The Method of CDCC for Four-Body Breakup Reactions

CDCC : Continuum-Discretized Coupled-Channels

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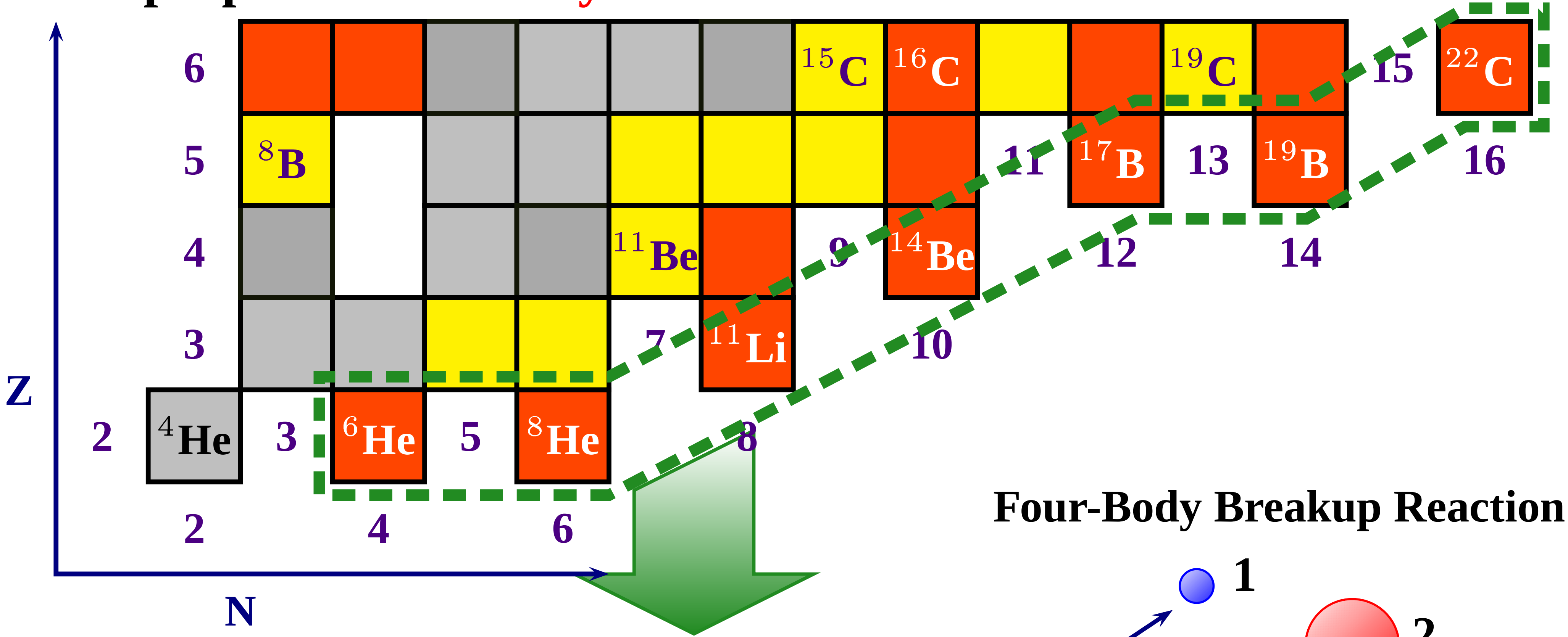
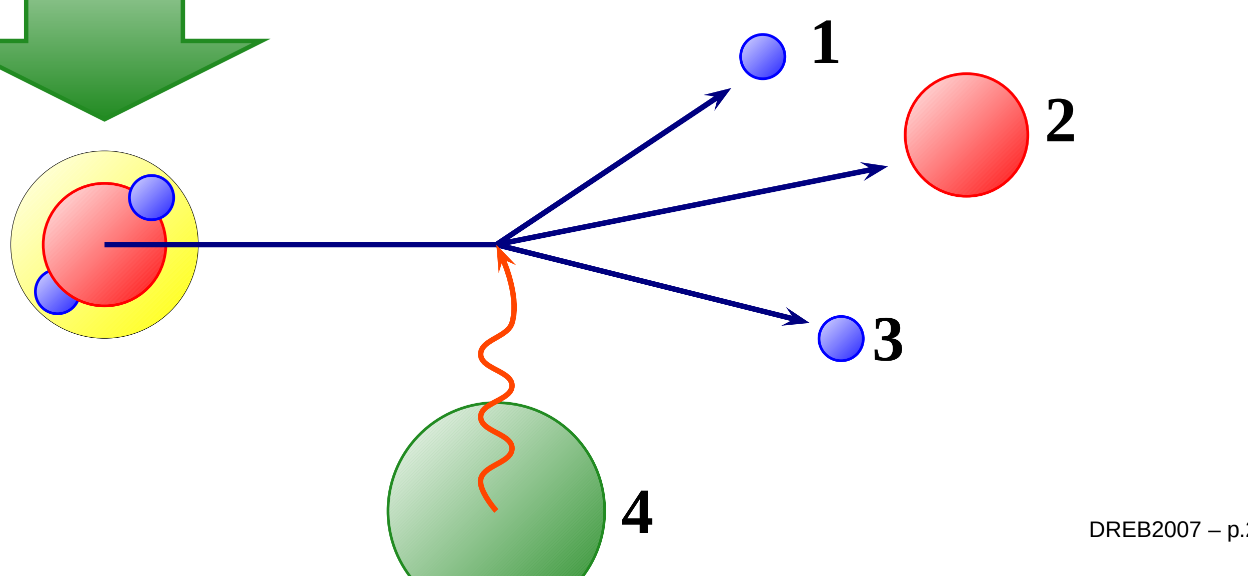
2007 Summer meeting “Direct Reaction with Exotic Beams”

Region of Interest: Neutron & Proton Rich

Breakup reactions have played key roles in investigating properties of **weakly bound nuclei**.





Three-Body System
(core+n+n)

Purpose of This Study

We propose an accurate method of treating four-body breakup processes by extending CDCC

- **Continuum-Discretized Coupled-Channels (CDCC)**
  - **Developed by Kyushu group about 20 years ago**

    —— M. Kamimura *et al.*, PTP Suppl. 89, 1 (1986).
  - **Treats breakup states explicitly**

    ——non-adiabatic and non-perturbative calculation
  - **Applied to only three-body breakup reactions**

    ——two-body projectile

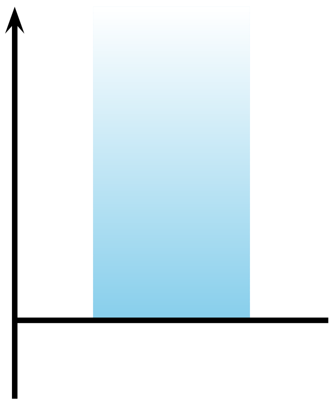
Four-Body CDCC

Application to analyses of ^{6}He breakup reactions

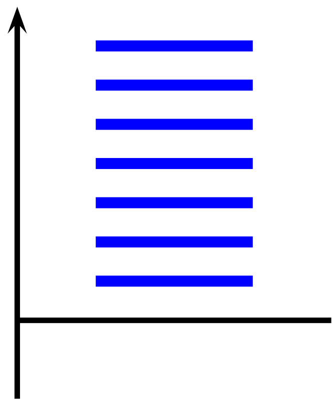
Continuum-Discretized Coupled-Channels

Essence of CDCC

- **Breakup continuum states are described by a finite number of discretized continuum states.**



$$\Phi(\varepsilon) \longrightarrow \sum_{i}^{N} \hat{\Phi}_i(\varepsilon_i)$$



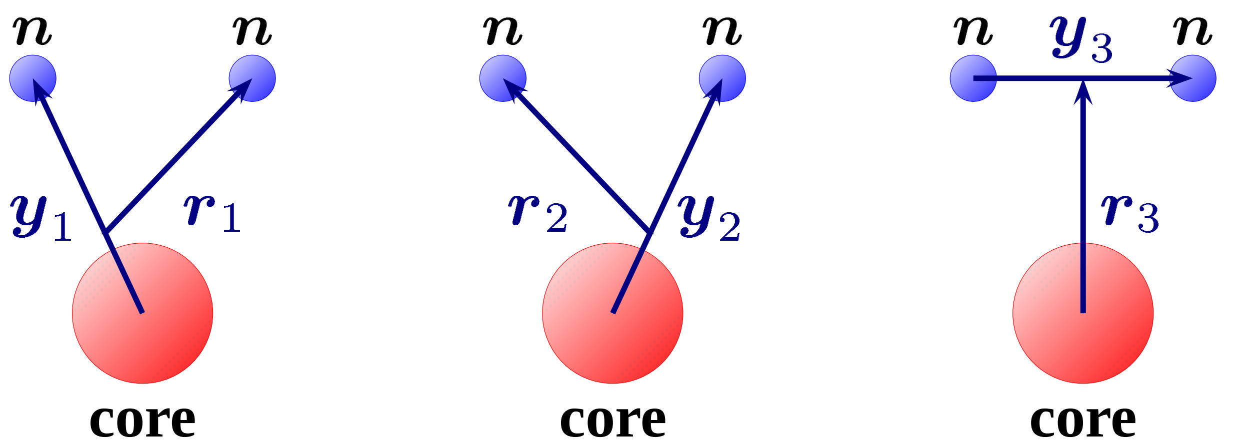
- **A set of eigenstates forms a complete set within a finite model space that is important for breakup processes.**

How to calculate discretized continuum states for three-body projectile

Gaussian Expansion Method (GEM)

E. Hiyama, Y. Kino and M. Kamimura, Prog. Part. Nucl. Phys. 51, 223 ('03)

- **GEM : an accurate method of solving few-body problems.**



— **Gaussian basis function** —

$$\Phi_{Im}(\mathbf{y},\mathbf{r}) = \sum_{\lambda,\ell,\Lambda,S} A_\gamma y^\lambda r^\ell e^{-\alpha y^2 - \beta r^2} \left[[Y_\ell(\hat{y}) \otimes Y_\lambda(\hat{r})]_\Lambda \otimes S \right]_{Im}$$

- **Bound and discretized continuum states are obtained by diagonalizing of three-body Hamiltonian with the basis functions**

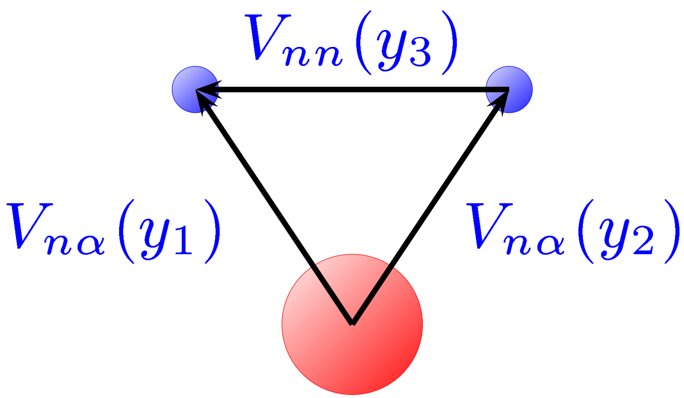
Bound and Discretized Continuum states of 6He

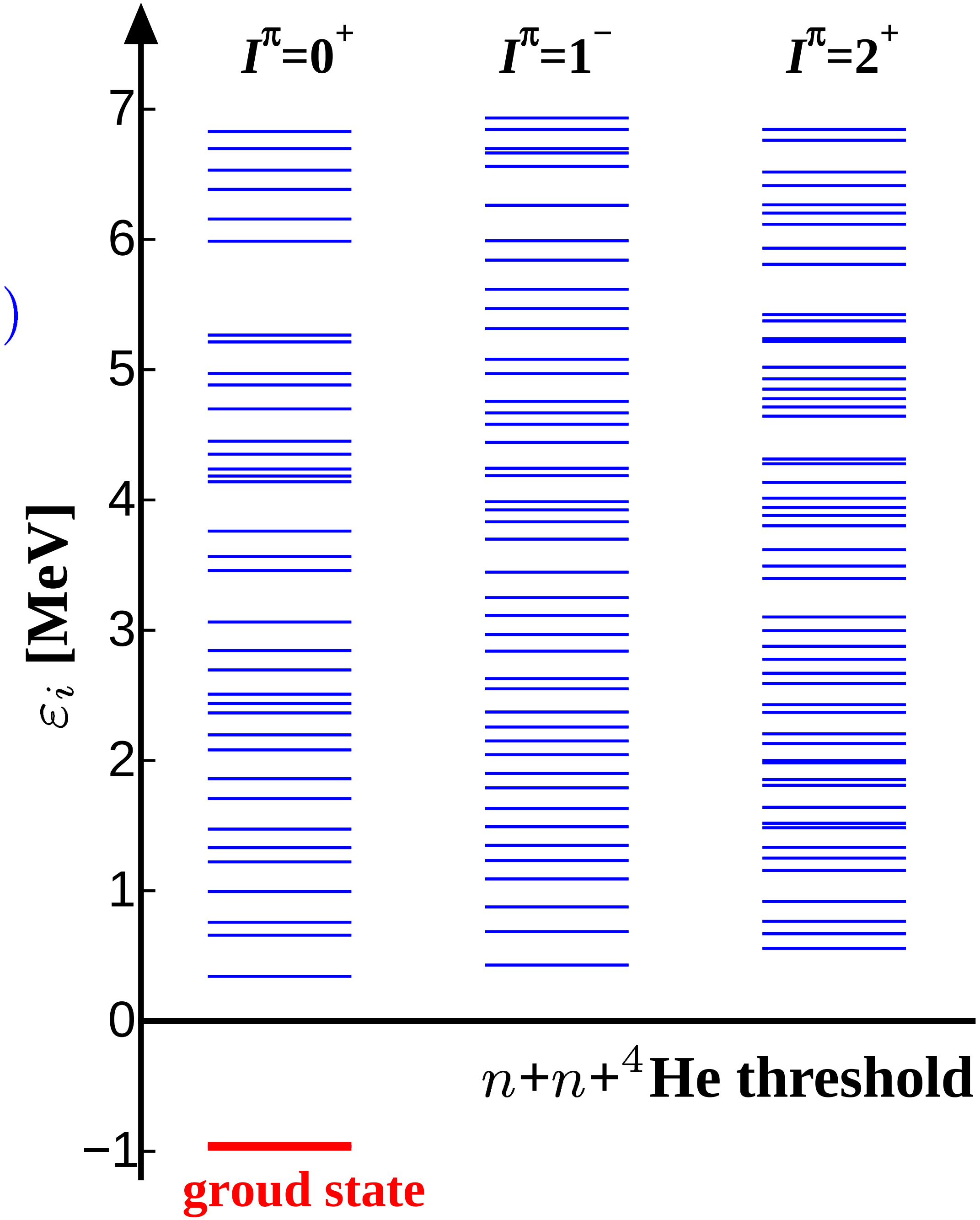
- **Three-body Hamiltonian of ^{6}He**

$$H = T_y + T_r + V_{n\alpha}(y_1) + V_{n\alpha}(y_2) + V_{nn}(y_3)$$

—— V_{nn} : **BonnA**

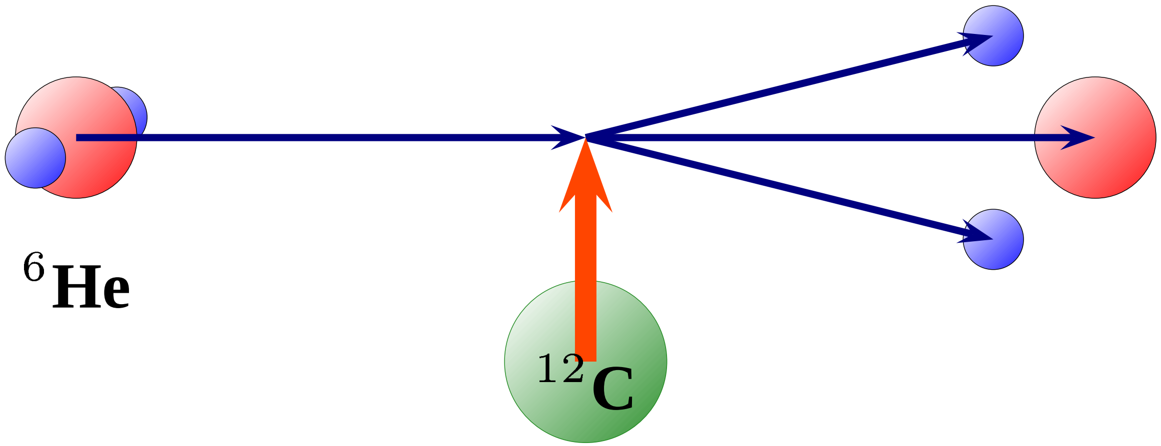
—— $V_{n\alpha}$: **Kanada pot.**



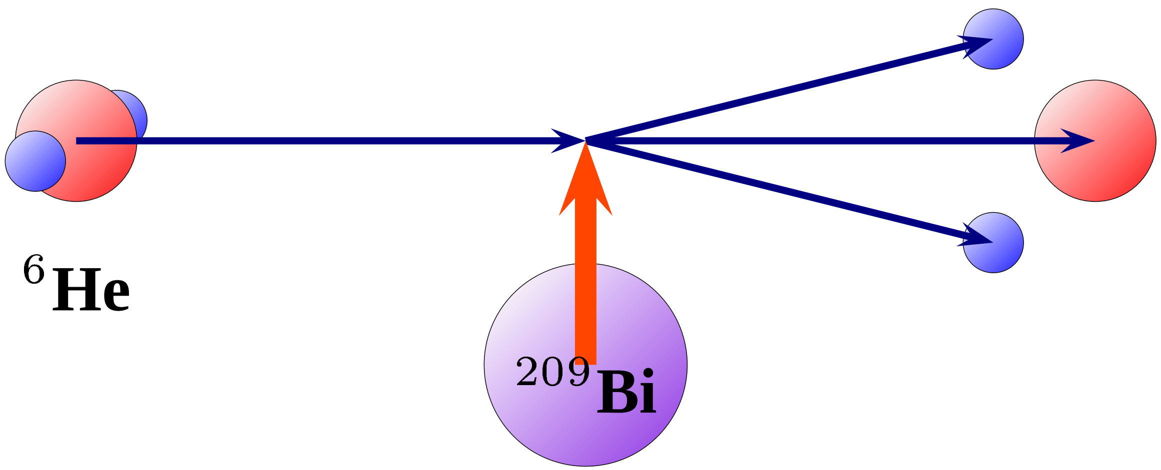


6He Breakup Reaction

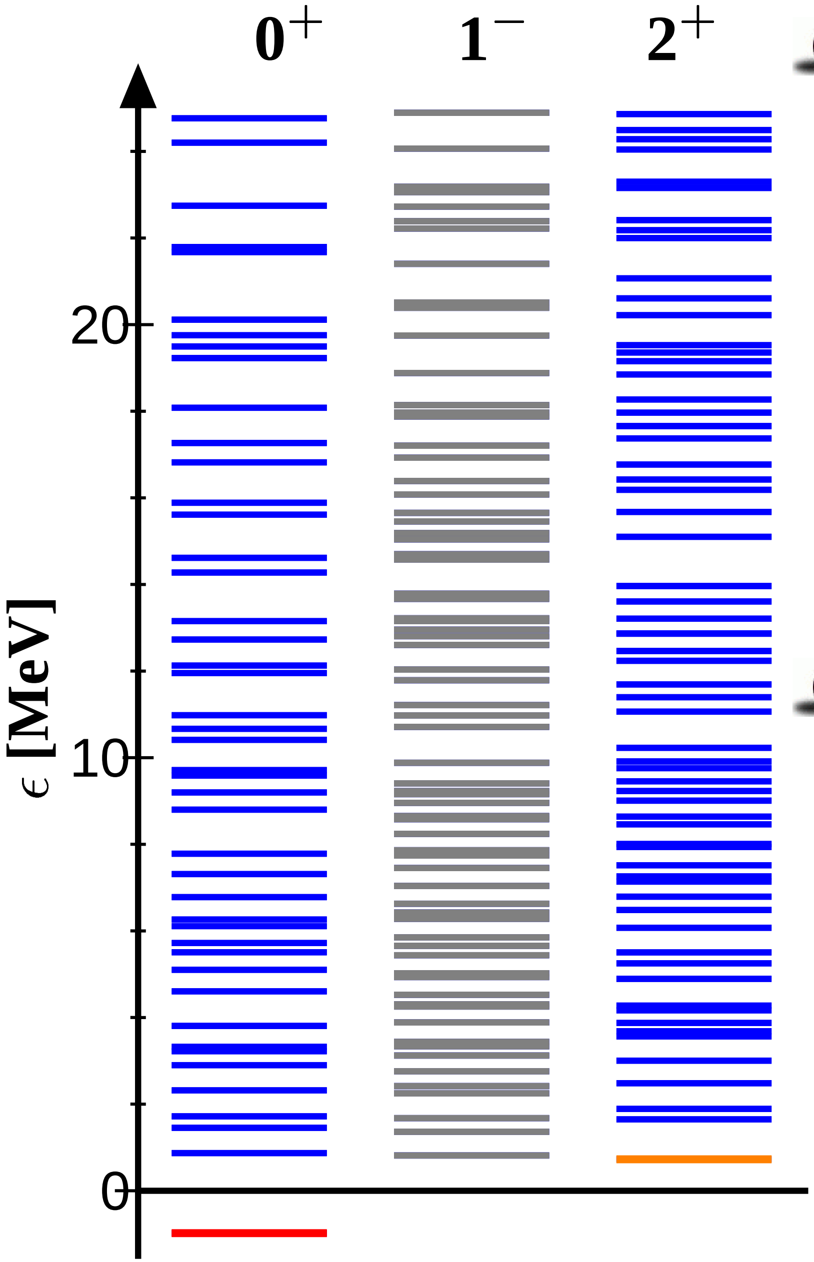
- ^{6}He + ^{12}C scattering: E_{lab} » Coulomb barrier
  - Coulomb breakup effects are negligible.



- ^{6}He + ^{209}Bi scattering: $E_{\mathrm{lab}} \approx$ Coulomb barrier
  - Coulomb breakup is to be significant.



Breakup Continuum States of 6He



- **Coupling Potential : Double-Folding**

$$\mathrm{Re}[U_{\gamma\gamma'}(\mathbf{R})] = \int d\mathbf{r}_{\mathrm{P}} d\mathbf{r}_{\mathrm{T}} \rho_{\gamma\gamma'}(\mathbf{r}_{\mathrm{P}}) \rho_{gs}(\mathbf{r}_{\mathrm{T}}) v_{\mathrm{NN}}(\mathbf{s})$$

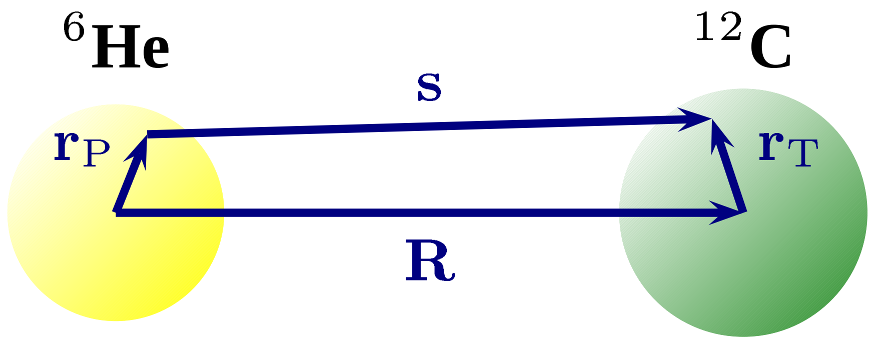
v_{NN} **is taken as DDM3Y**

$$\mathrm{Im}[U_{\gamma\gamma'}(\mathbf{R})] = N_I \times \mathrm{Re}[U_{\gamma\gamma'}(\mathbf{R})]$$

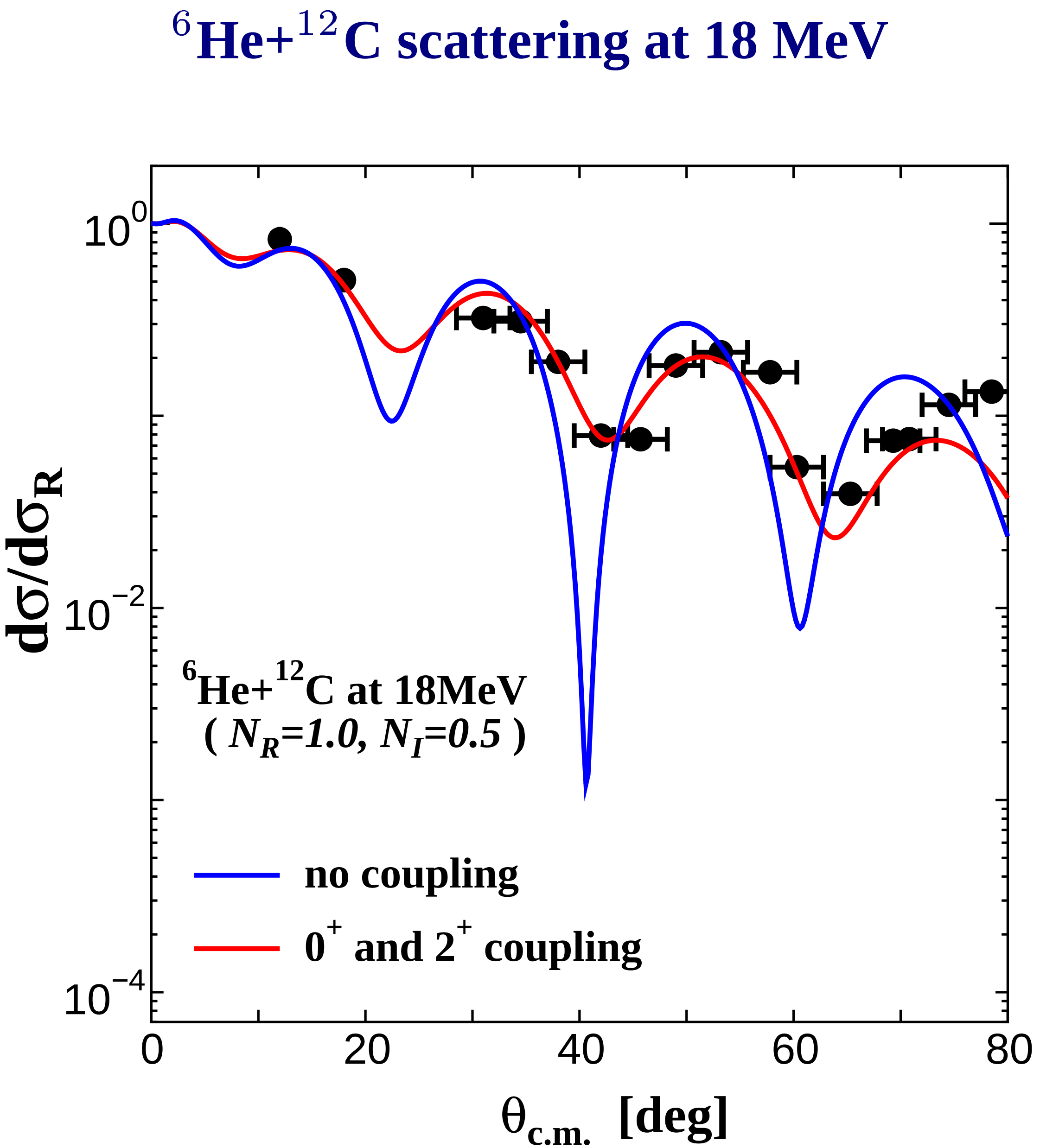
N_I **is optimized to reproduce the experimental data**

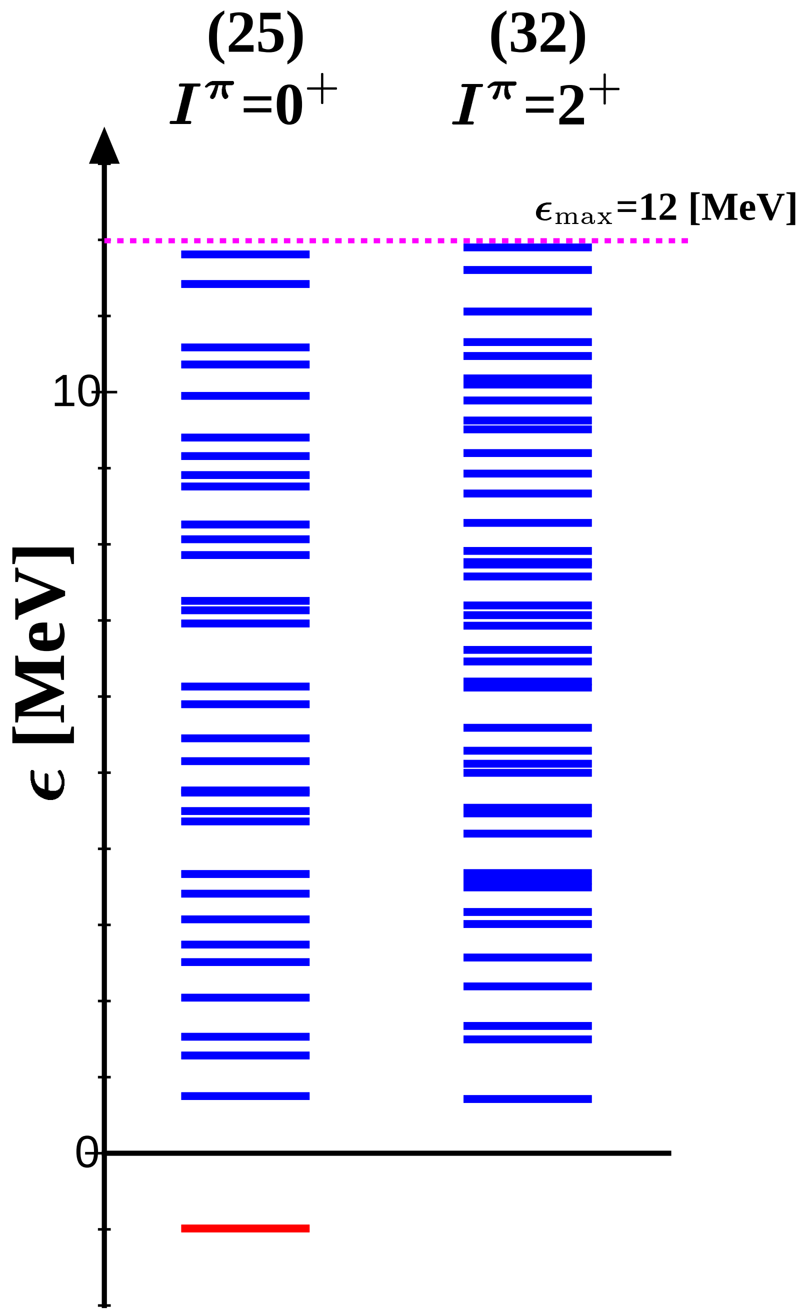
- **Transition Density**

$$\rho_{\gamma\gamma'}(\mathbf{r}_{\mathrm{P}}) = \langle \Phi_\gamma | \delta(\mathbf{r}_{\mathrm{P}} - \mathbf{t}) | \Phi_{\gamma'} \rangle$$



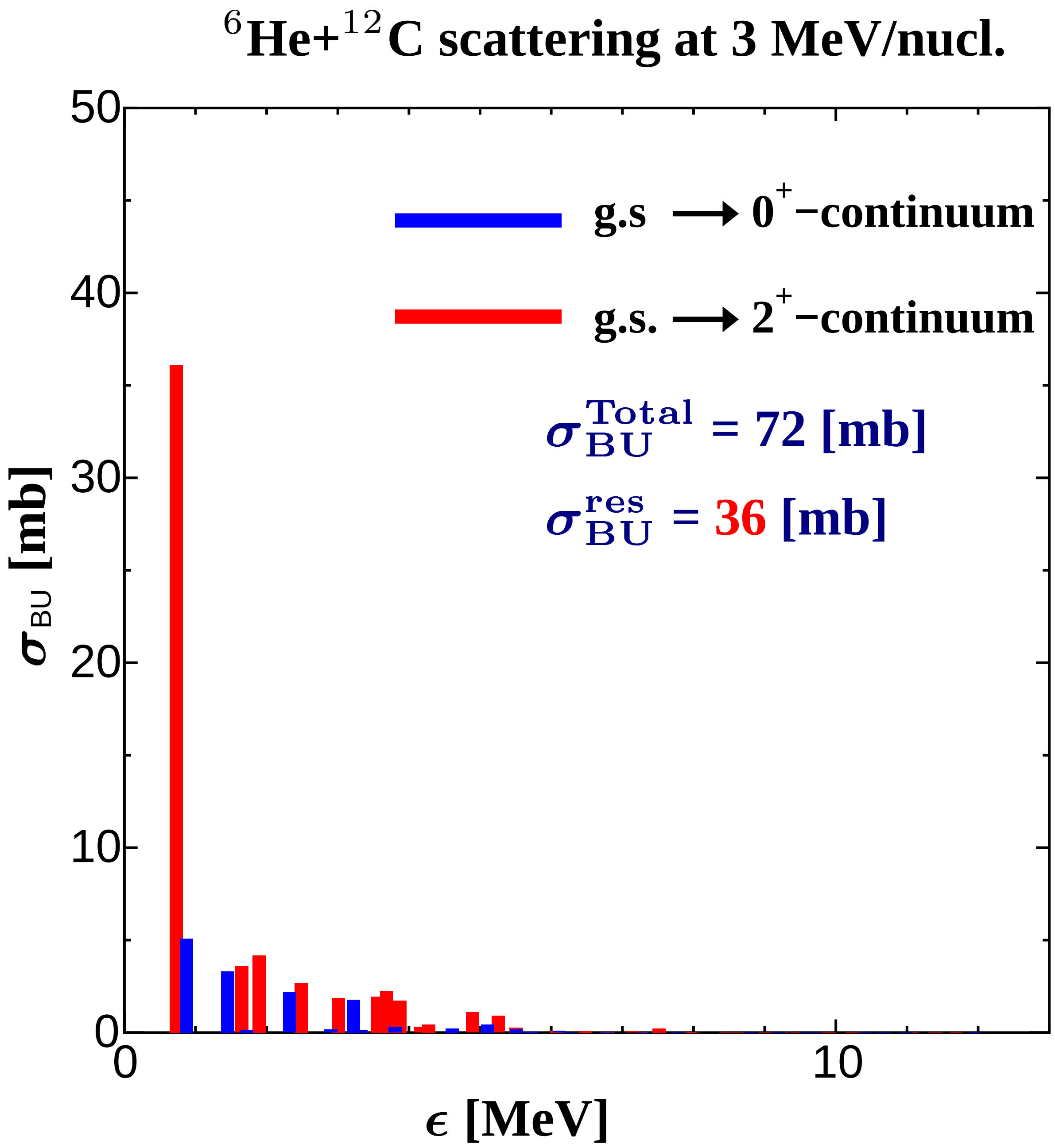
Elastic Cross Section (6He+12C @ 18 MeV)

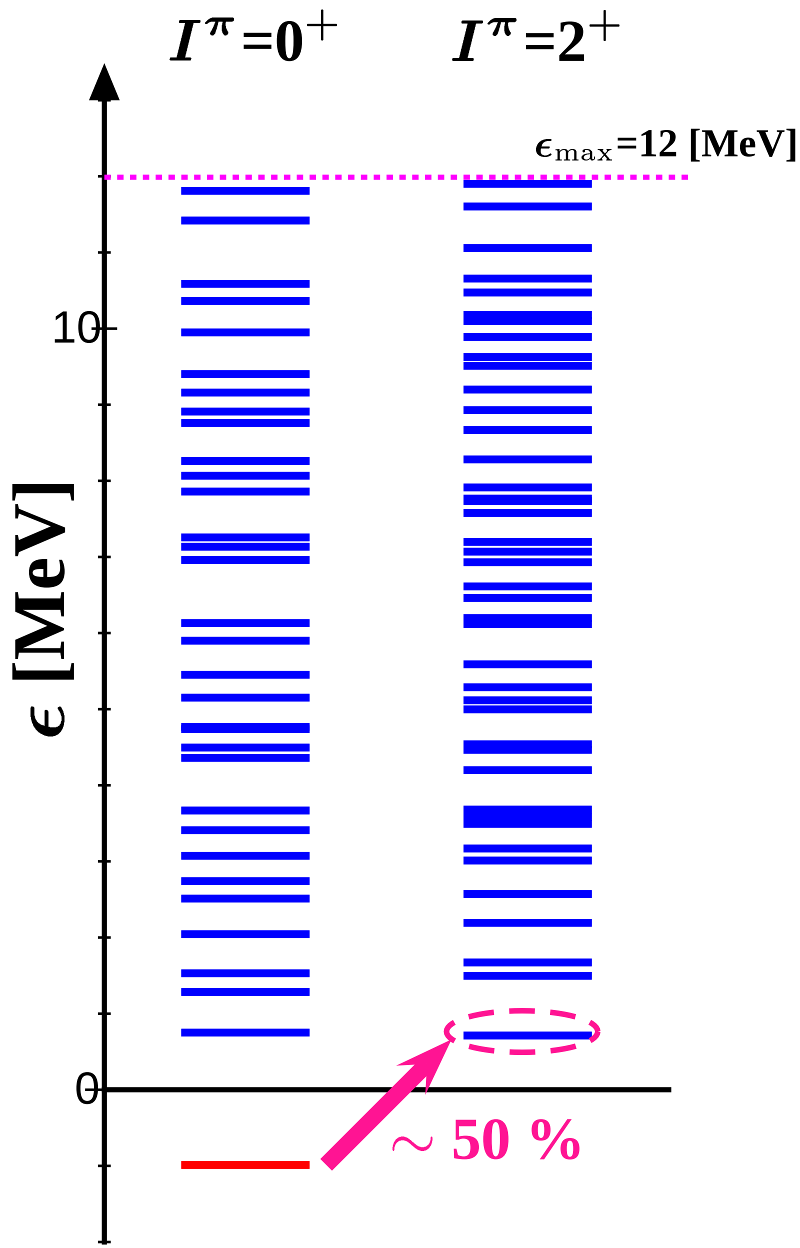




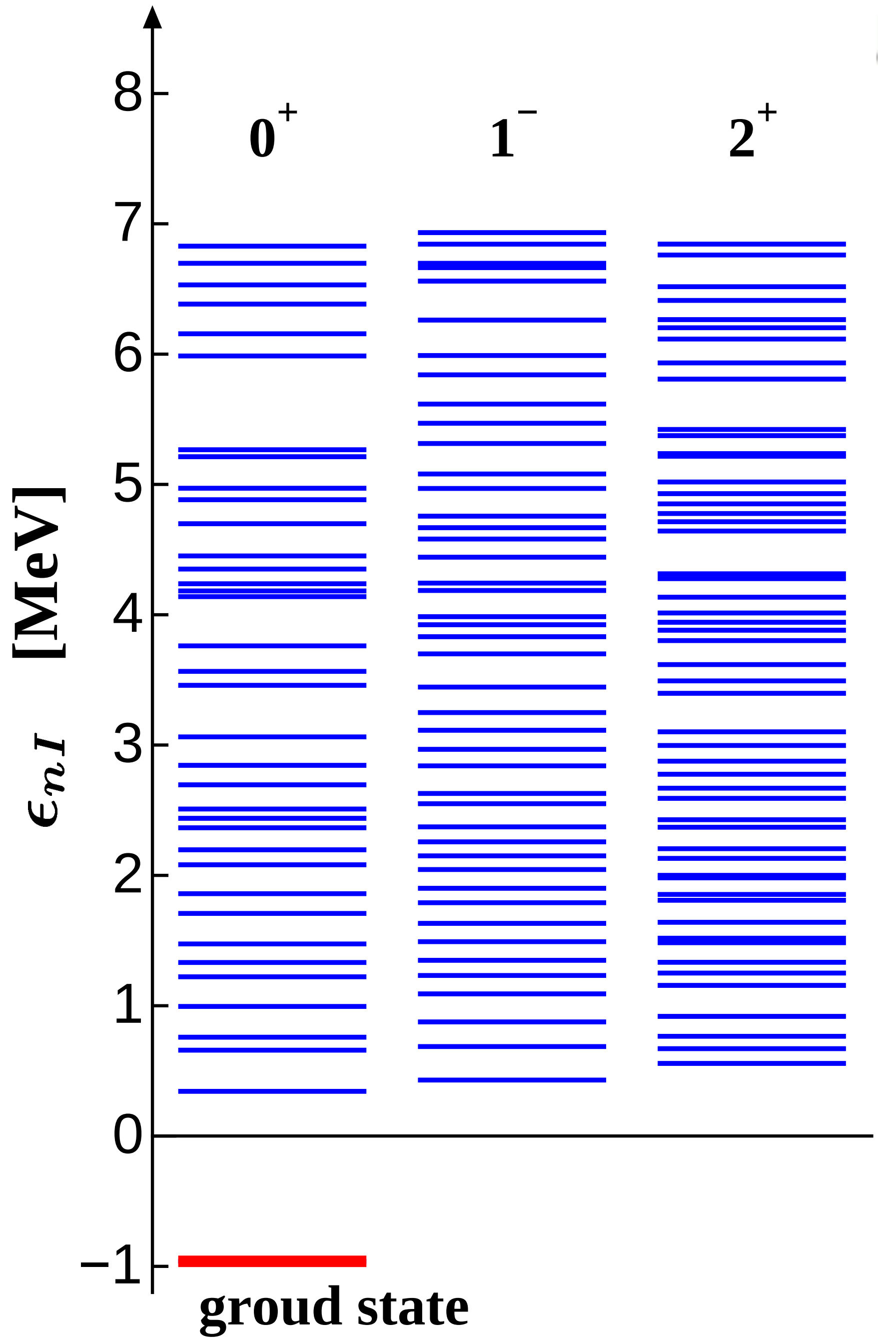
M. Milin *et al.*, Nucl. Phys. A730, 285 (2004).

Breakup Cross Section (6He+12C @ 18 MeV)





Breakup Continuum States of 6He



- **Coupling Potential : Cluster-Folding**

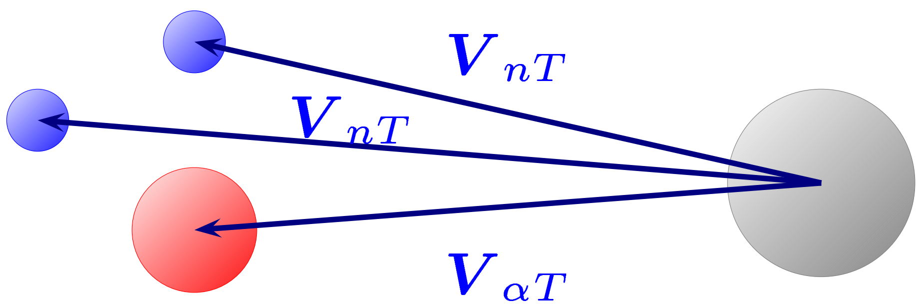
^{4}He–^{209}Bi potential : $V_{\alpha T}(\boldsymbol{r}_\alpha)$

· **Barnet and Lilley, PRC 9, 2010.**

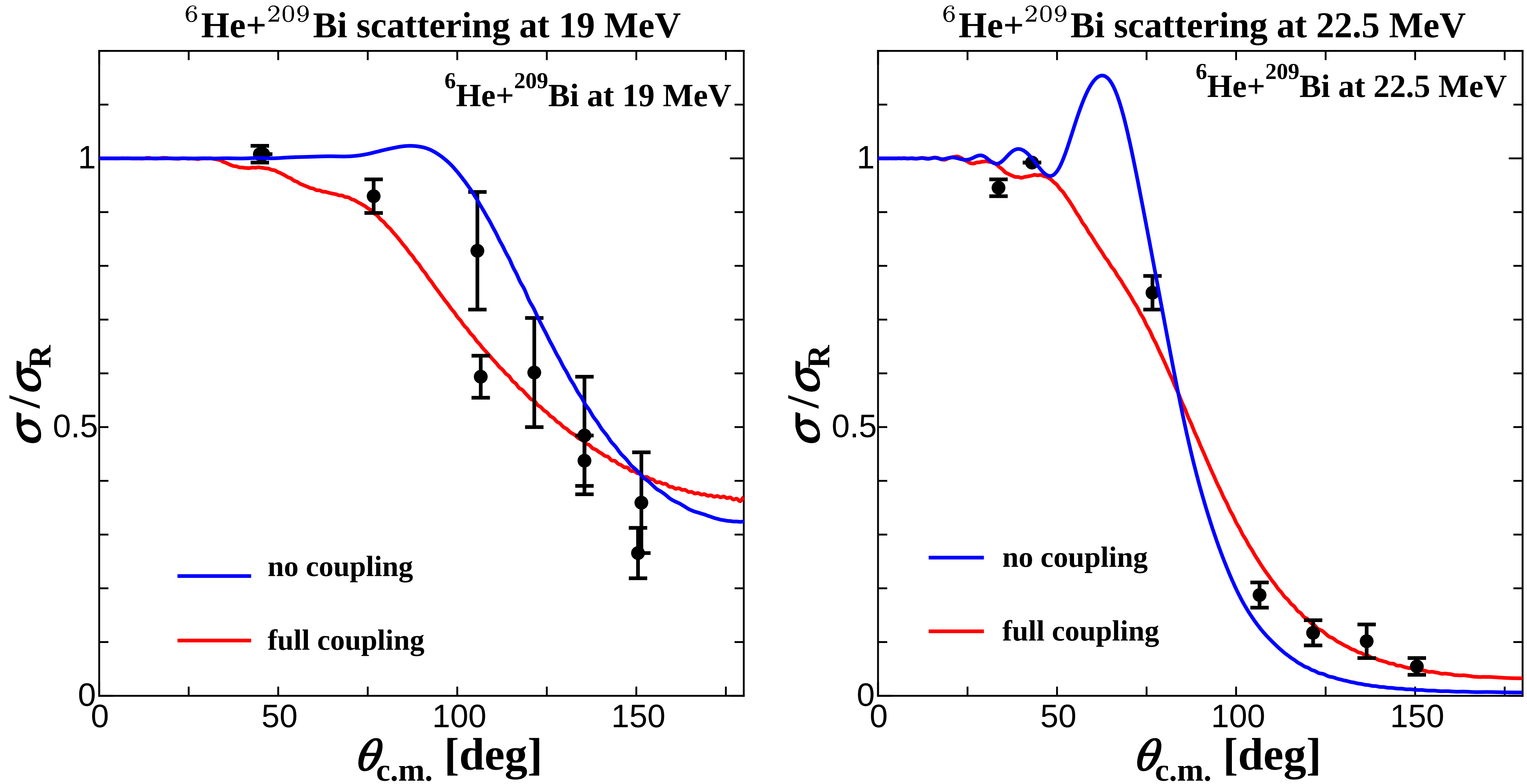
n–^{209}Bi potential : $V_{nT}(\boldsymbol{r}_n)$

· **Koning and Delaroche, NPA 713, 231.**

$$U_{nn'}(\boldsymbol{R}) = \int d\boldsymbol{r}_{\mathrm{p}} \boldsymbol{\rho}_{nn'}(\boldsymbol{r}_{\mathrm{p}}) \boldsymbol{V}_{\alpha T}(\boldsymbol{r}_\alpha) + \int d\boldsymbol{r}_{\mathrm{p}} \boldsymbol{\rho}_{nn'}(\boldsymbol{r}_{\mathrm{p}}) \boldsymbol{V}_{nT}(\boldsymbol{r}_{n_1}) + \int d\boldsymbol{r}_{\mathrm{p}} \boldsymbol{\rho}_{nn'}(\boldsymbol{r}_{\mathrm{p}}) \boldsymbol{V}_{nT}(\boldsymbol{r}_{n_2})$$

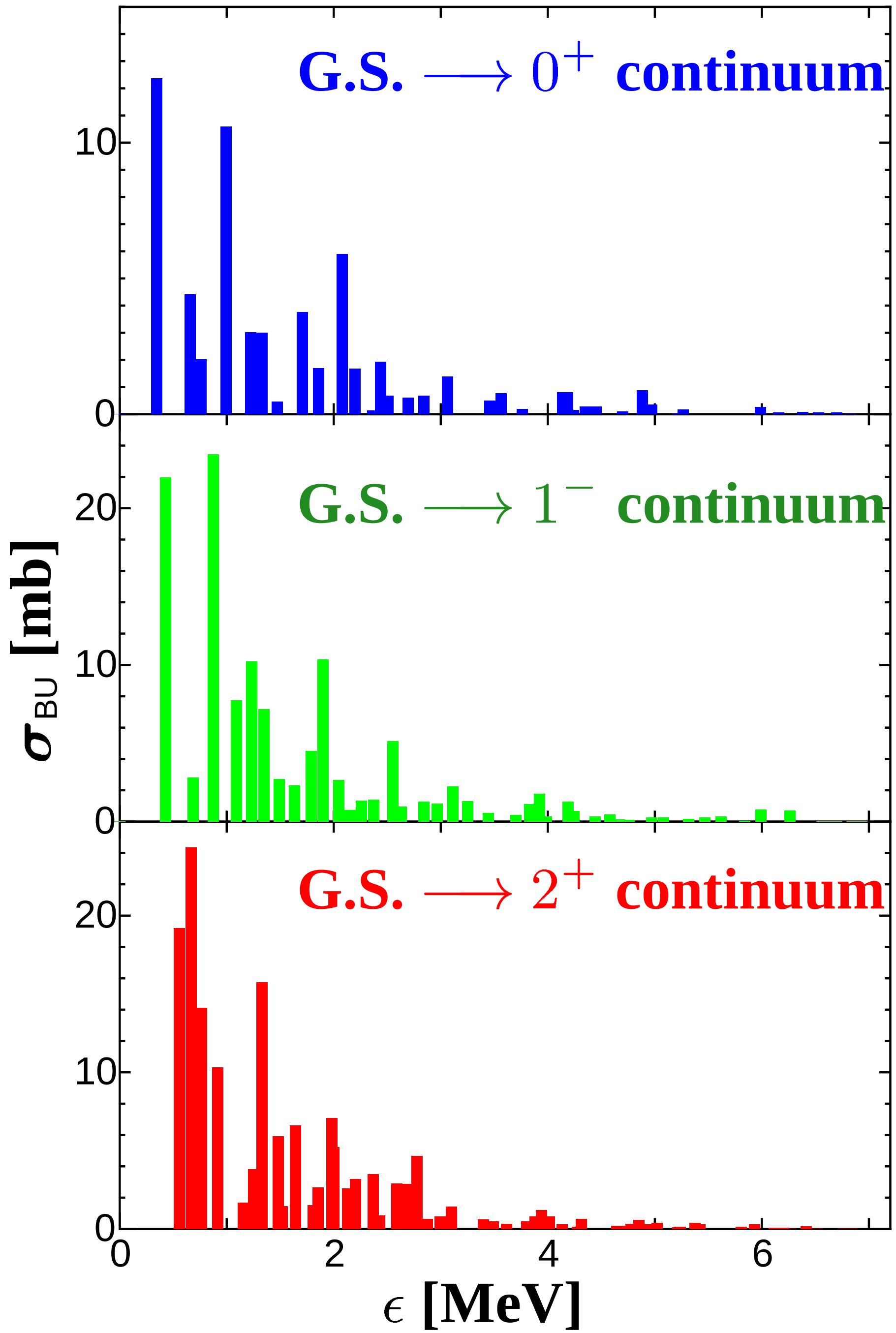


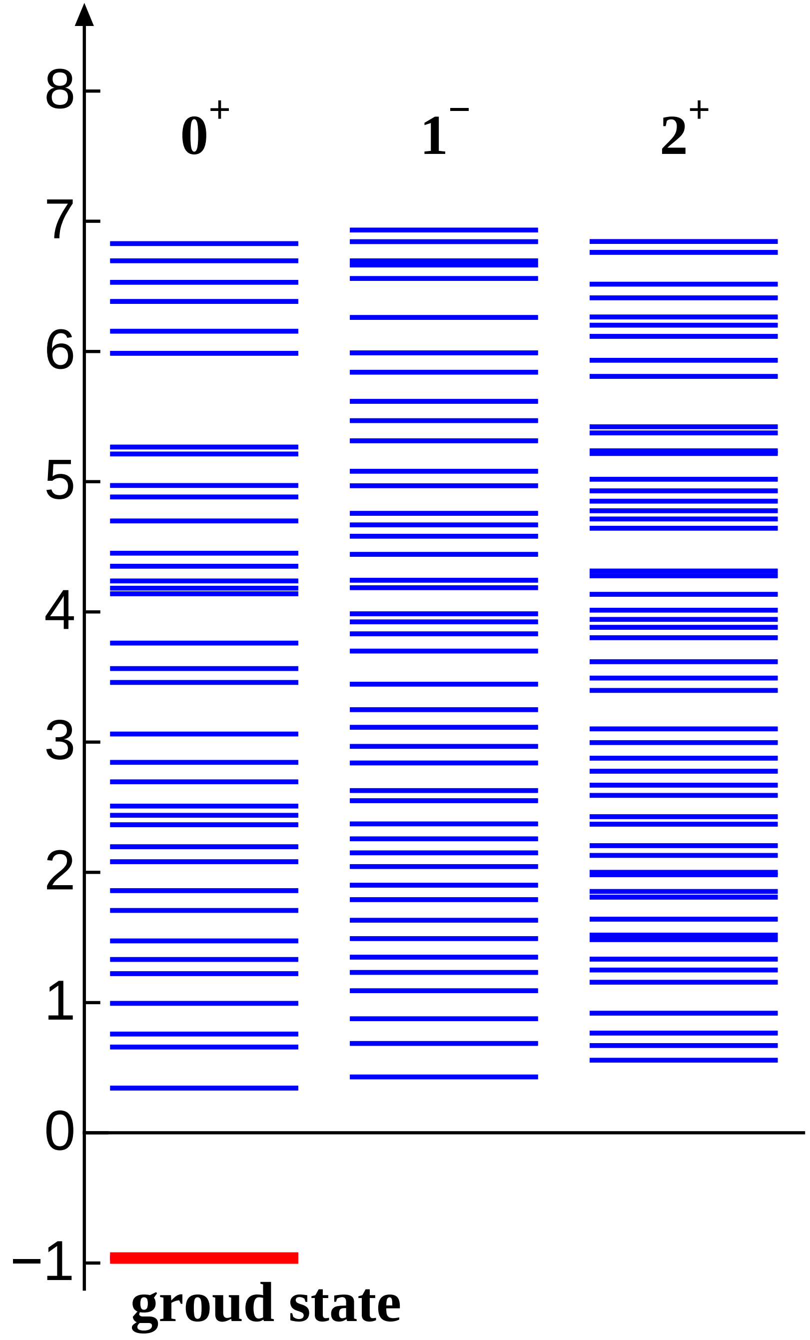
Angular Distribution of Elastic Cross Section



The four-body CDCC calculation well reproduces the data.

Breakup Cross Section (6He+209Bi @ 19 MeV)





Summary

- We propose a fully quantum-mechanical method called four-body CDCC, which can describe four-body nuclear and Coulomb breakup.
- We apply four-body CDCC to analyses of ^{6}He nuclear and Coulomb breakup reactions, and found that four-body CDCC can reproduce the experimental data.
- Thus four-body CDCC is indispensable to analyse various four-body breakup reactions in which both nuclear and Coulomb breakup processes are to be significant.
- In a future work, we are developing a new method of calculation of energy distribution of breakup cross section and momentum disrtibution of breakup particles.