \sum_{i=1}^{N} \left|\phi_i(\mathbf{r})\right|^2 \qquad \Phi(\mathbf{r}_1, \cdots, \mathbf{r}_N) = \frac{1}{\sqrt{N!}} \det\left\{\phi_i(\mathbf{r}_j)\right\}$$: Slater determinant

Basic concepts of DFT: HK theorem & KS scheme

✔ By solving the KS equation for the non-interacting system, we can get exact solution for the interacting system

Kohn-Sham equation

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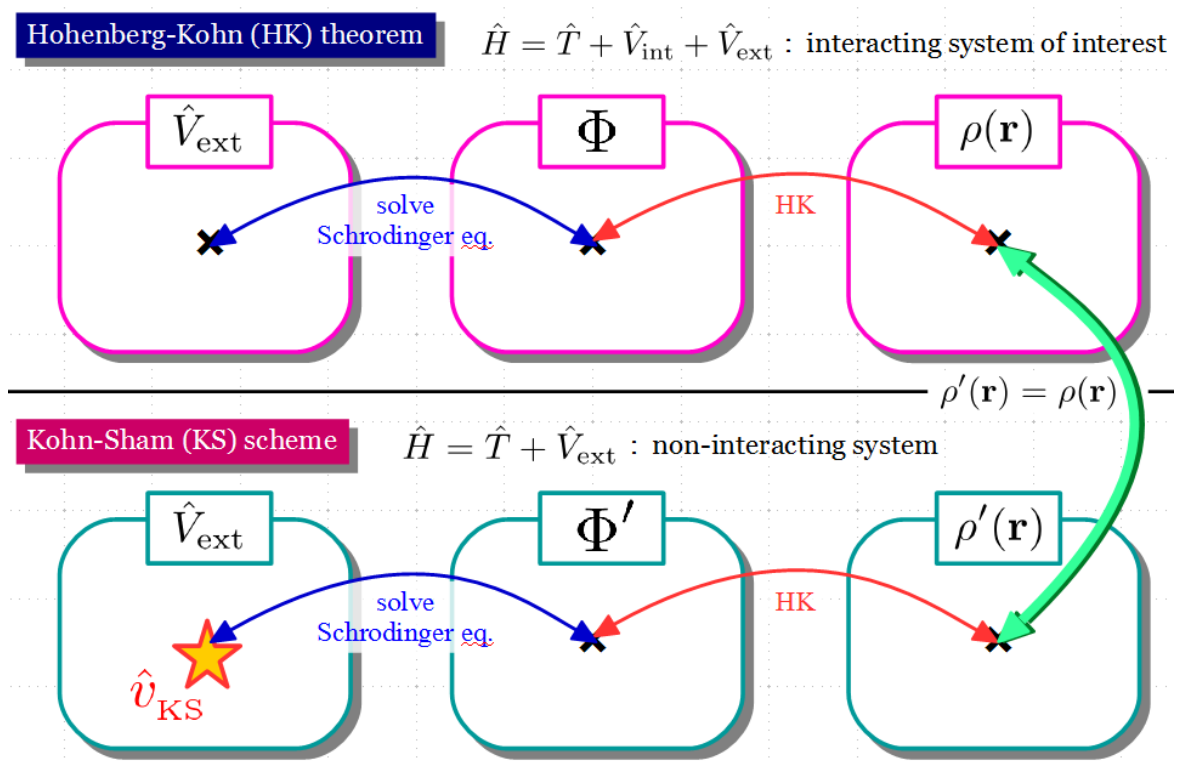
Get everything!

$$\Phi = \Phi[\rho(\mathbf{r})]$$

$$\mathcal{O}[\rho] = \langle \Phi[\rho] | \hat{\mathcal{O}} | \Phi[\rho] \rangle$$

We solve this



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Time-dependent version: time-dependent density functional theory (TDDFT)

Runge-Gross (RG) theorem: E. Runge and E.K.U. Gross, Phys. Rev. Lett. **52**, 997 (1984)

Time-dependent Kohn-Sham equation

$$i\hbar\frac{\partial\phi_i(\mathbf{r},t)}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + \hat{v}_{\mathrm{KS}}[\rho(\mathbf{r},t)]\right]\phi_i(\mathbf{r},t)$$

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Application: Real-time/real-space simulation of heavy ion reactions

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Ground-state calculation

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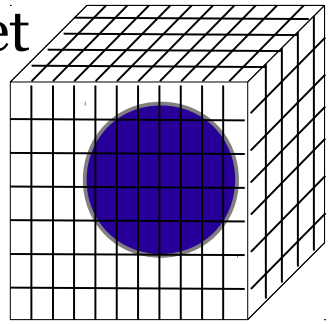
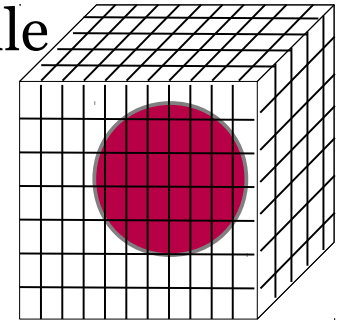
$$x \equiv \{\mathbf{r},\sigma,q\}$$

# of grid points: 30×30×30=27,000
Mesh size: 0.8 fm → L_{box}= 24 fm
Imaginary time method

Target



Projectile



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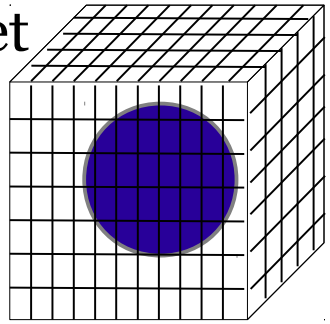

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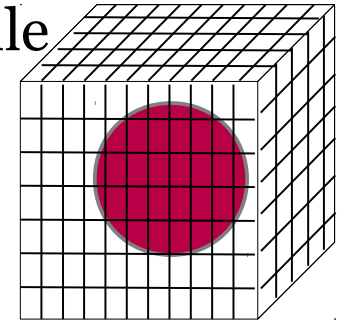

Reaction calculation

Application: Real-time/real-space simulation of heavy ion reactions

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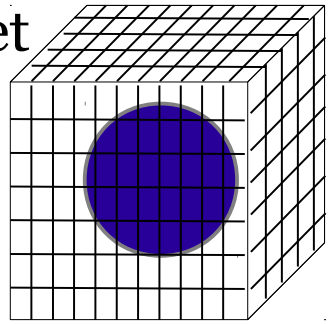

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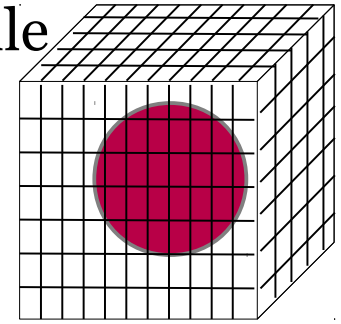
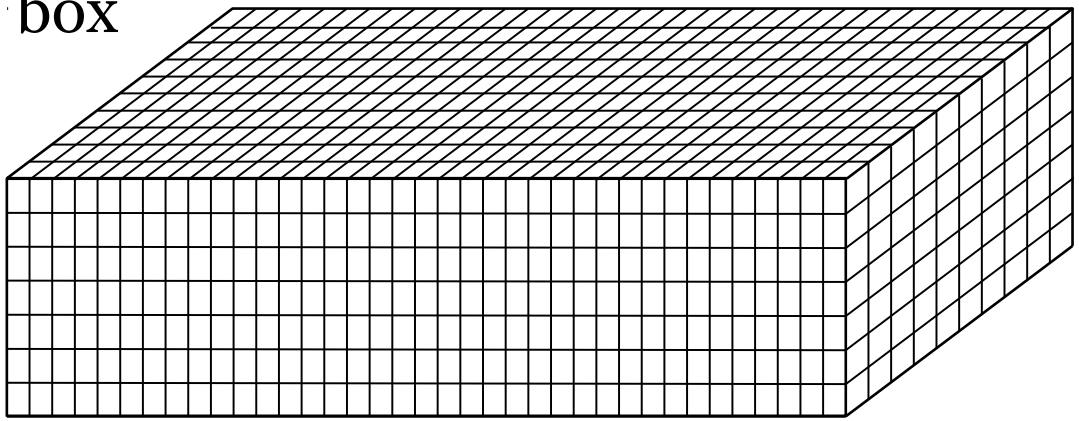


Reaction calculation

A large numerical box



Application: Real-time/real-space simulation of heavy ion reactions

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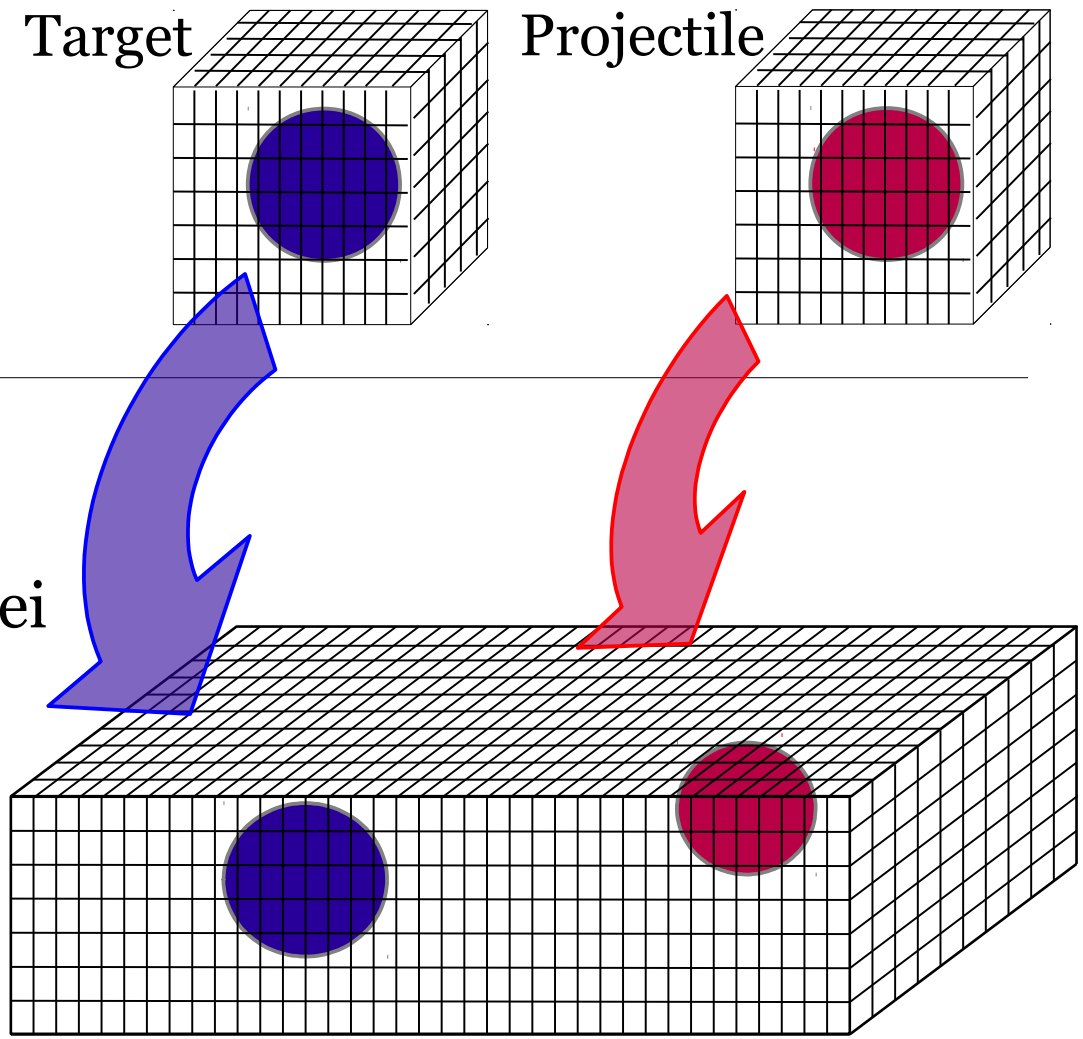
Reaction calculation

Put projectile/target nuclei



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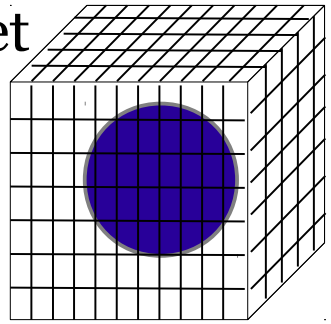
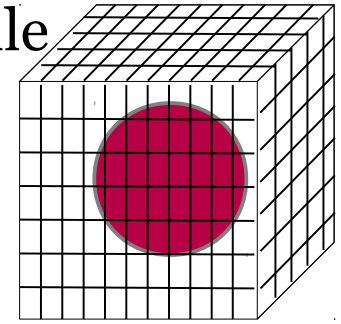
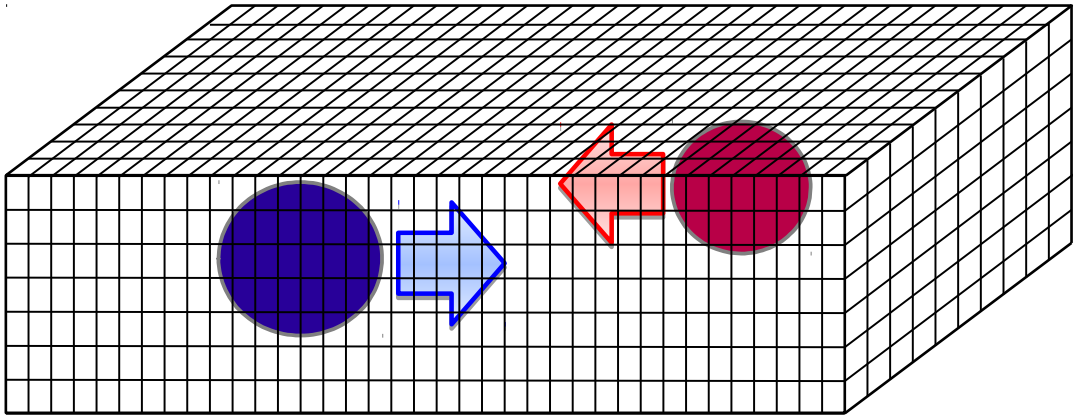


Projectile



Reaction calculation

Give a relative momentum for c.m. motion



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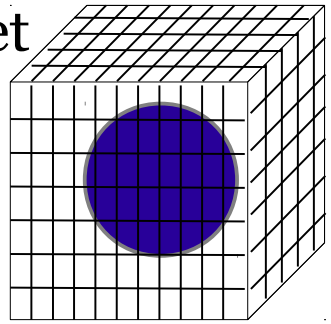

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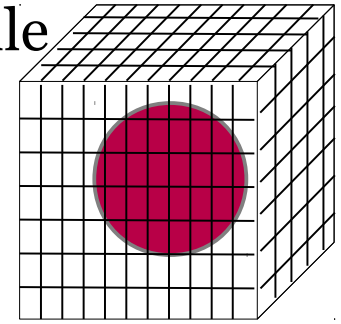


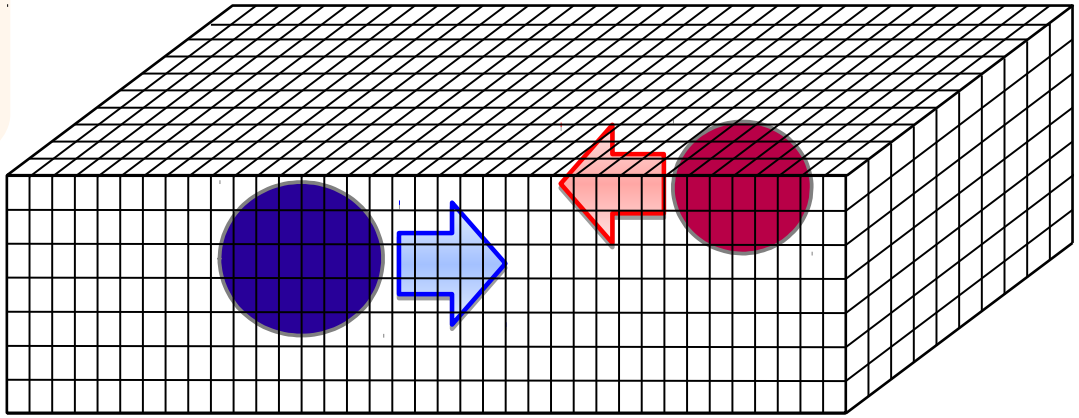
Reaction calculation

of grid points: 70×70×30=147,000
Time evolution: 4th order Taylor expansion

Time-dependent Kohn-Sham eq.

$$i\hbar\frac{\partial}{\partial t}\phi_i(\mathbf{r},\sigma,q,t) = \hat{h}[\rho]\,\phi_i(\mathbf{r},\sigma,q,t)$$

Solve time evolution



Outline

What I would like to tell you today

1. Introduction: Our interests for low-energy heavy ion reactions
2. Method: Time-dependent density functional theory (TDDFT)
3. Example: $^{238}U+^{124}Sn$ reaction
4. Proposal and conclusion

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Example of TDDFT calculation: $^{238}_{92}U_{146}+^{124}_{50}Sn_{74}$ *at* E_{lab}=5.7 MeV/*A*

➢Reactions with different orientations of ^{238}U

Projectile (Uranium, ^{238}U): largely deformed in prolate shape

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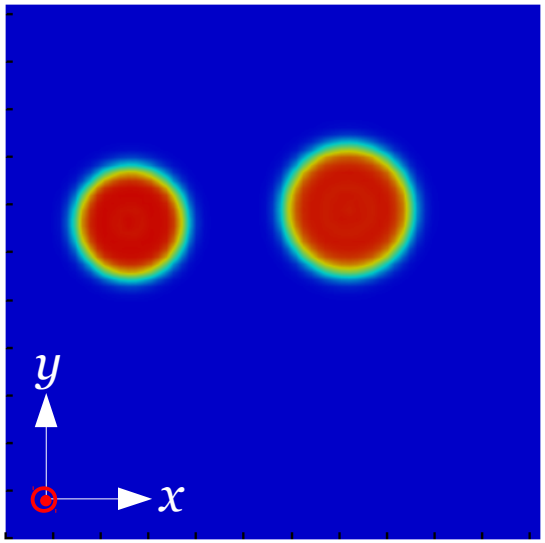
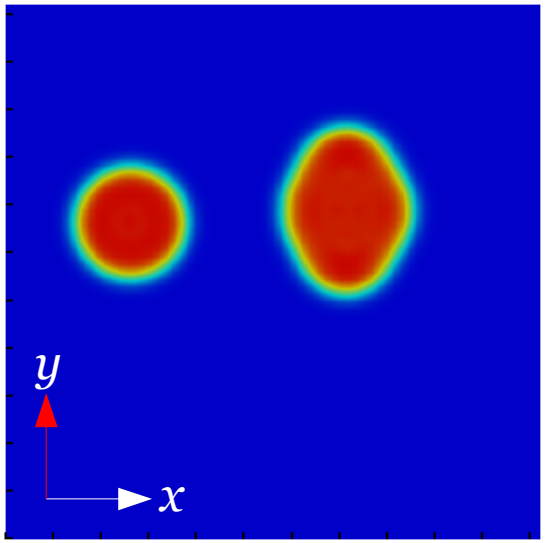
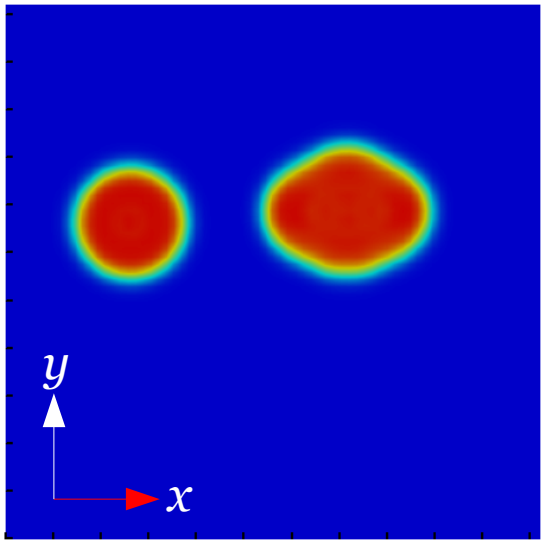
symm. axis of ^{238}U: z-direction



y-direction



x-direction



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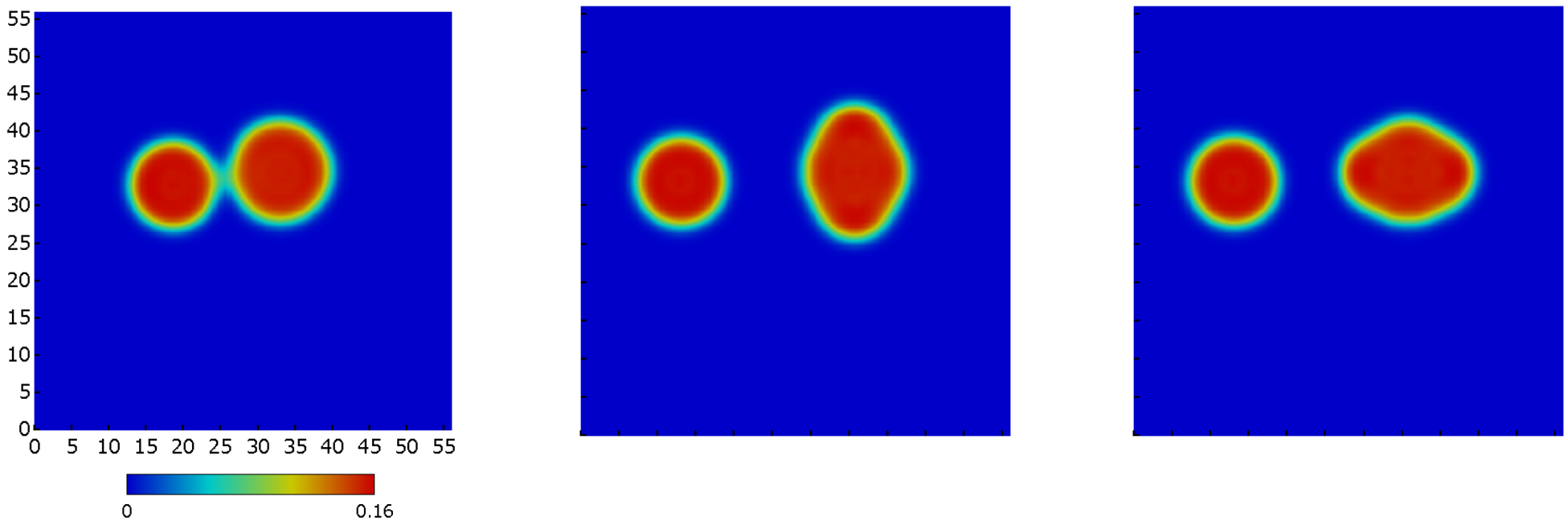

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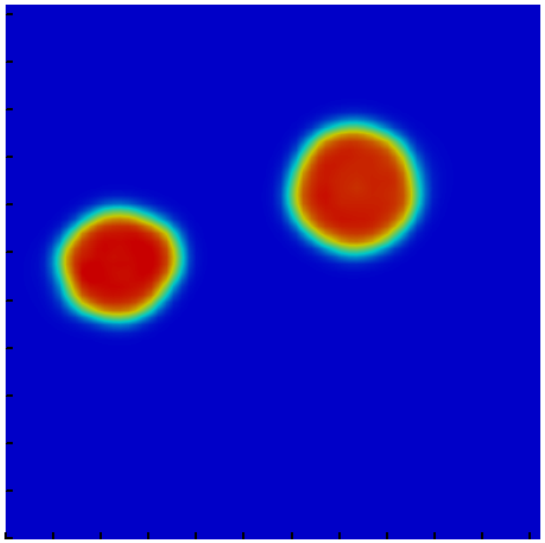

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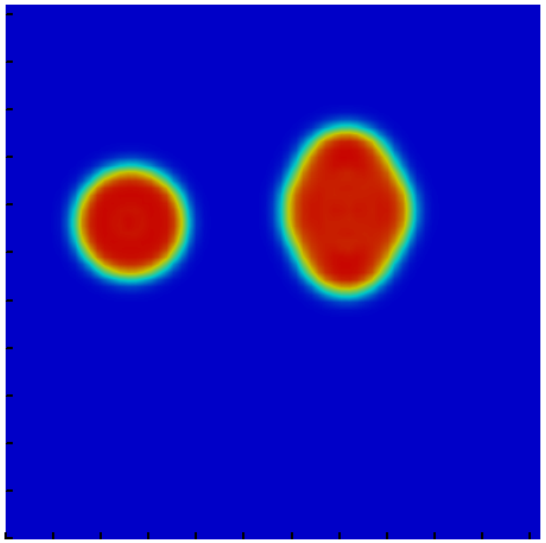

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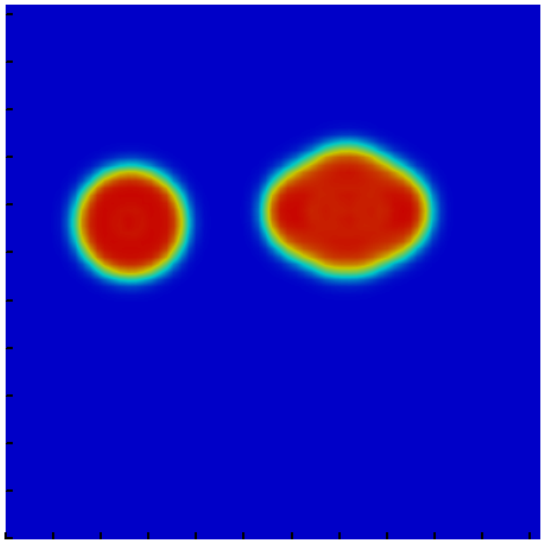

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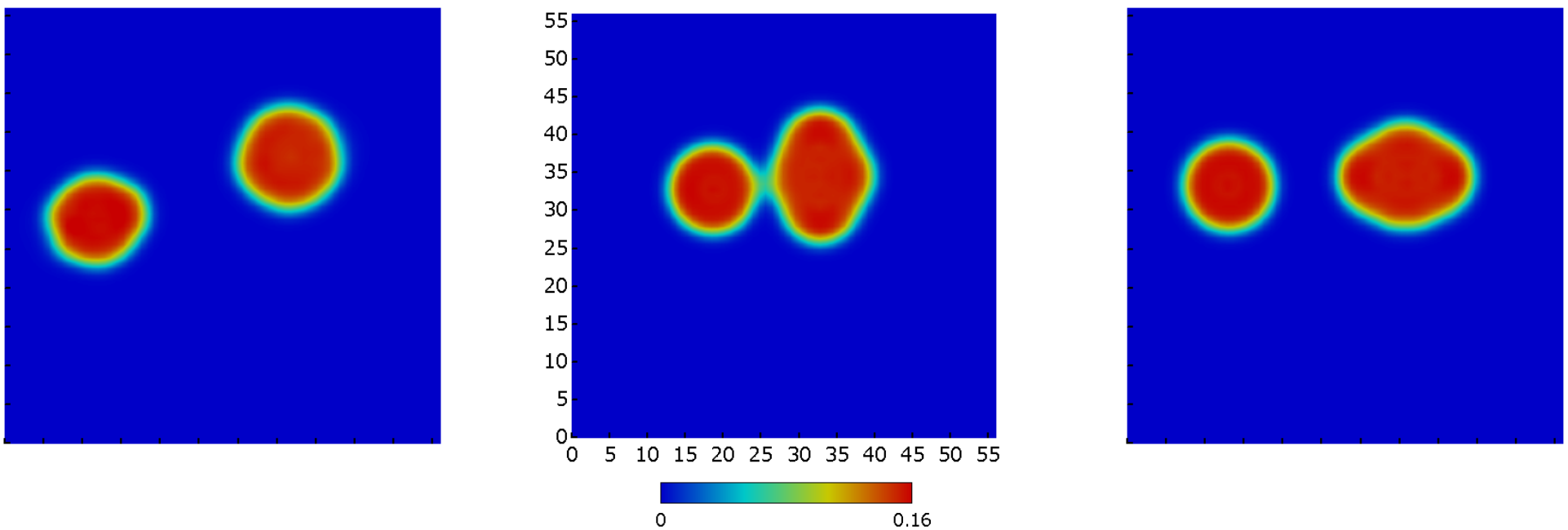

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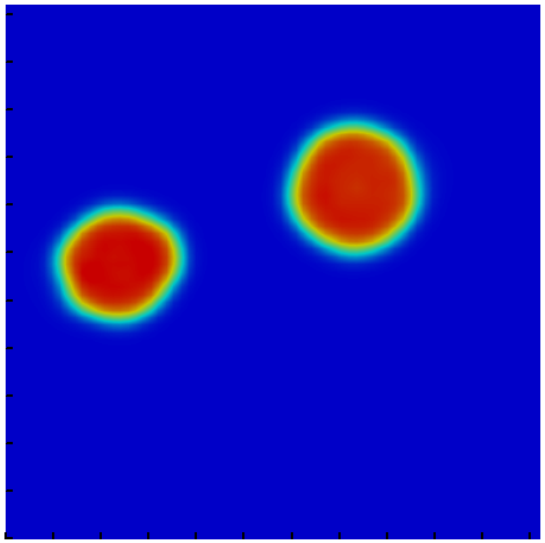
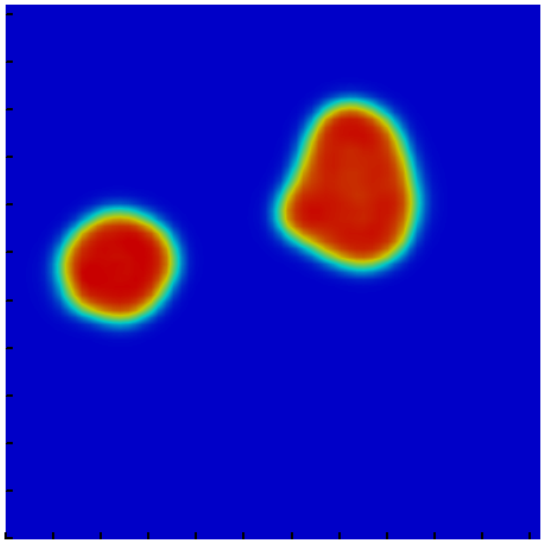


y-direction



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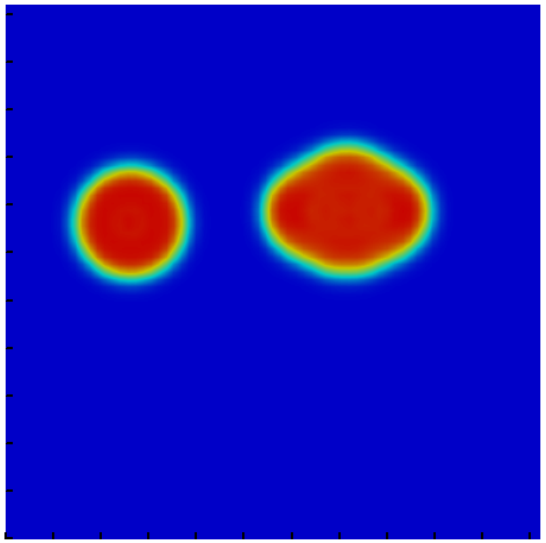

almost no transfer

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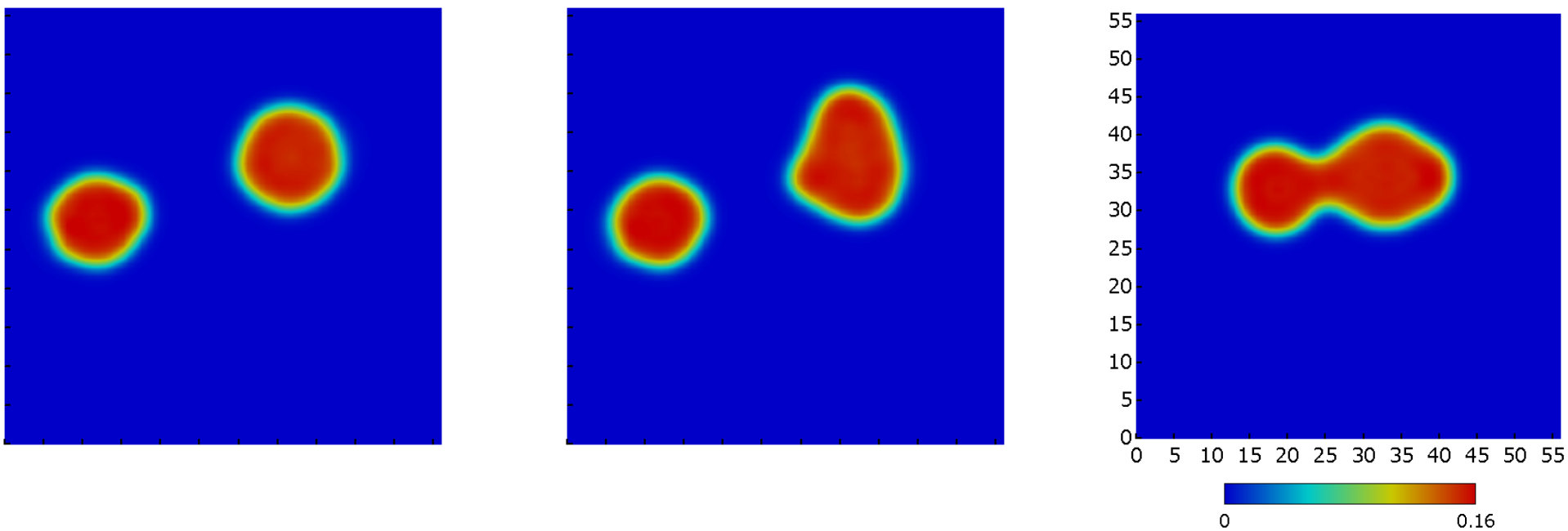

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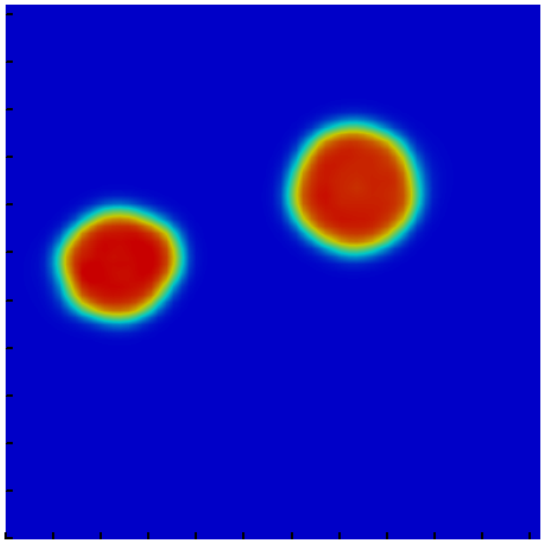

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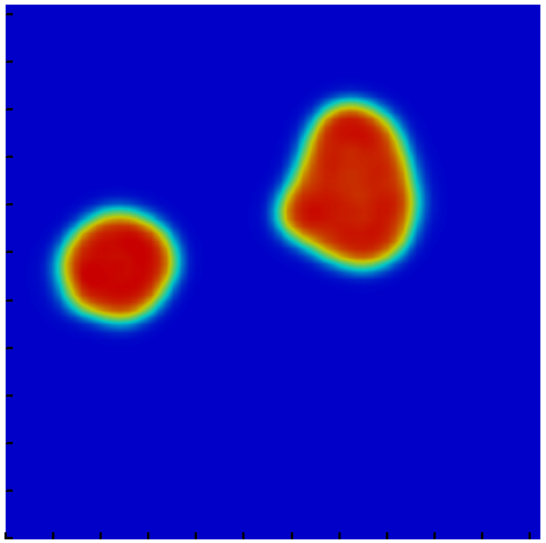
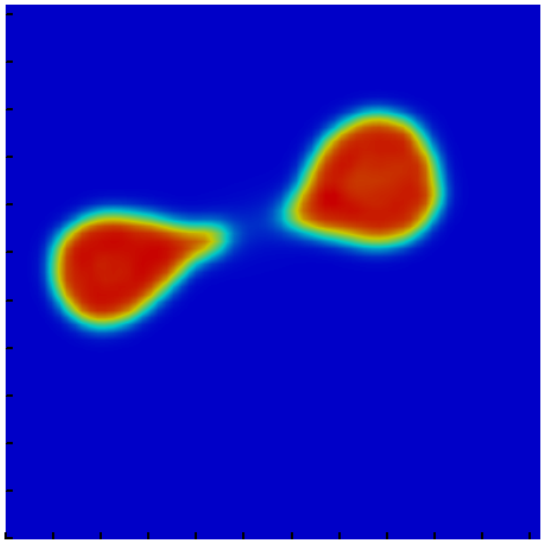


x-direction



Sn ⬅ U, 17 nucleons

Example of TDDFT calculation: $^{238}_{92}U_{146}+^{124}_{50}Sn_{74}$ *at* E_{lab}=5.7 MeV/*A*

✔ Amount of transferred nucleons depends much on orientations of ^{238}U

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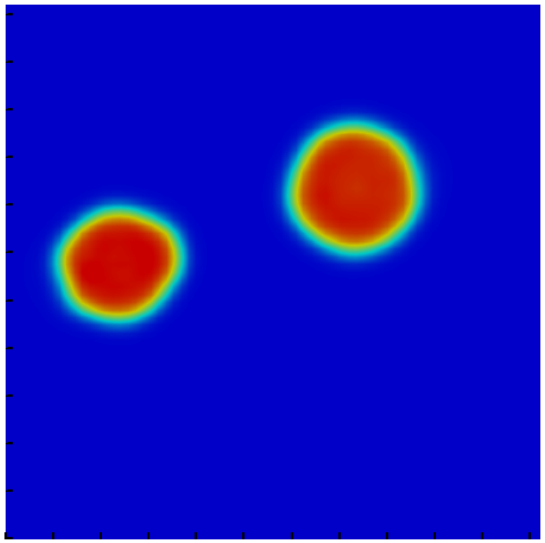

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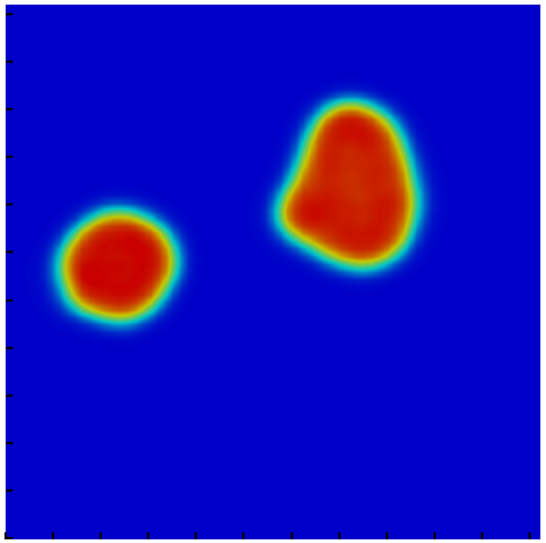
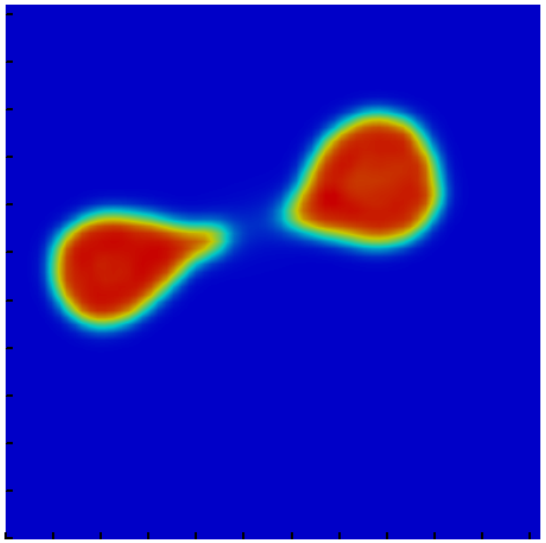


almost no transfer

x-direction



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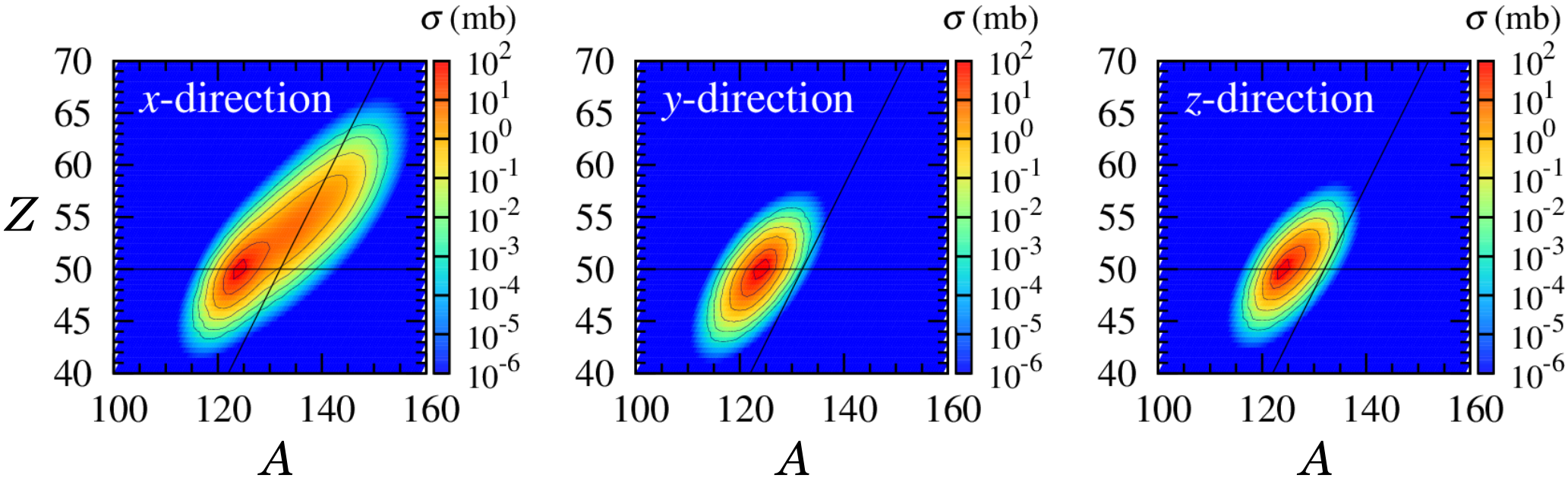
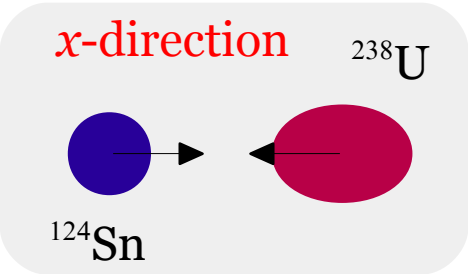
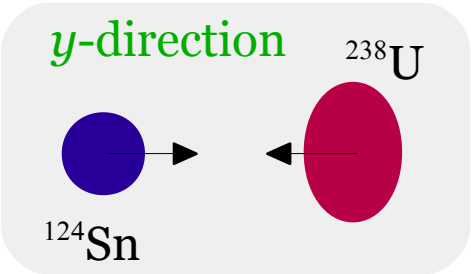
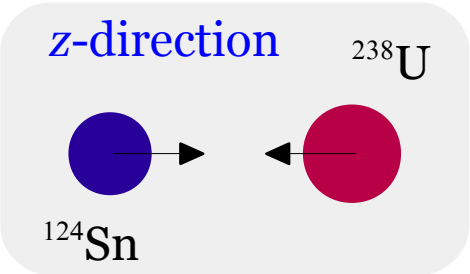
Production cross sections for lighter (^{124}Sn-like) fragments

$$\sigma(N,Z) = 2\pi \int_0^\infty b\, P_{N,Z}(b)\, db$$









Example of TDDFT calculation: $^{238}_{92}U_{146}+^{124}_{50}Sn_{74}$ *at* E_{lab}=5.7 MeV/*A*

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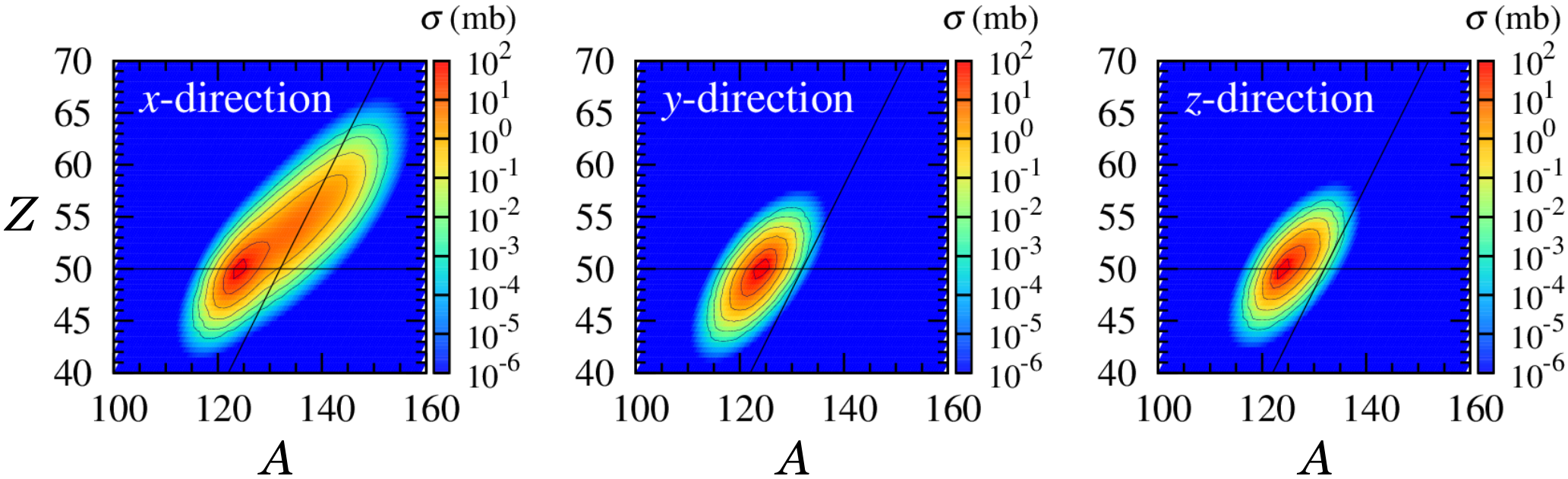

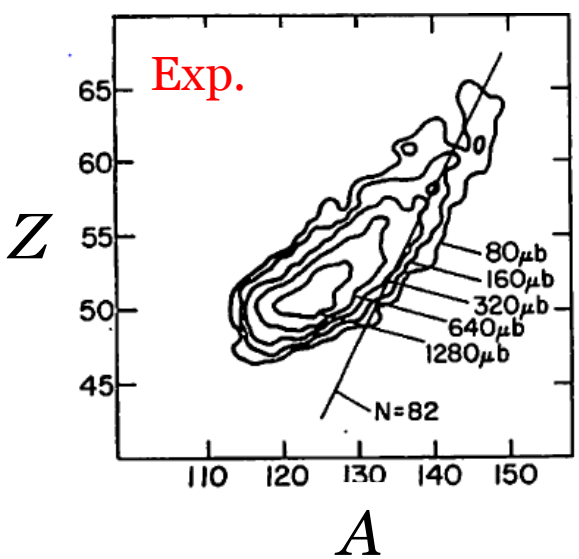

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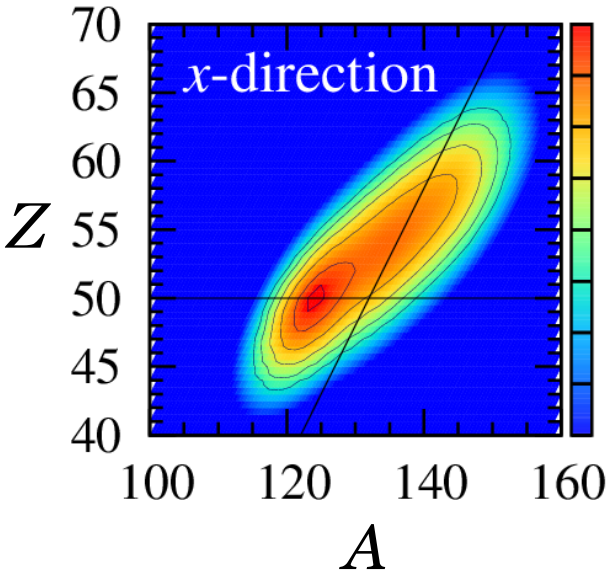
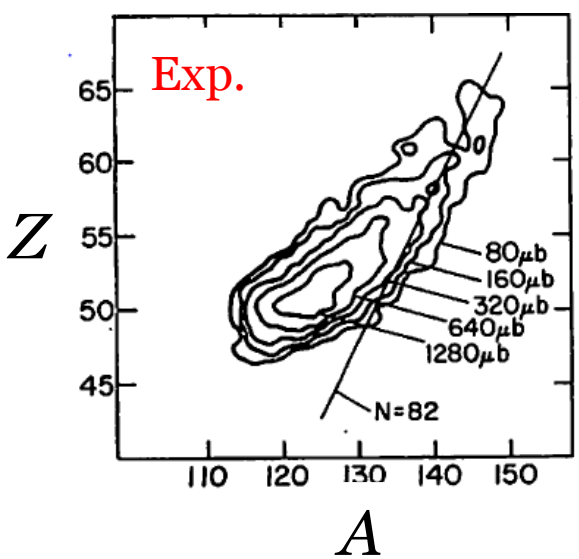
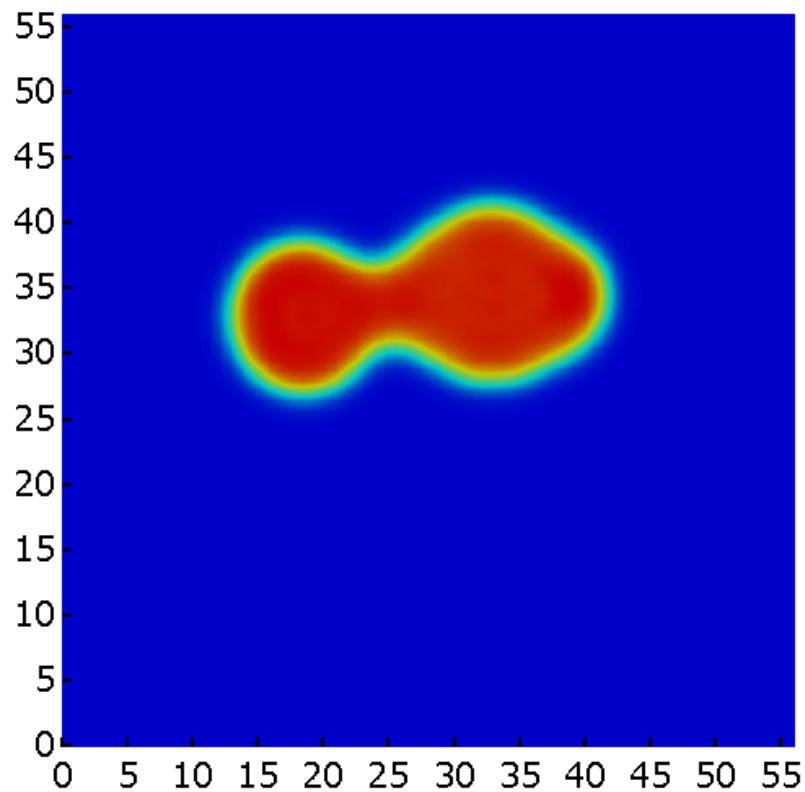


- Measured proton flow would be contributed from the "*x*-direction" configuration with the neck breaking dynamics





Outline

What I would like to tell you today

1. Introduction: Our interests for low-energy heavy ion reactions
2. Method: Time-dependent density functional theory (TDDFT)
3. Example: ^{238}U+^{124}Sn reaction
4. Proposal and conclusion

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I have treated nucleons as independent particles...

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FIG: http://www.hdwalls.xyz/images/welcome-to-dance-this-is-our-first-time-dancing-

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..., but, in actual nuclei, they are known to be "*correlated*"

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FIG: http://allabout.co.jp/gm/gc/433680/

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A superfluid nucleus

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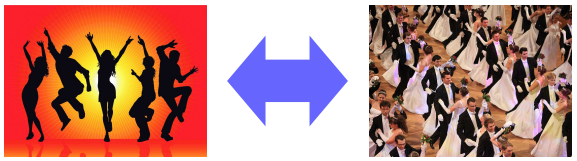

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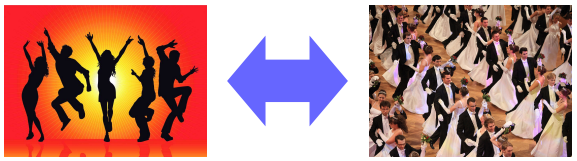

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My short answer:

Quantum many-body dynamics!!

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Dziękuję Bardzo!!

About me:

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Thank you for your attention.