Theoretical Studies on Reaction Mechanisms of Unstable Nuclei

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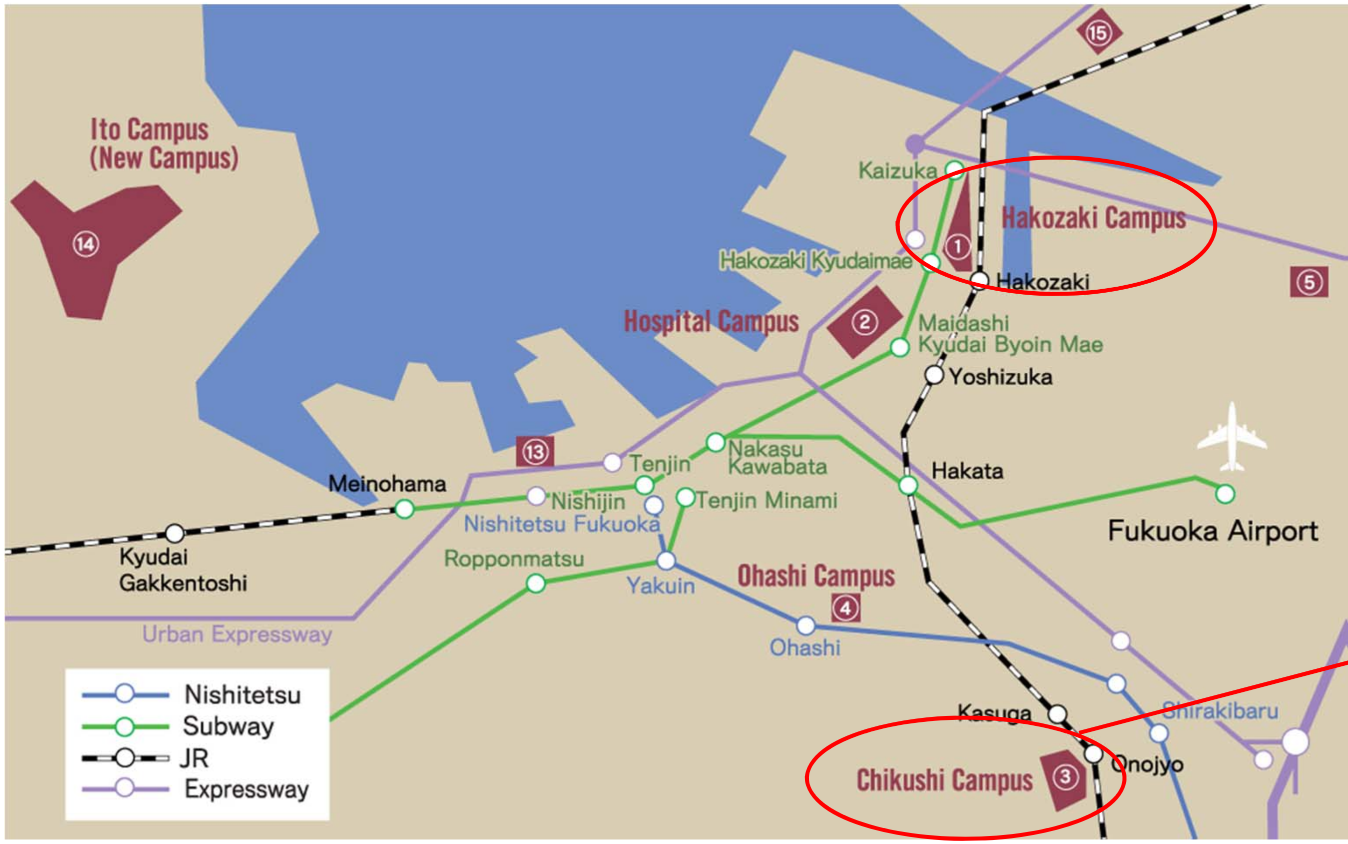

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Outline

0) Brief introduction to *CDCC*

—— *M. Kamimura, Yahiro, Iseri, Sakuragi, Kameyama and Kawai, PTP Suppl.* ***89****, 1 (1986);*
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1) *Four-body breakup* processes for ^{6}He induced reaction

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2) *Microscopic description* of projectile breakup processes

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3 New approach *to inclusive breakup processes*

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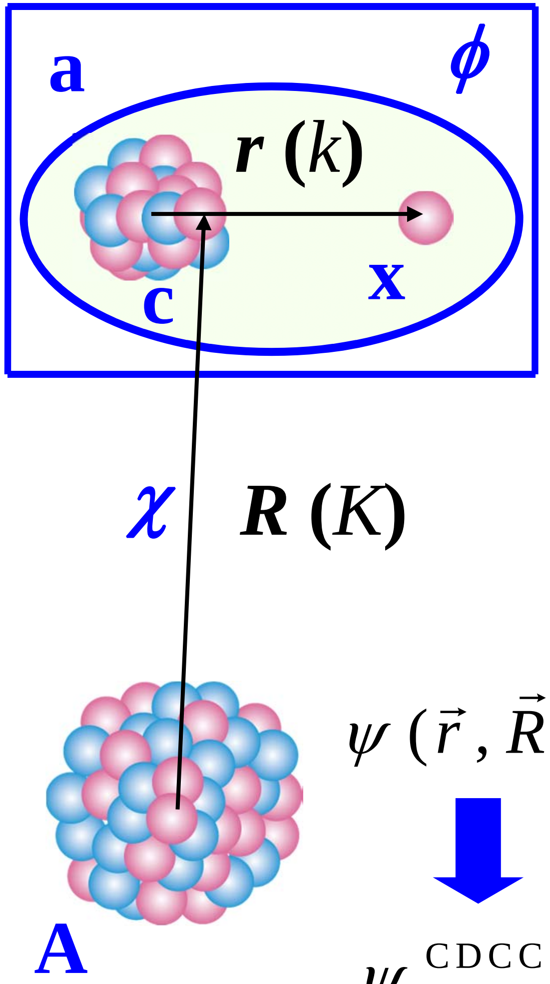
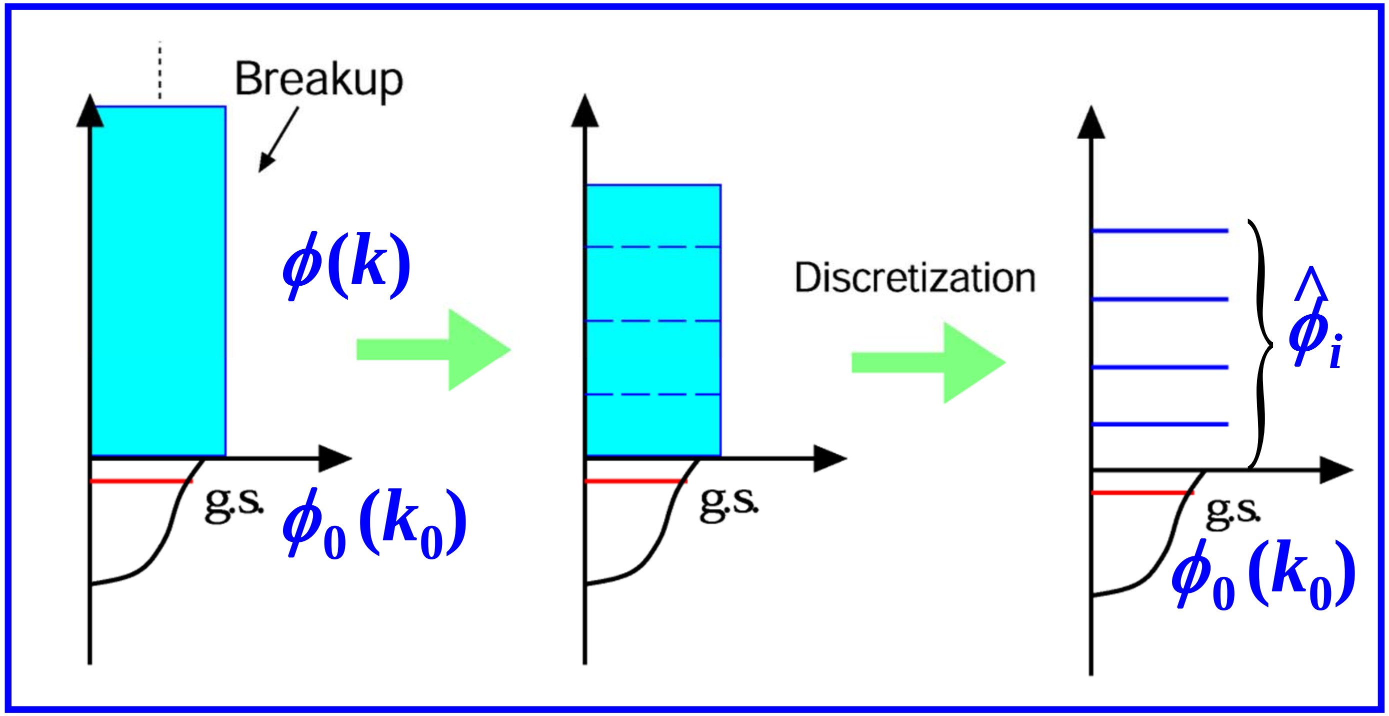
The Continuum-Discretized Coupled Channels method (CDCC)





$$\psi(\vec{r},\vec{R}) \cong \phi_0(k_0,\vec{r})\chi_0(K_0,\vec{R}) + \sum_{i=1}^{i_{max}} \hat{\chi}(\hat{K}_i,\vec{R})\int_{k_{i-1}}^{k_i} \phi(k,\vec{r})dk$$

Truncation and Discretization

$$\psi^{CDCC}(\vec{r},\vec{R}) = \sum_{i=0}^{i_{max}} \hat{\phi}_i(\vec{r})\hat{\chi}_i(\hat{K}_i,\vec{R})$$

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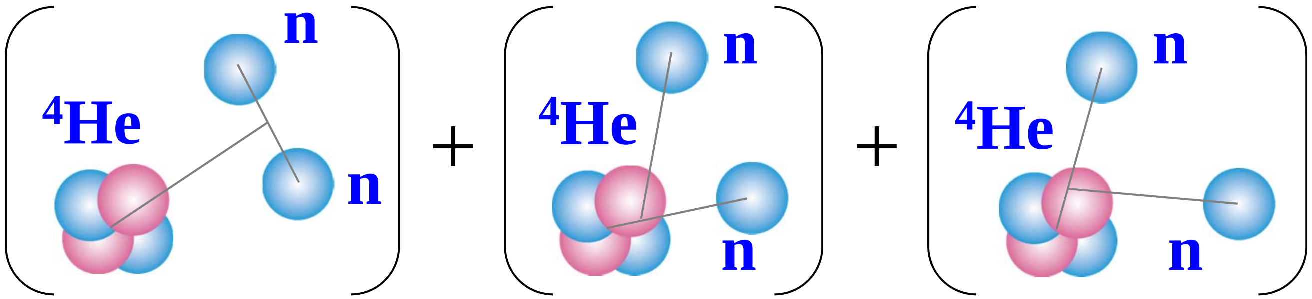
4-body CDCC

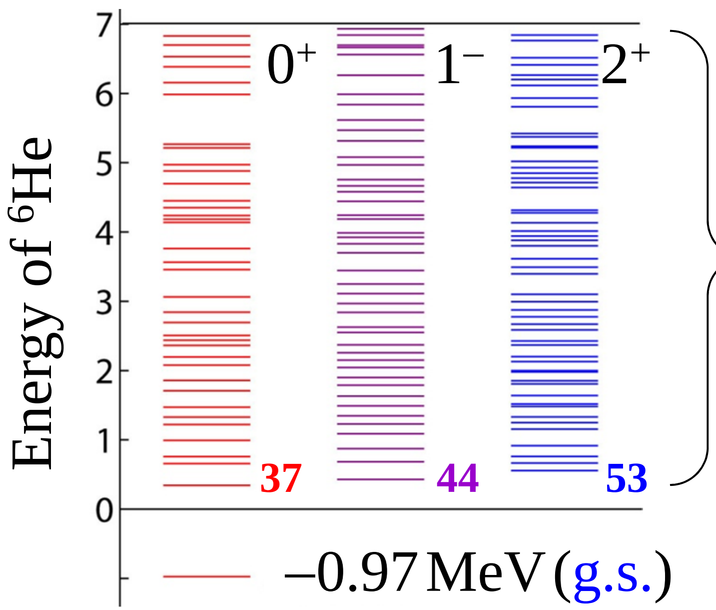
- **Discretization of ^{6}He W. Fn. by diagonalizing internal Hamiltonian.**
  - ✓ Gaussian Expansion Method (GEM)

$\phi^{6\mathrm{He}} =$



— Hiyama, Kino, Kamimura, Prog. Part. Nucl. Phys. 51, 223 (2003).

  - ✓ Diagonalization of internal Hamiltonian



Discretized continuum states!

3-body structure of ^{6}He

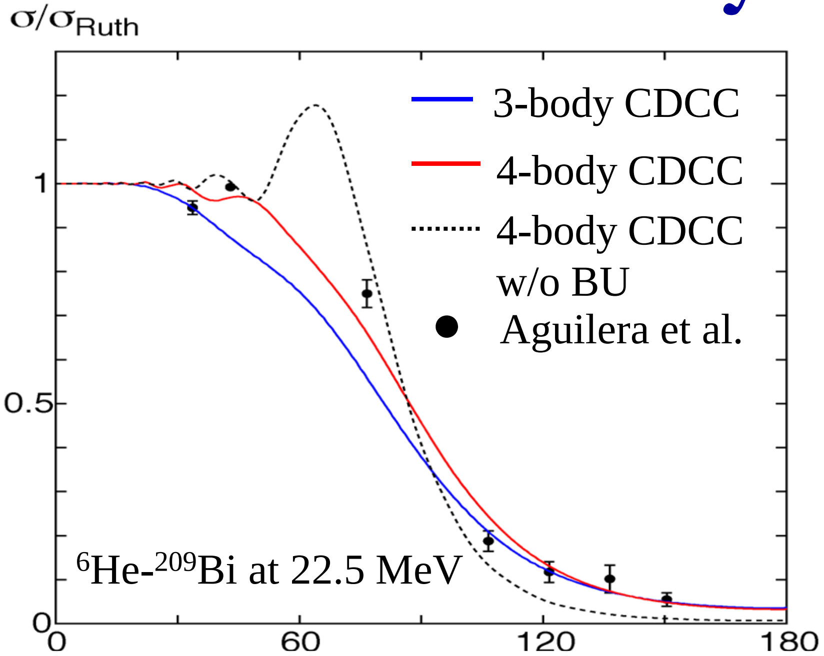
4-body W. Fn.

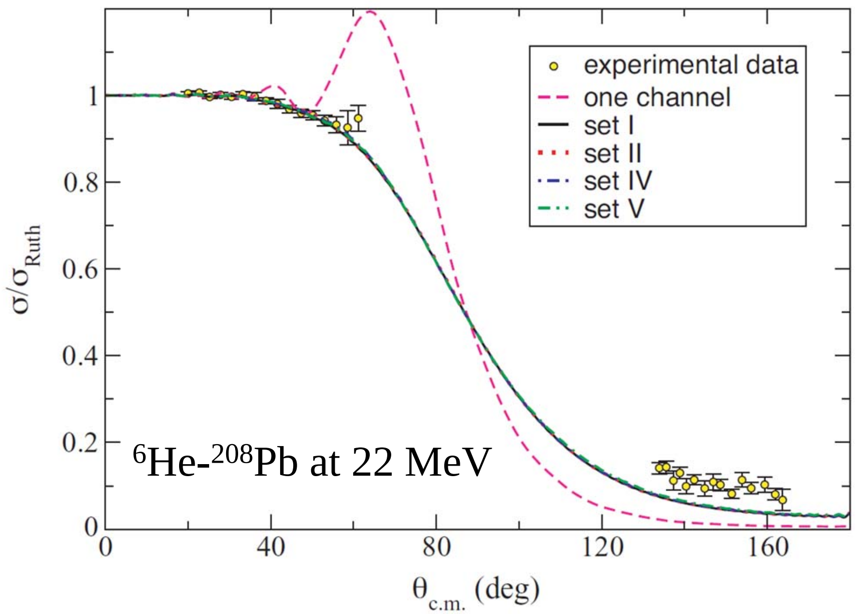
$$\psi^{\text{4-CDCC}} = \sum_{i=0}^{i_{\max}} \hat{\phi}_i \hat{\chi}_i$$

C.M. motion between ^{6}He and A

— T. Matsumoto, Hiyama, O., Iseri, Kamimura, Chiba, Yahiro, PRC70, 061601(R) (2004).

Virtual 4-body breakup of ^{6}He by ^{209}Bi





Key points

- ✓ 4-body CDCC reproduces well the data.
- ✓ 3-body CDCC not.
- ✓ *Virtual* breakup of ^{6}He is important.

—— **T. Matsumoto, Egami, O., Iseri, Kamimura, Yahiro, PRC73, 051602 (R) (2006).**

New topic

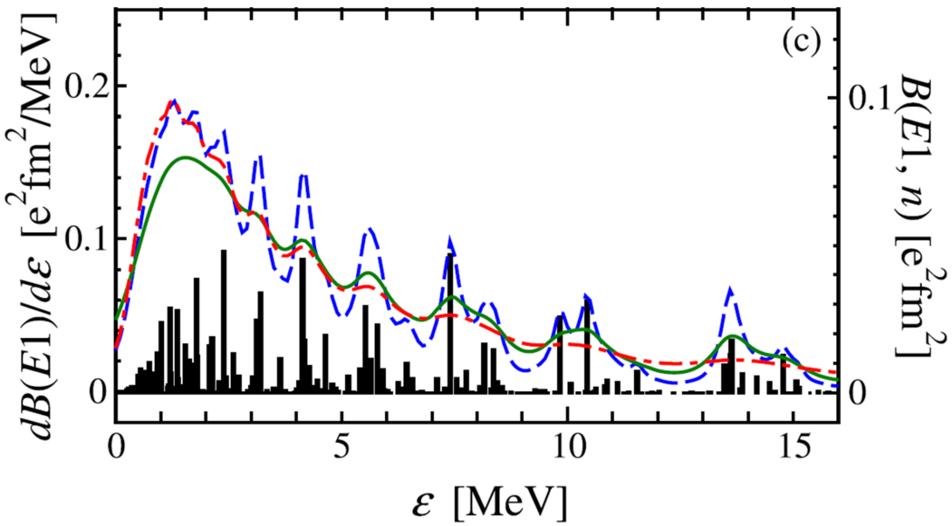
- ✓ 4-body CDCC based on binning method

—— **M. Rodriguez-Gallardo, Arias, Gomez-Camacho, Moro, Thompson, PRC80, 051601 (R) (2009).**

Future work

- ✓ Systematic analysis of 4-body breakup
- ✓ 5-body and 6-body CDCC (with COSM)

Real 4-body breakup of ^{6}He



Key points

- ✓ Smoothing discrete observables
- ✓ Simple Lorenzian procedure fails.
- ✓ A smoothing method with L-S Eq. works.

—— **T. Egami, Matsumoto, O., Yahiro, PTP121, 789 (2009).**

New topic

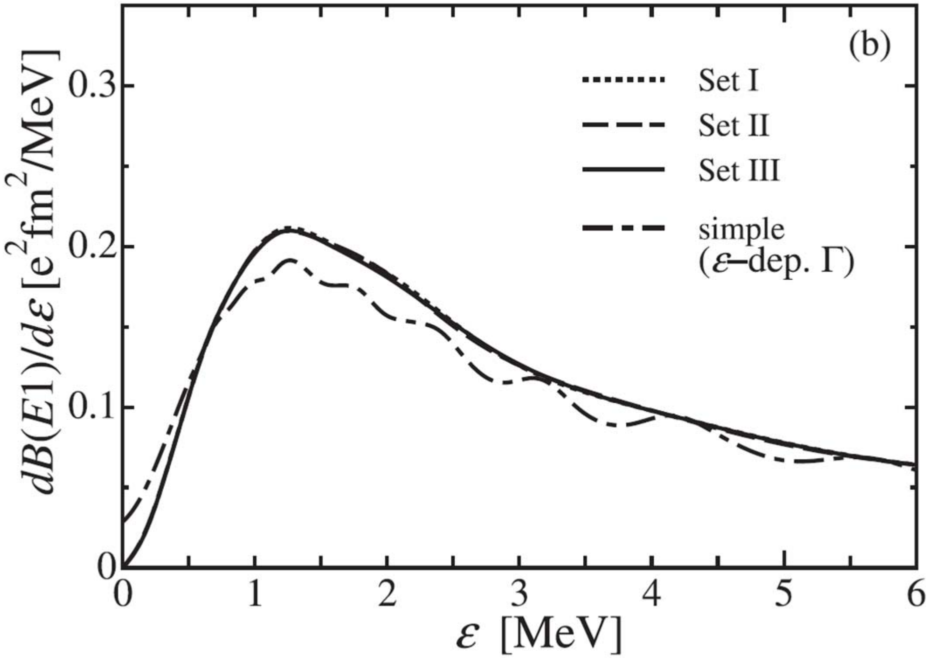
- ✓ Complex-scaled smoothing method

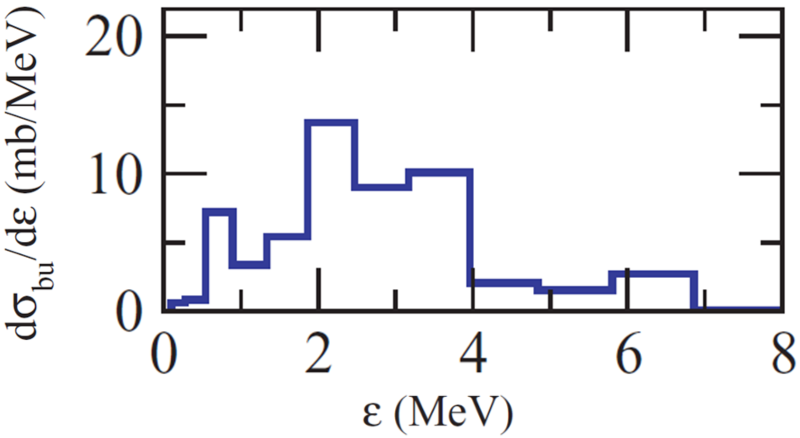
—— **T. Matsumoto, Kato, Yahiro, arXiv:1006.0668 (2010).**

Future work

- ✓ Direct comparison with exp. data

Real 4-body breakup of ^{6}He





—— **M. Rodriguez-Gallardo, Arias, Gomez-Camacho, Moro, Thompson, PRC<u>80</u>, 051601 (R) (2009).**

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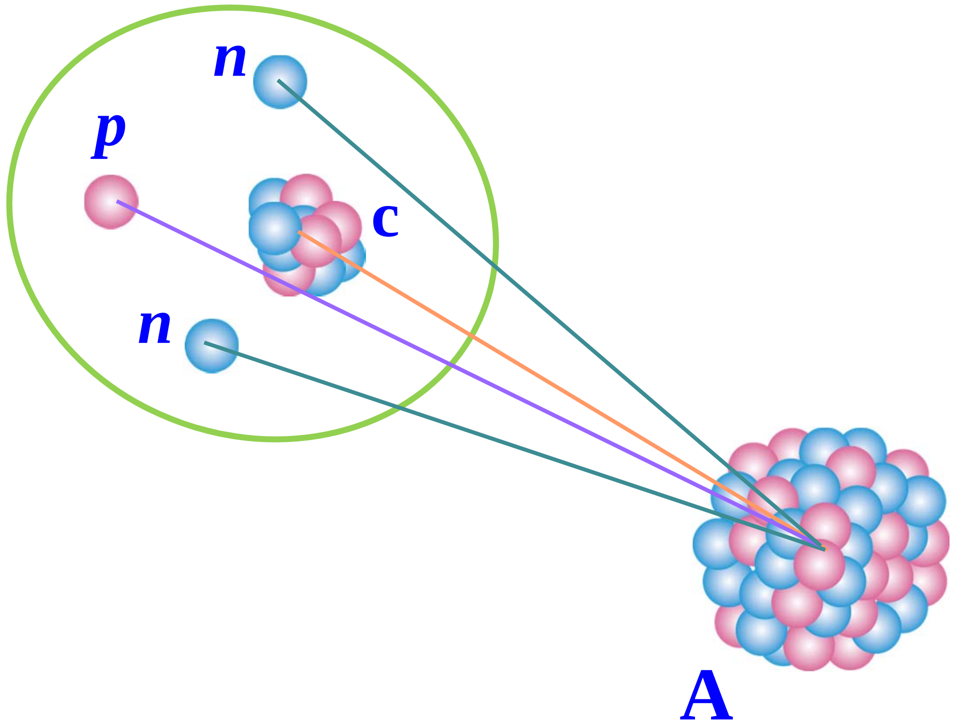
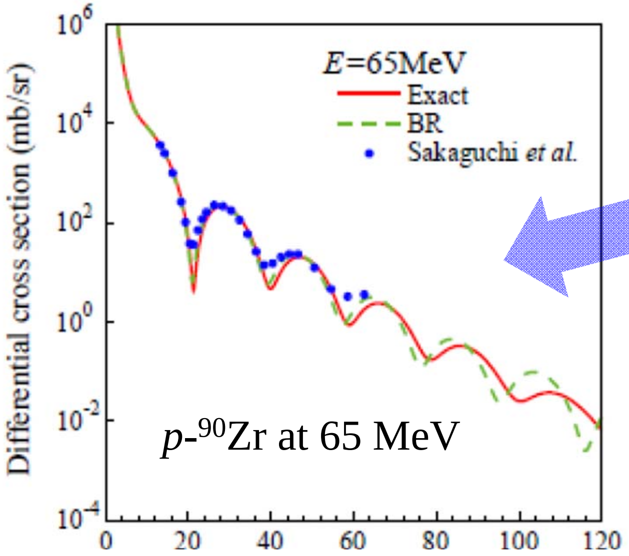
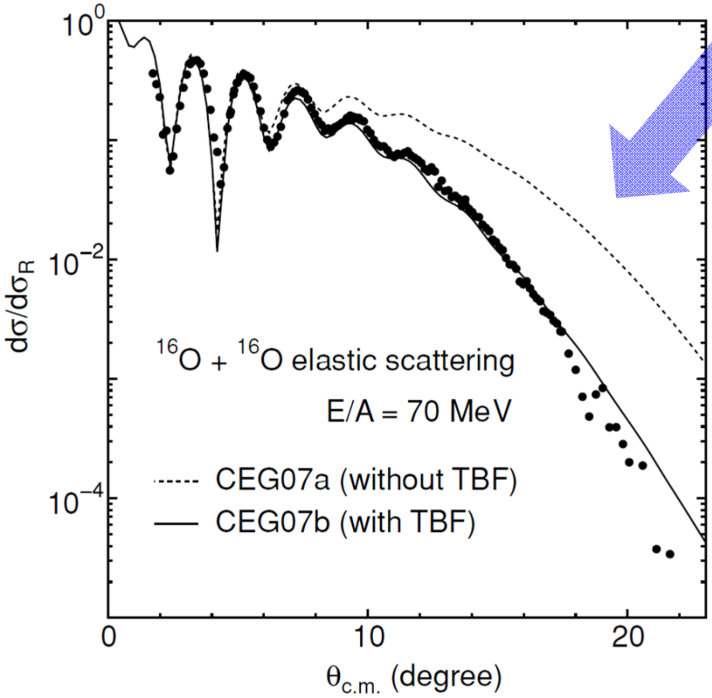
Microscopic CDCC

- (Global) *N*-A and A-A optical potentials are necessary for systematic analysis with CDCC



Microscopic optical potentials





Key points

✓ Localization of microscopic opt. pot.

—— **K. Minomo, O., Shimizu, Kohno, Yahiro, JPG in press; arXiv:0911.1184**

***c.f.* F. A. Brieva and J. R. Rook, NP A291, 317 (1977).**

✓ Proper *NN* eff. int. in nuclear medium

—— **T. Furumoto, Sakuragi, Yamamoto, PRC78, 044610 (2008); 79, 011601(R) (2009).**

✓ "Predictability" and applicability

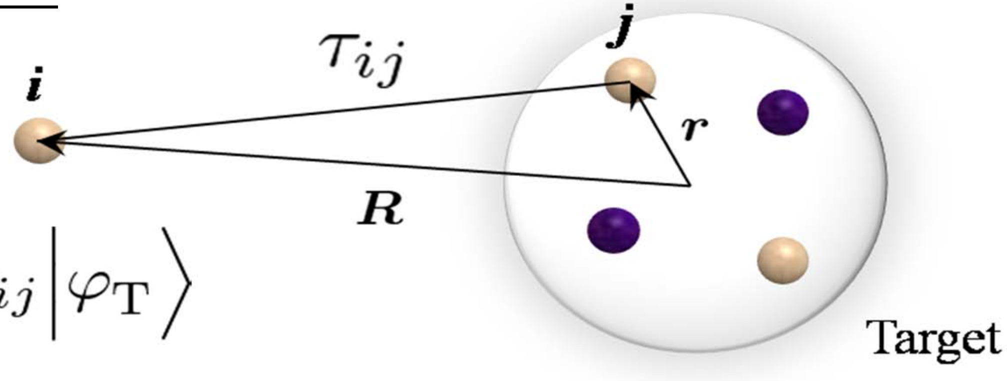
***c.f.* K. Amos *et al*., adv. Nucl. Phys. 25, 275 (2000).**

Nucleon-nucleus scattering

☐ Folding model

The equation for the relative motion $\chi(\boldsymbol{R})$

$$\left[K + U - E_{\rm in}\right]\chi(\boldsymbol{R}) = 0$$



Folding potential $$U = \left\langle \varphi_{\rm T} \middle| \sum_{j \in {\rm T}} \tau_{ij} \middle| \varphi_{\rm T} \right\rangle$$

$|\varphi_{\rm T}\rangle$: ground-state wave function of the target

We obtain the localized folding potential with the Brieva-Rook (BR) method.

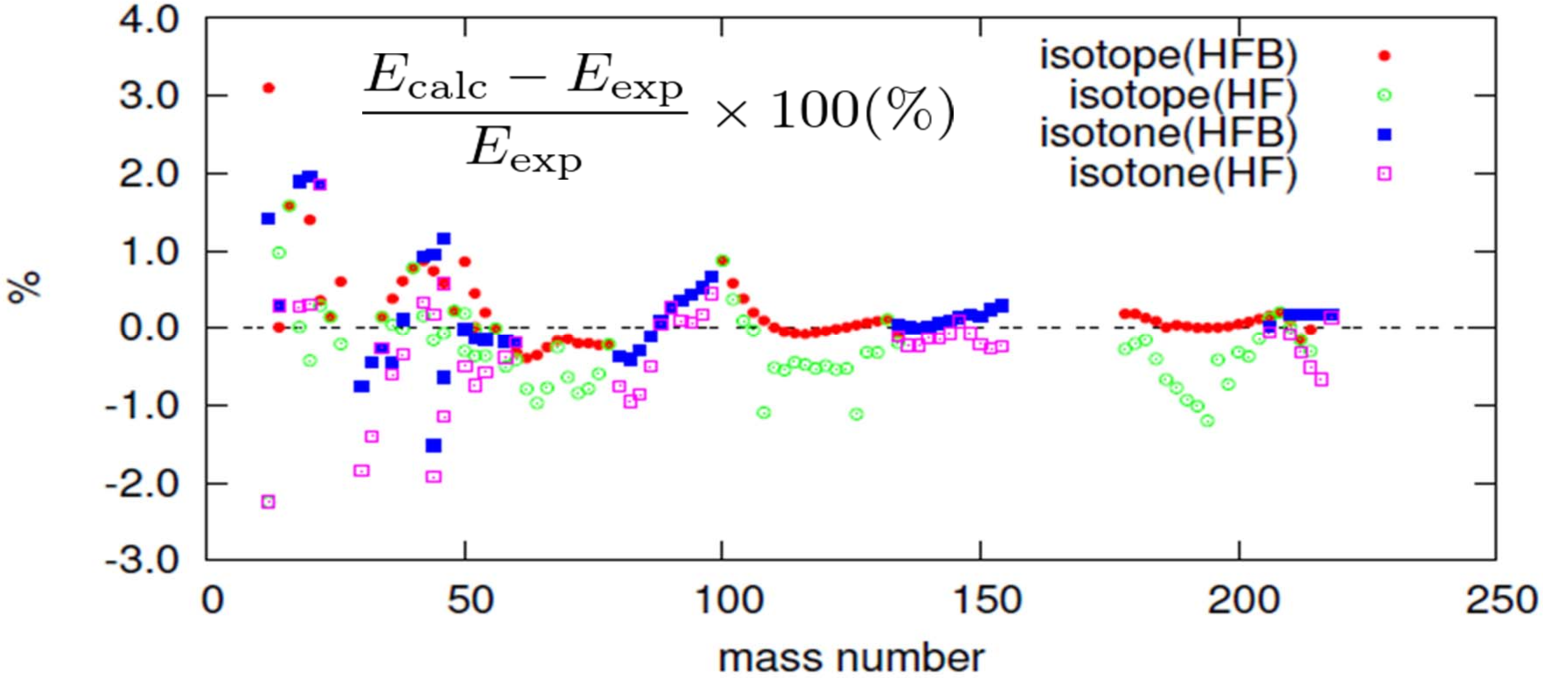
F. A. Brieva and J. R. Rook, Nucl. Phys. A **291**, 317 (1977).

Structure model

✓ **Hartree-Fock method with finite-range Gogny force**

It is applicable to obtain the ground-state wave function of all nuclei.

The properties of many stable nuclei such as the binding energy are well reproduced.



We find that this method is reliable.

Interaction for reaction dynamics

✓ **Melbourne *g*-matrix**

Two-body interaction which depends on the target density

K. Amos, P. J. Dortmans, H. V. von Geramb, S. Karataglidis and J. Raynal,
Adv. Nucl. Phys. **25**, 275 (2000).

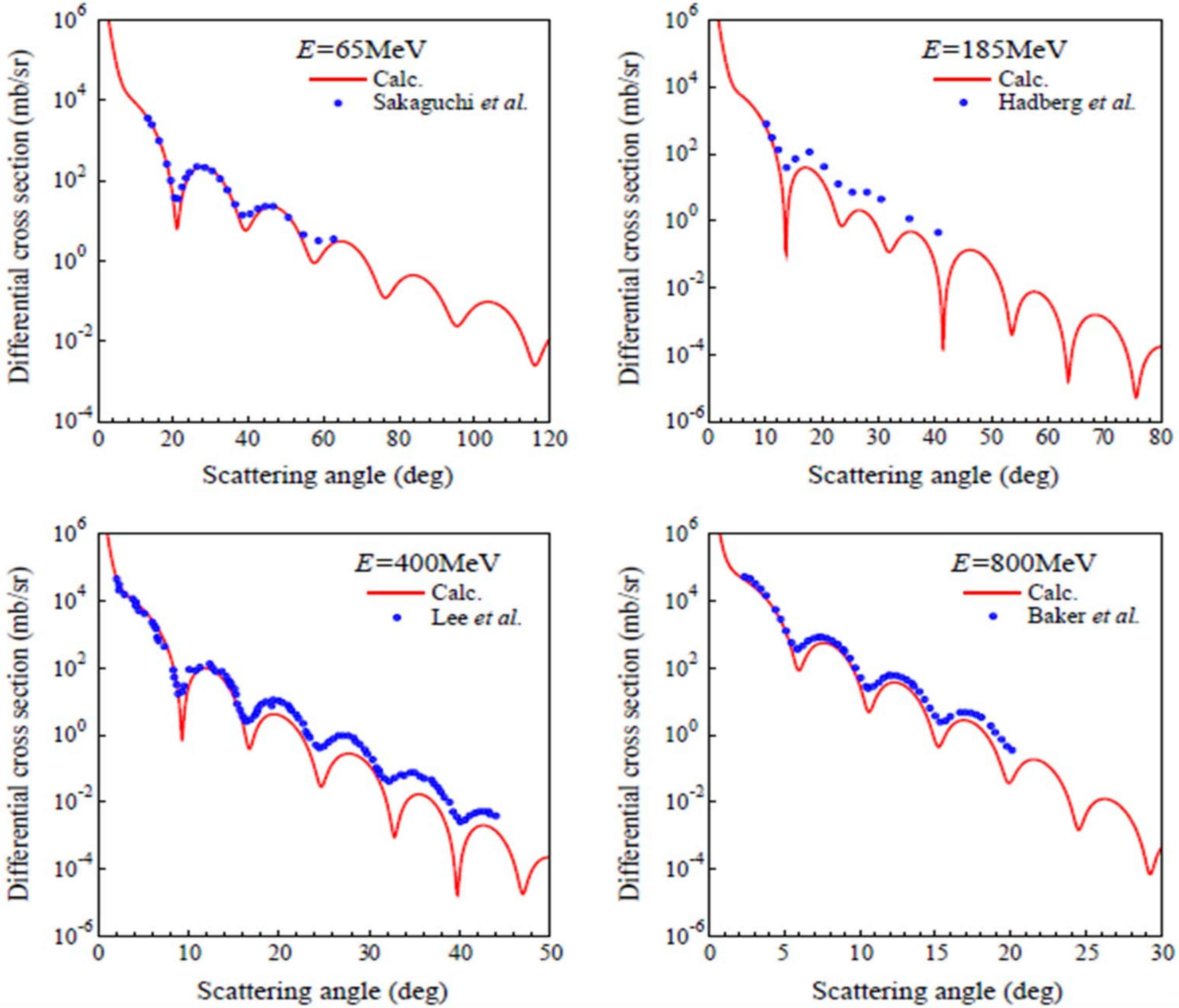
□ The framework in this study

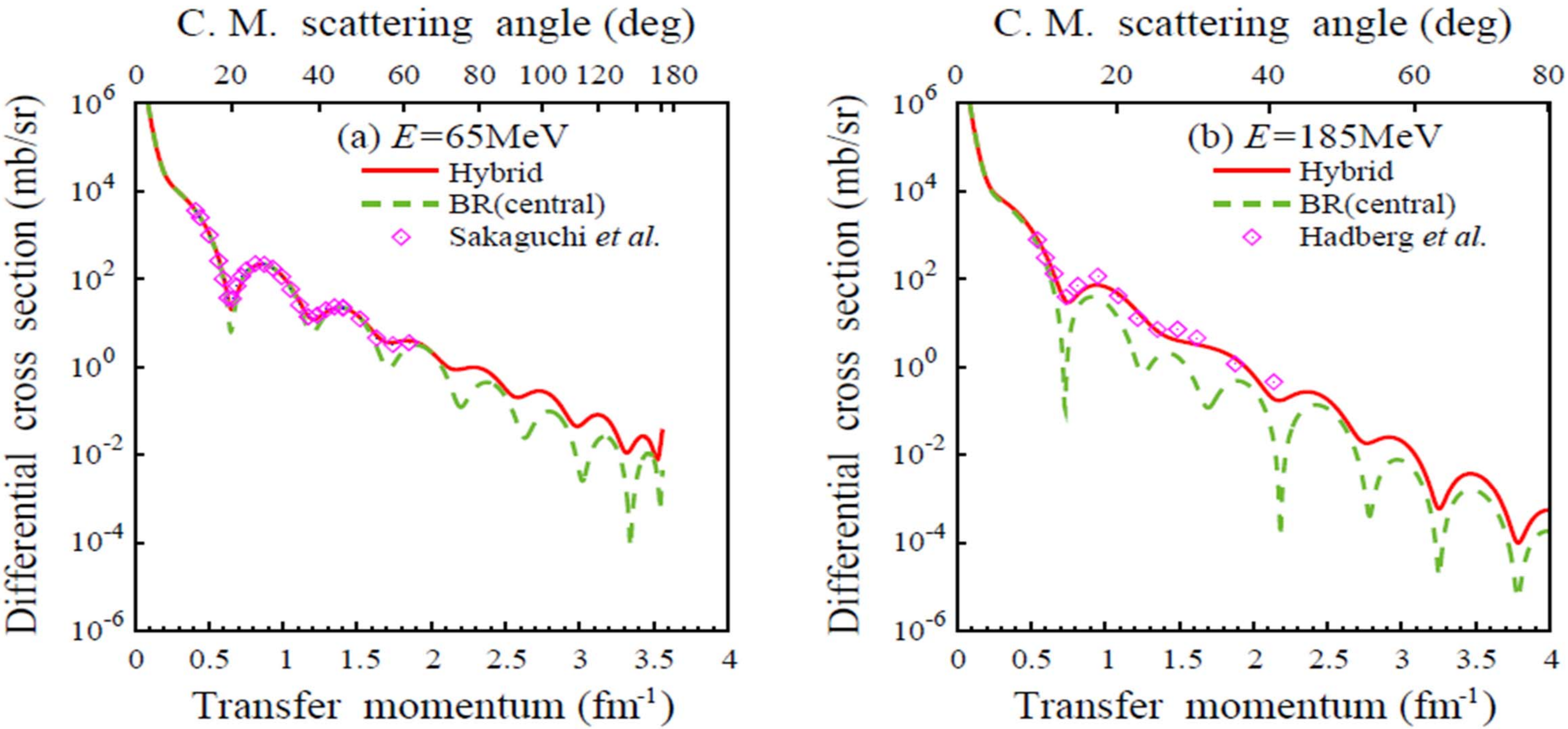
- HF method with Gogny force
- Melbourne *g*-matrix
- BR localization

Pure theoretical framework without any parameter

$p + {}^{90}Zr$ elastic scattering

Stable nucleus
^{90}Zr

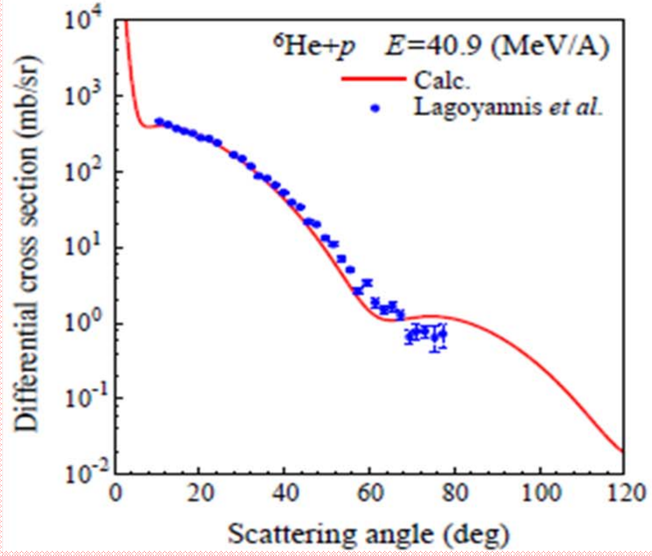


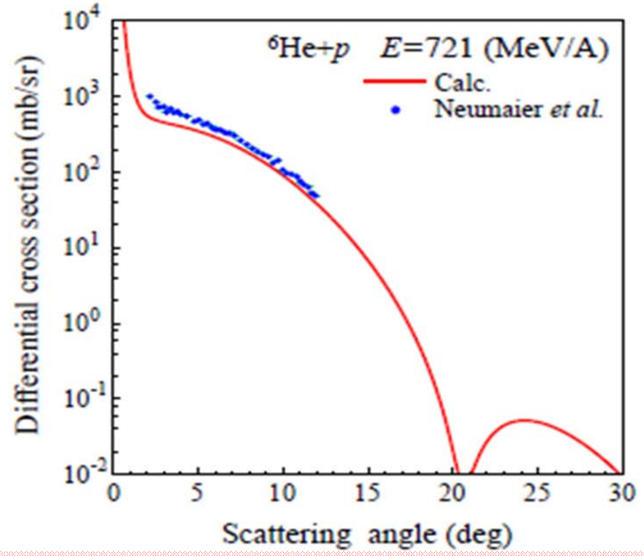


Central (microscopic) + LS (Dirac phenomenology)

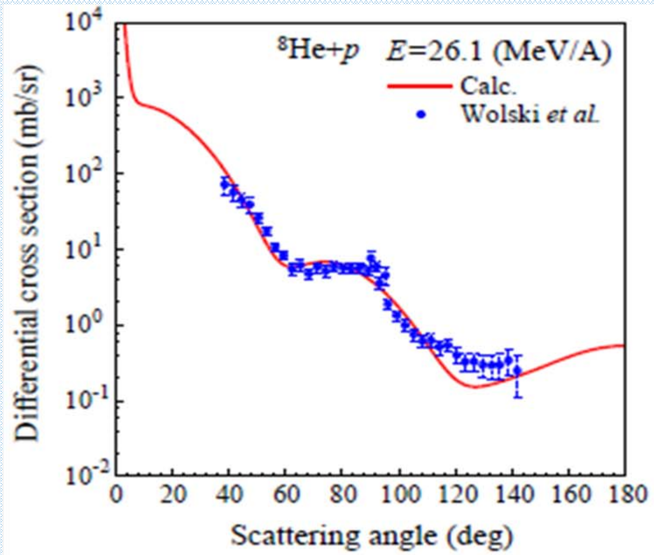
^{6,8}He+*p elastic scattering*

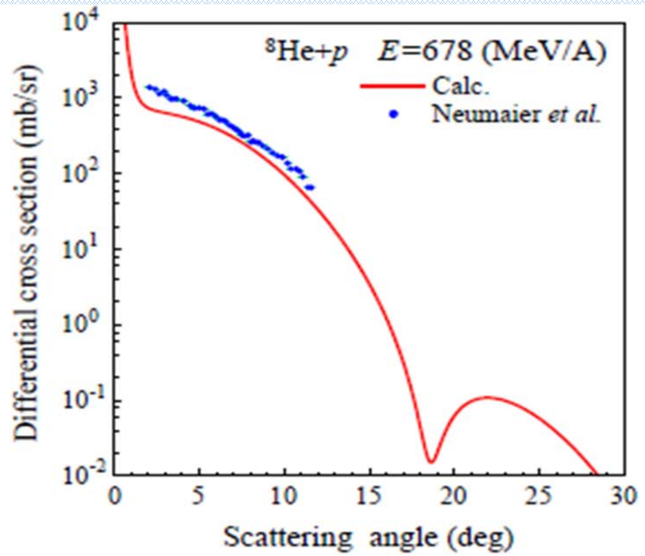
Unstable nucleus
^{6}He





Unstable nucleus
^{8}He





The validity of BR localization

It is necessary to test the accuracy of the BR localization.

We have to solve the Schrödinger equations

Exact: $$\Big(T_{\boldsymbol{R}} - E\Big)\chi(\boldsymbol{R}) = \int U(\boldsymbol{R},\boldsymbol{r})\chi(\boldsymbol{r})d\boldsymbol{r}$$

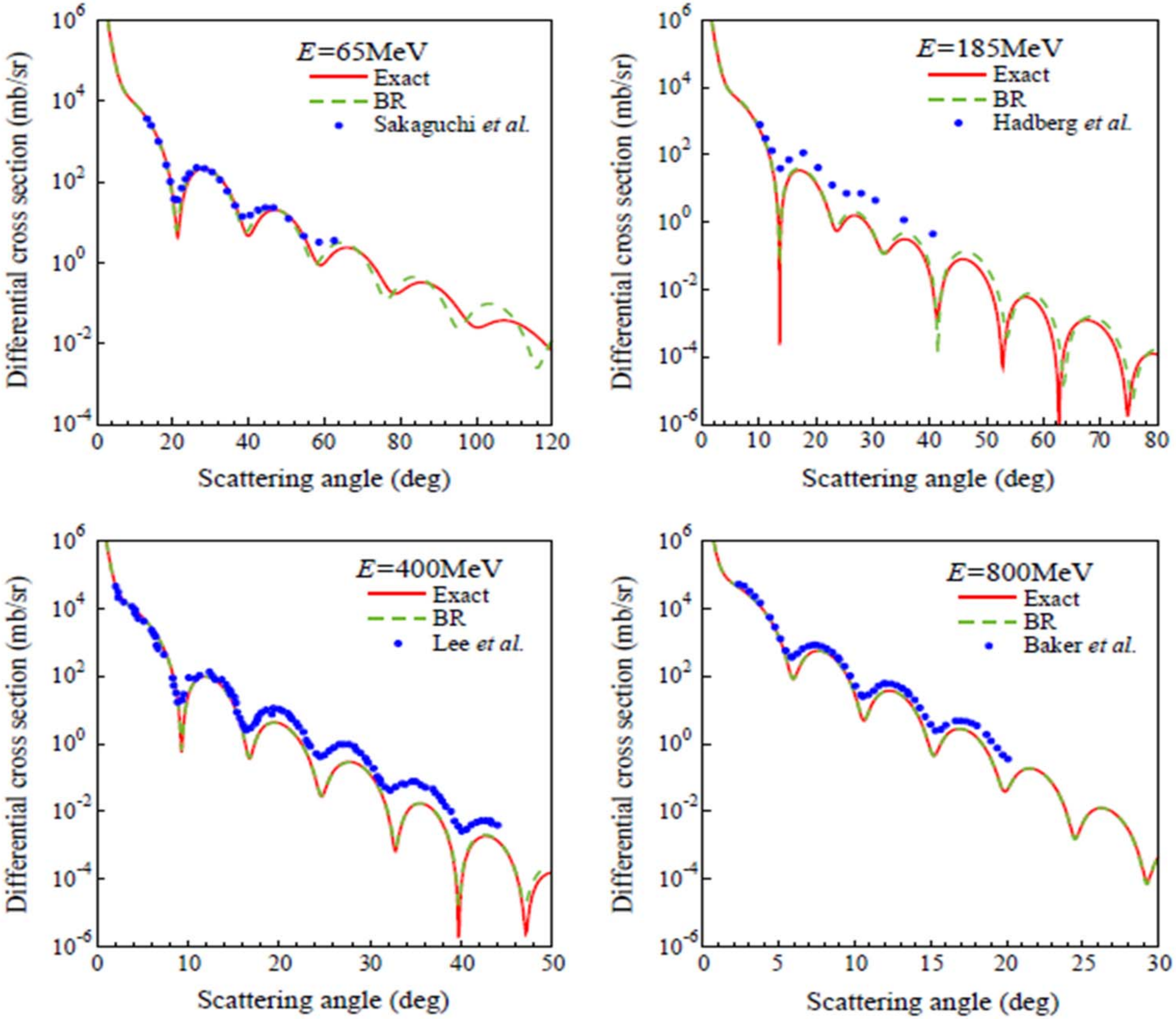
For only elastic scatterings, one can calculate the exact form.

BR: $$\Big(T_{\boldsymbol{R}} + U_{\mathrm{loc}}(\boldsymbol{R}) - E\Big)\chi(\boldsymbol{R}) = 0$$

We tested the validity of the BR localization by comparison of the exact calculation and BR calculation.

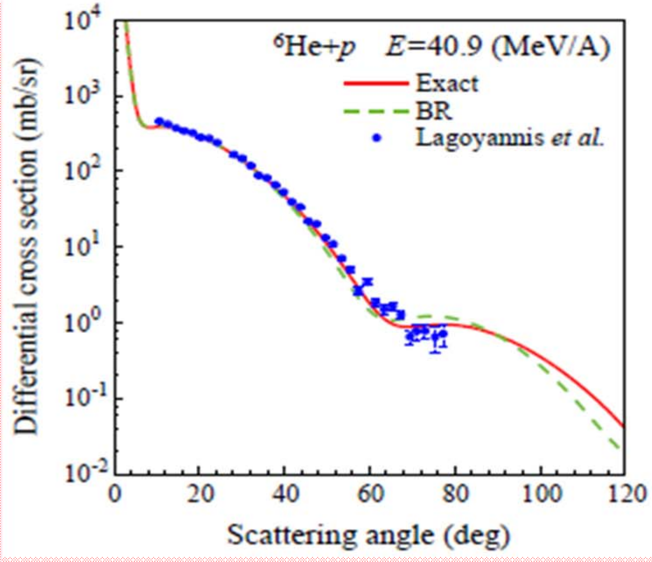
Exact vs BR for p +^{90}Zr

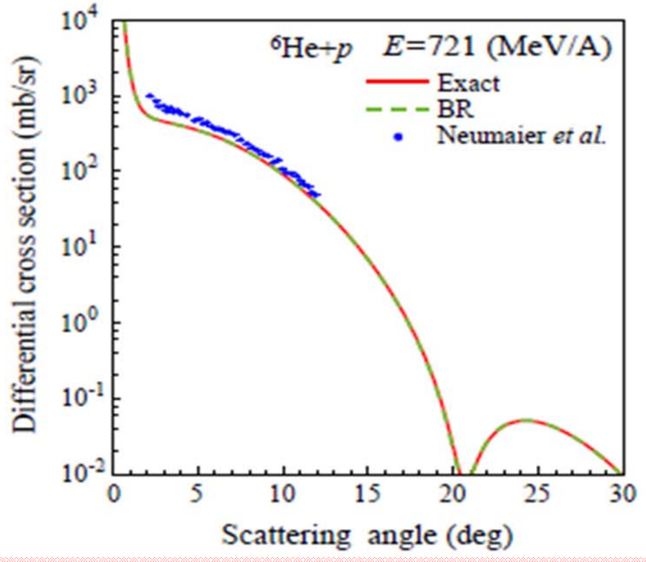
^{90}Zr



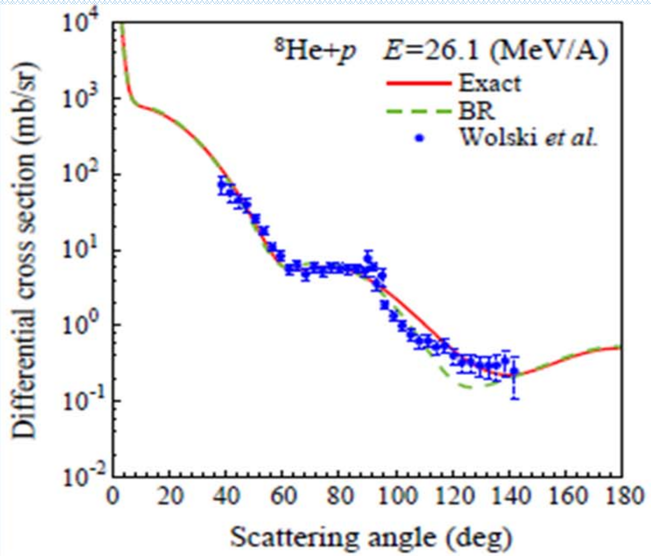
Exact vs BR for ^6He+p and ^8He+p

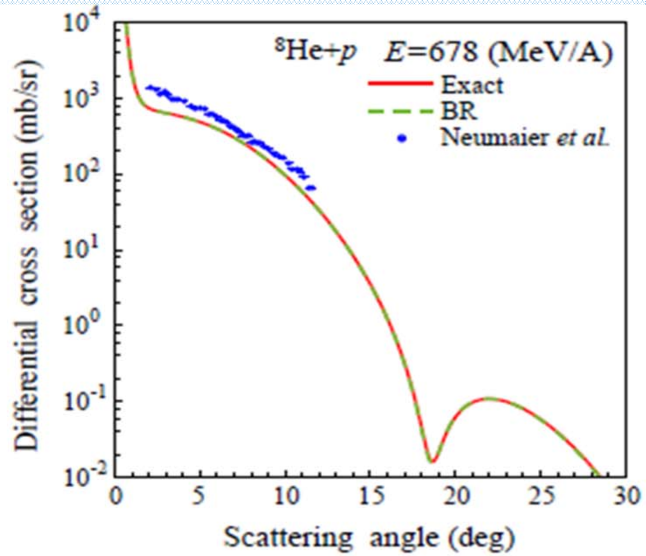
^6He

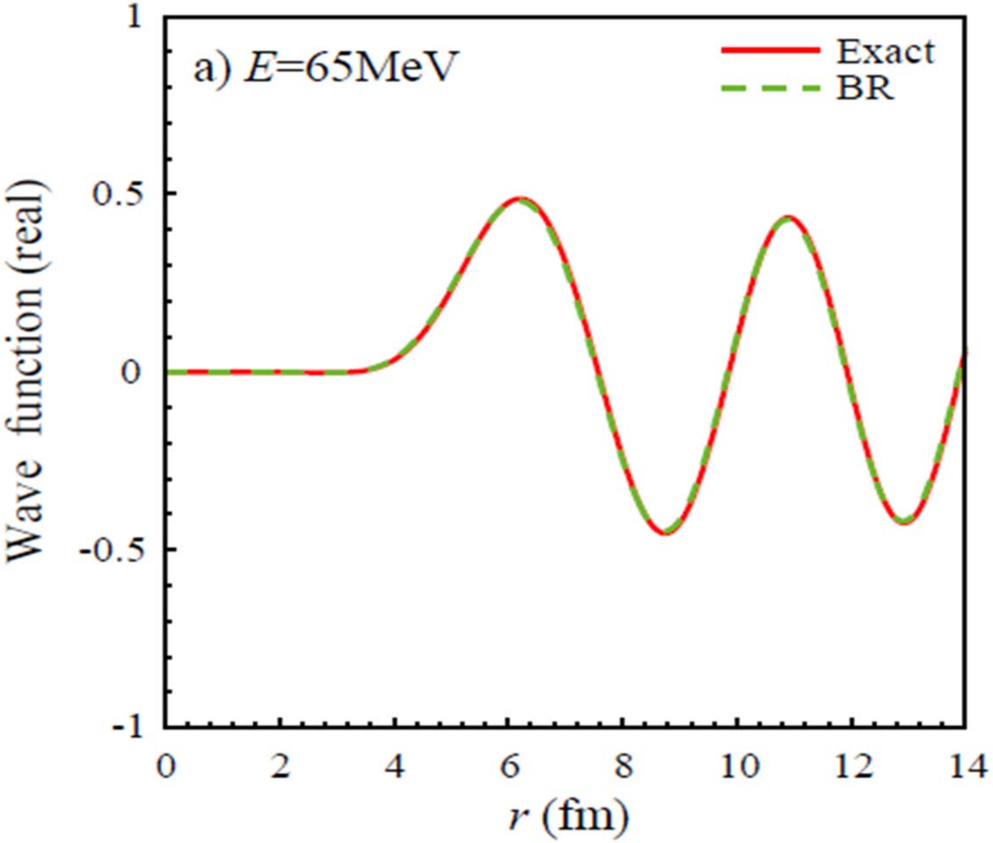


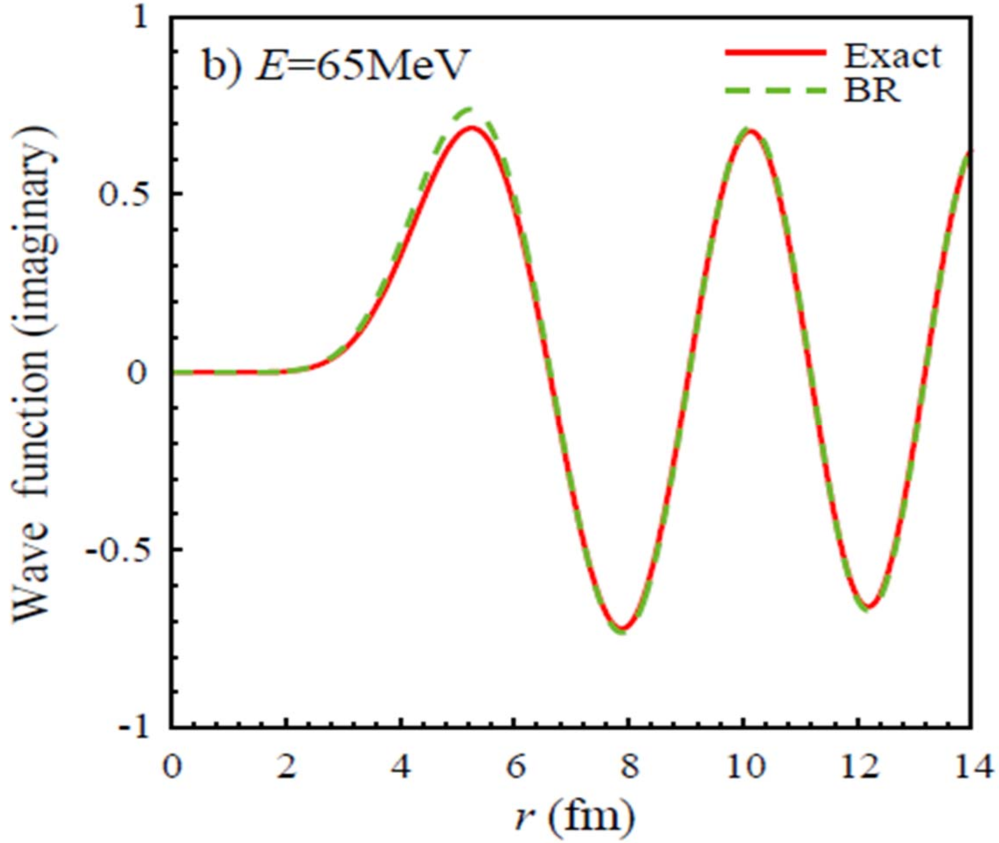


^8He









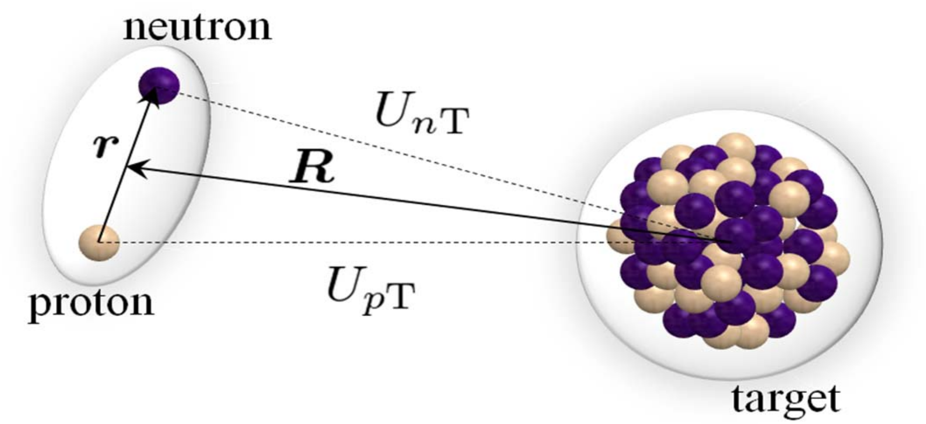
No Perey factor needed!

Application

- For deuteron induced reaction

$$\left[K + h_{pn} + h_{\mathrm{T}} + \sum_{j\in\mathrm{T}} \left(\tau_{pj} + \tau_{nj}\right) - E\right]\Psi = 0$$

three-body model



Optical potentials as an input

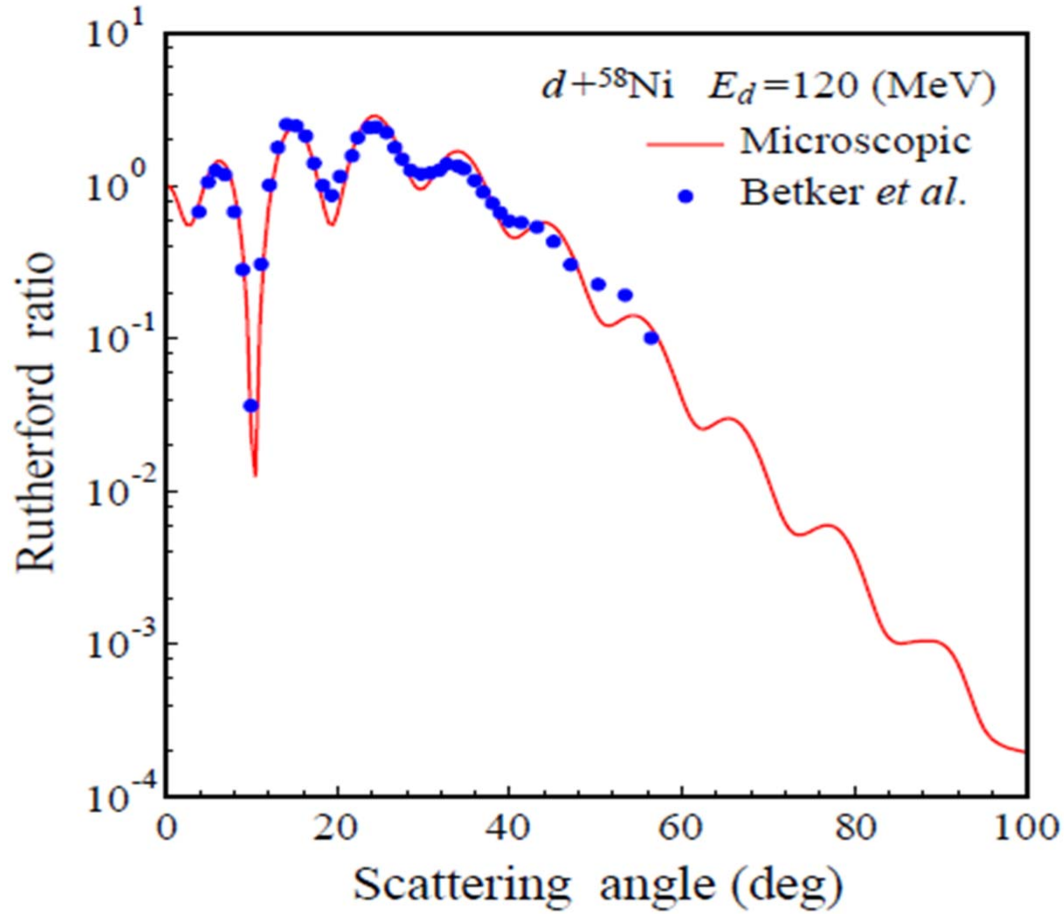
$$U_{p\mathrm{T}} = \left\langle \varphi_{\mathrm{T}} \middle| \sum_{j\in\mathrm{T}} \tau_{pj} \middle| \varphi_{\mathrm{T}} \right\rangle$$

$$U_{n\mathrm{T}} = \left\langle \varphi_{\mathrm{T}} \middle| \sum_{j\in\mathrm{T}} \tau_{nj} \middle| \varphi_{\mathrm{T}} \right\rangle$$

✓ **Continuum-Discretized Coupled-Channels method (CDCC)**

It is a standard direct reaction theory to describe real and virtual breakup.

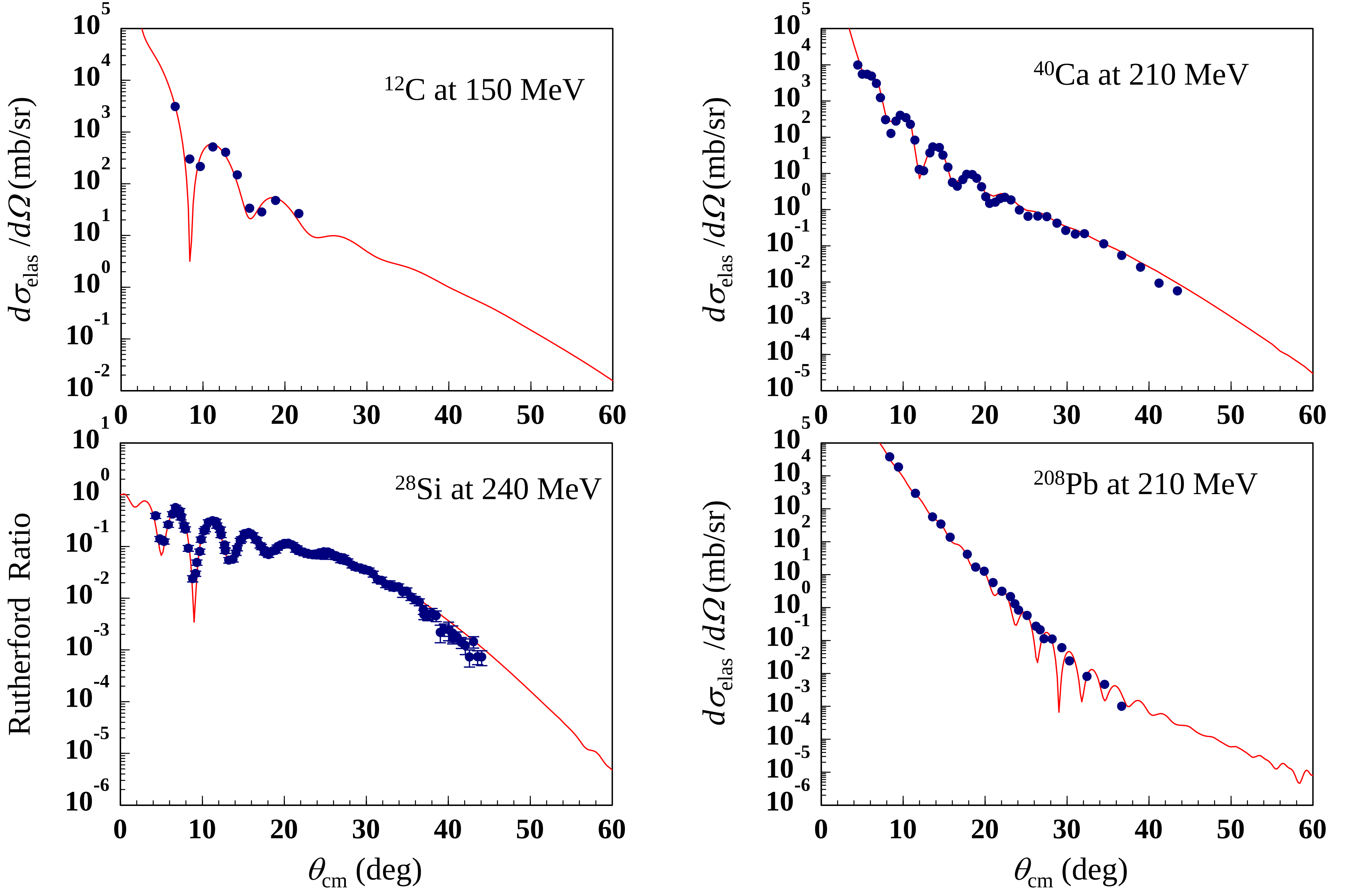
$d + ^{58}Ni$ elastic scattering



Success of Microscopic CDCC

Microscopic CDCC for ^{6}Li induced reactions

(d+α)+A model: d-A and α-A potentials are evaluated with JLM eff. int. and HF densities.



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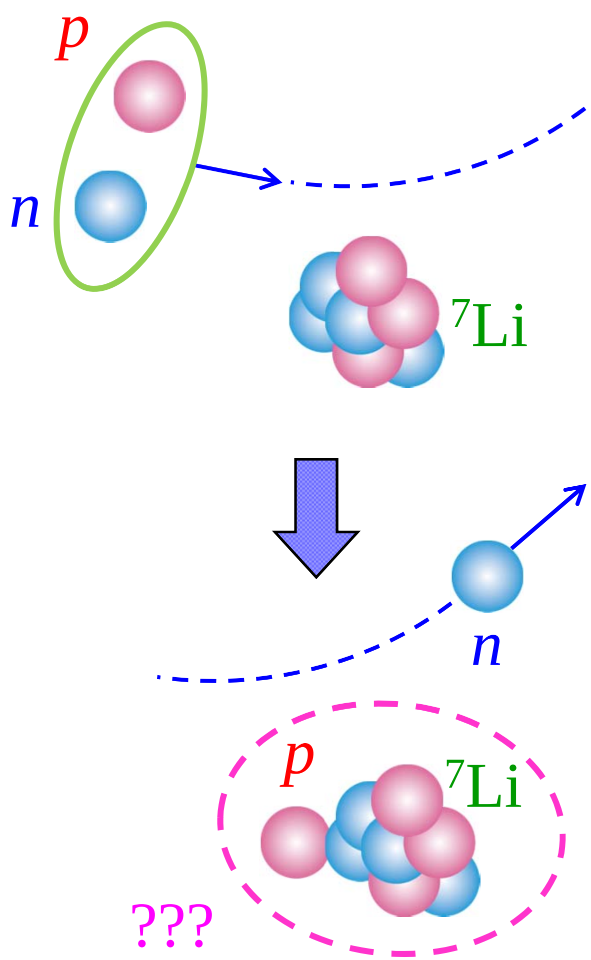
Inclusive BU (incomplete fusion) process

^{7}Li(*d*,*nx*)



c.f. IFMIF project

——— **S. Hashimoto, O., Chiba, Yahiro, PTP122, 1291 (2009).**

Dividing the integration region with respect to absorbing radii of p and n.

Total Fusion: $\sigma_{\rm TF} = \dfrac{2\mu_R}{\hbar^2 K_0} \left| \langle \Psi | (-W_p - W_n) | \Psi \rangle \right|$

p and n *absorbed* ***only p*** *absorbed*

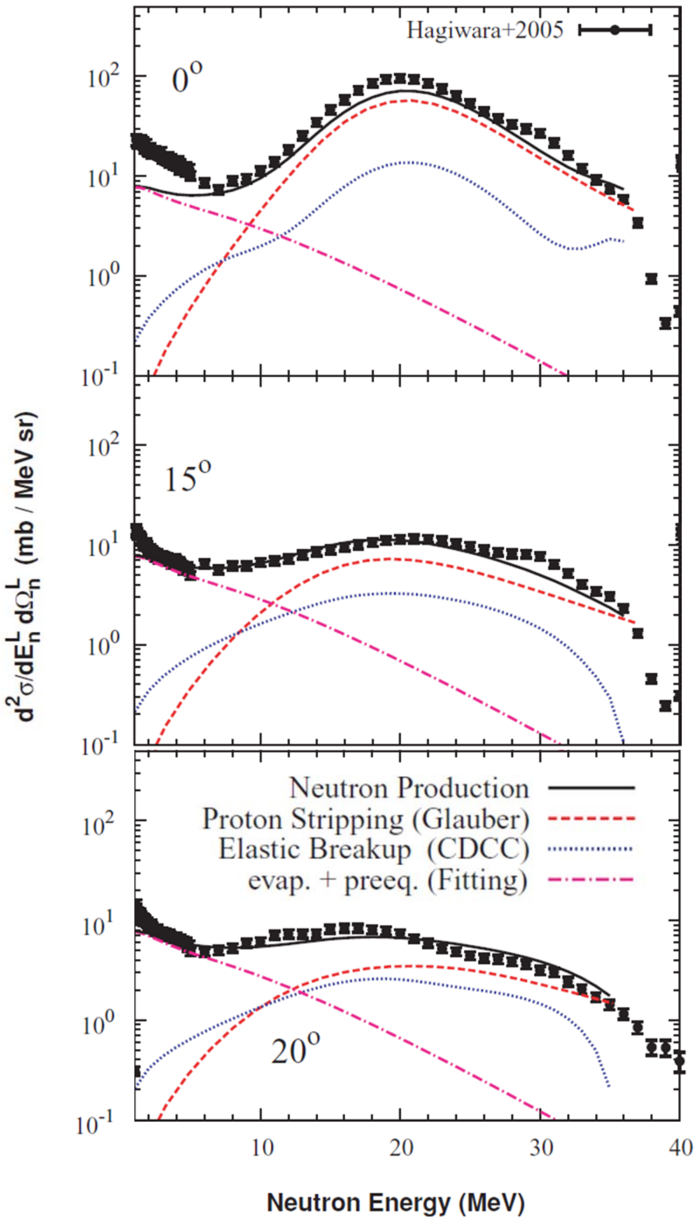
$$\int_{r_p<r_p^{\rm ab}} d\boldsymbol{r}_p \int_{r_n<r_n^{\rm ab}} d\boldsymbol{r}_n + \int_{r_p<r_p^{\rm ab}} d\boldsymbol{r}_p \int_{r_n>r_n^{\rm ab}} d\boldsymbol{r}_n$$

$$+ \int_{r_p>r_p^{\rm ab}} d\boldsymbol{r}_p \int_{r_n<r_n^{\rm ab}} d\boldsymbol{r}_n + \int_{r_p>r_p^{\rm ab}} d\boldsymbol{r}_p \int_{r_n>r_n^{\rm ab}} d\boldsymbol{r}_n$$

only n *absorbed* no contribution

Determination of abs. rad.

^{7}Li(d,nx) at 40 MeV



<u>Key points</u>

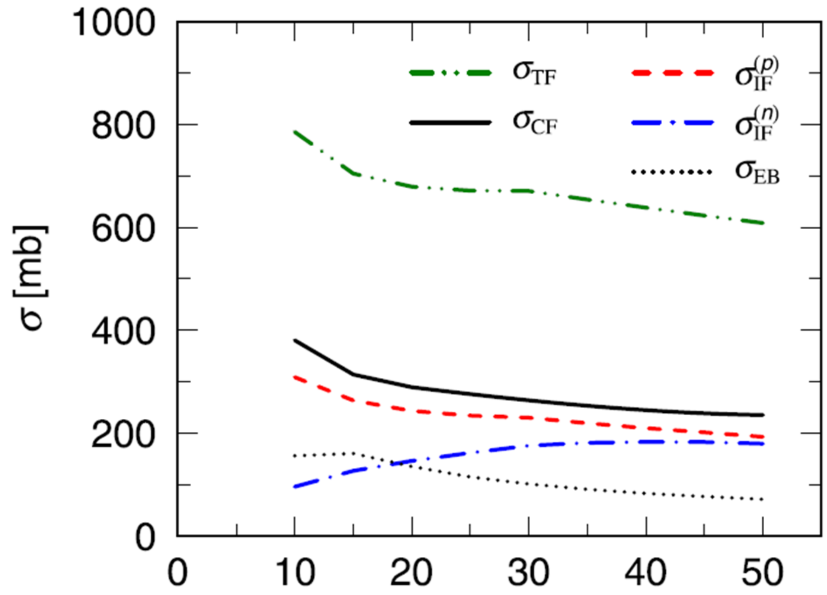
- ✓ CDCC + Glauber reproduces the data.

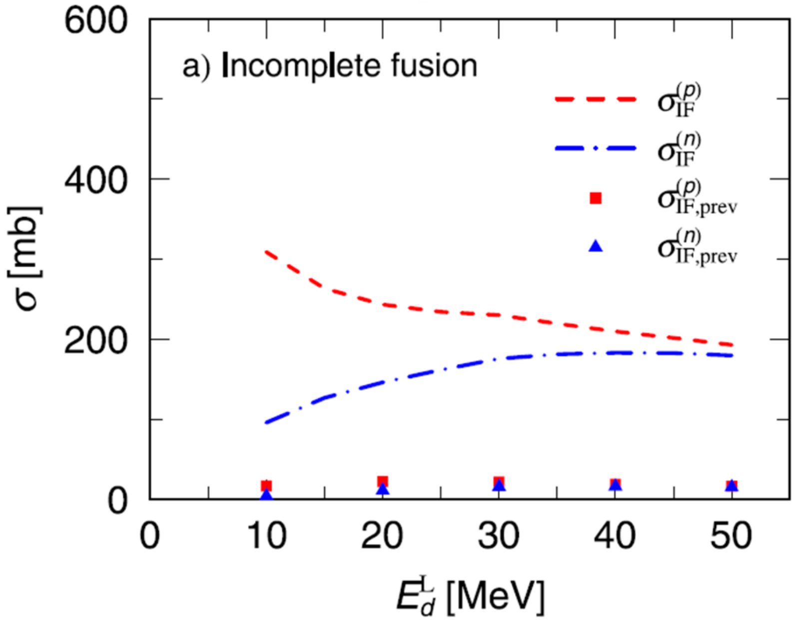
  —— **T. Ye, Watanabe, O., PRC<u>80</u>, 014604 (2009).**

- ✓ Integrated stripping X-sec. calculated with Glauber model is assumed to be an exp. value.

- ✓ <u>Abs. Rad. are adjusted to reproduce this value</u>.

Inclusive BU (incomplete fusion) X-sec.





Key points

✓ *Inclusive BUX* is very large.

✓ $\sigma_{\mathrm{IF}}^{(p)}$ and $\sigma_{\mathrm{IF}}^{(n)}$ have opposite E_d dependence.

—— **S. Hashimoto, O., Chiba, Yahiro, PTP122, 1291 (2009).**

✓ Previous method gives very different results.

—— **A. Diaz-Torres and I. J. Thompson, PRC65, 024606 (2002).**

Future work

✓ Calculation of inclusive triple diff. X-sec. (Eikonal Reaction Theory; ERT)

Summary

1) *Four-body breakup* processes for ^{6}He induced reaction

- ✓ Direct comparison with exp. data
- ✓ Five- and Six-body CDCC using Cluster-Orbital Shell Model

2) *Microscopic description* of projectile breakup processes

- ✓ Application of microscopic opt. pot. to systematic CDCC calculations

3) New approach to *inclusive breakup processes*

- ✓ Triple differential X-sec. of inclusive process

Collaborators

[A,B]Takuma Matsumoto, [C]Shintaro Hashimoto, [D]Kosho Minomo,
[E]Yasunori Iseri, [F]Michio Kohno, [C]Satoshi Chiba, [D]Taiga Hamada,
[D]Yoshifumi R. Shimizu, [G]Ye Tao, [G]Yukinobu Watanabe, and
[D]Masanobu Yahiro

[A]*RIKEN Nishina Center*

[B]*Meme Media Laboratory, Hokkaido University*

[C]*Japan Atomic Energy Agency*

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