The Method of CDCC for Four-Body Breakup Reactions

CDCC : Continuum-Discretized Coupled-Channels

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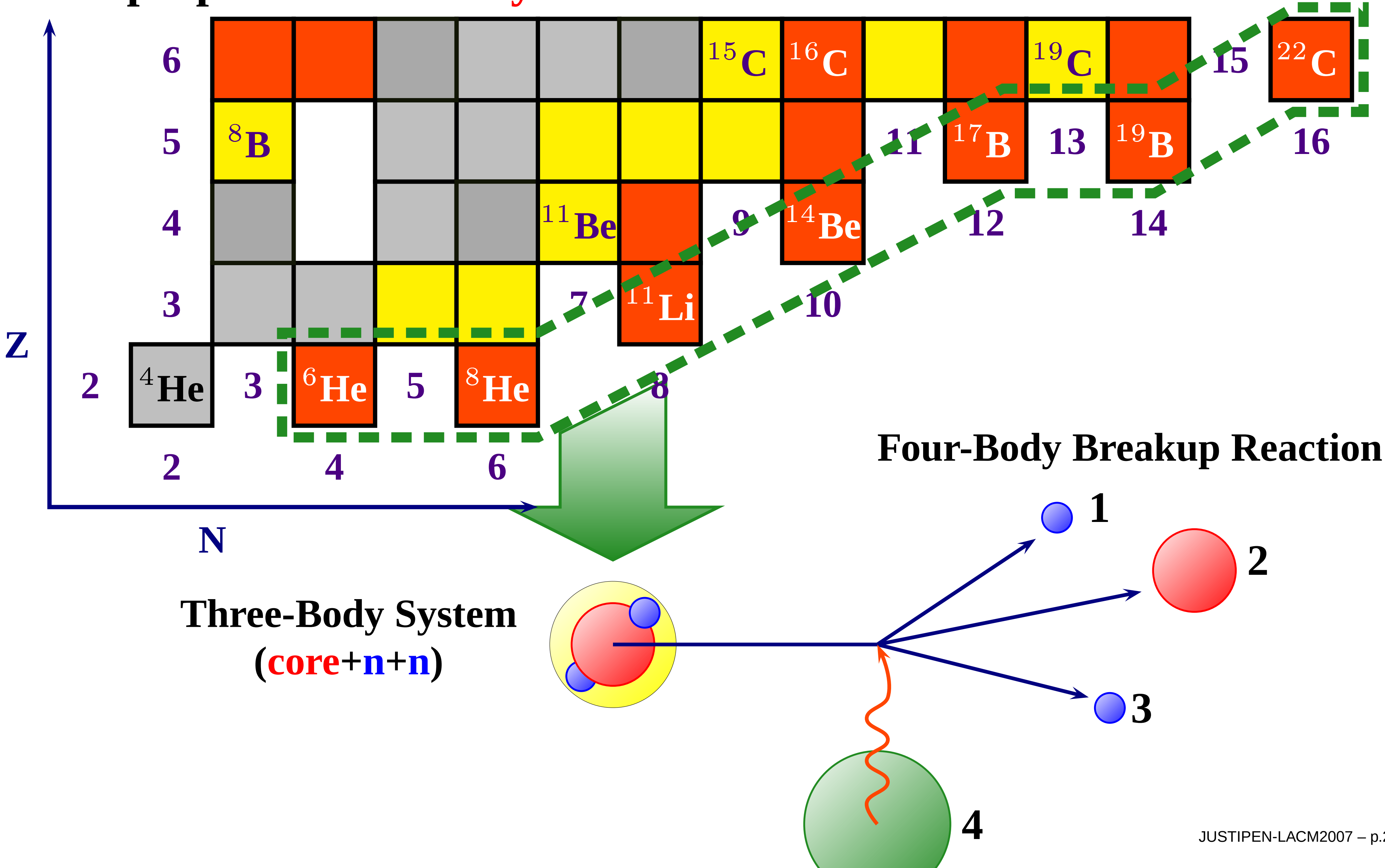
International Workshop “Joint JUSTIPEN-LACM Meeting”

Region of Interest: Neutron & Proton Rich

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



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**

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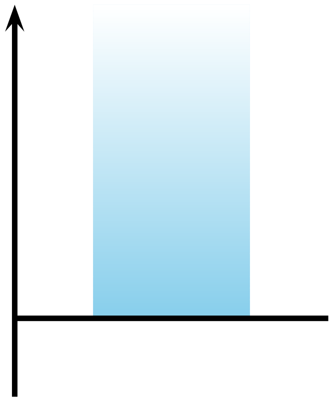
Four-Body CDCC

Application to analyses of ^{6}He breakup reactions

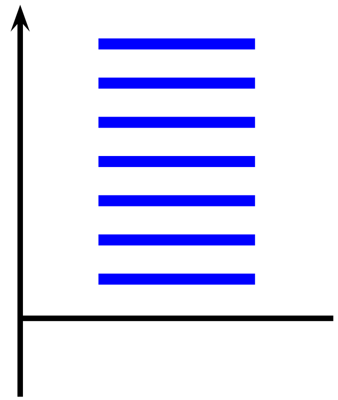
Continuum-Discretized Coupled-Channels

Essence of CDCC

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



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

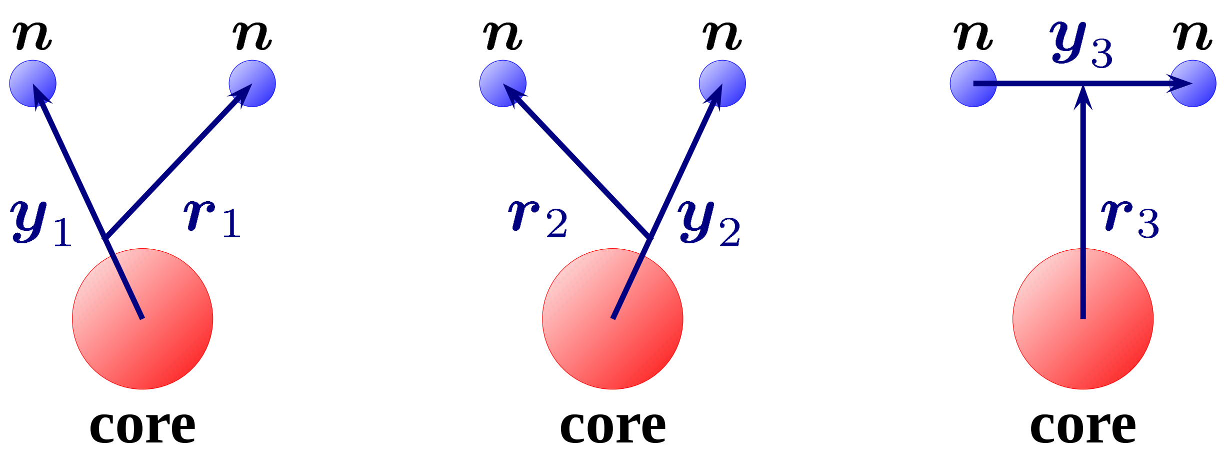


- **A set of eigenstates forms a complete set with good accuracy in a finite model space that is important for breakup processes concerned**

Gaussian Expansion Method (GEM)

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

- **GEM has been confirmed as an accurate method of solving few-body problems.**



— **Gaussian basis function** —

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

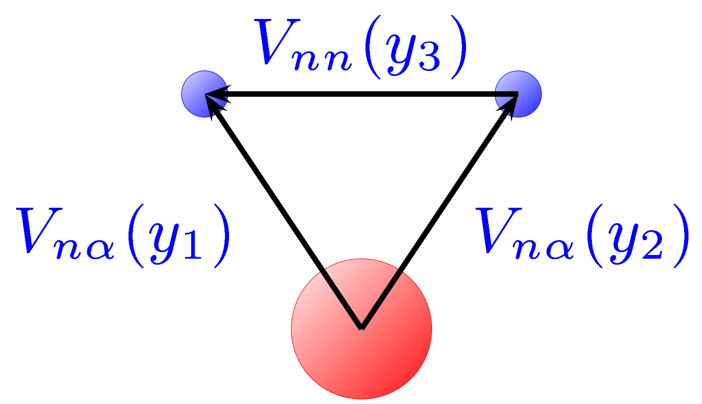
- **Bound and discretized continuum states are obtained by diagonalizing of three-body Hamiltonian with the basis functions**

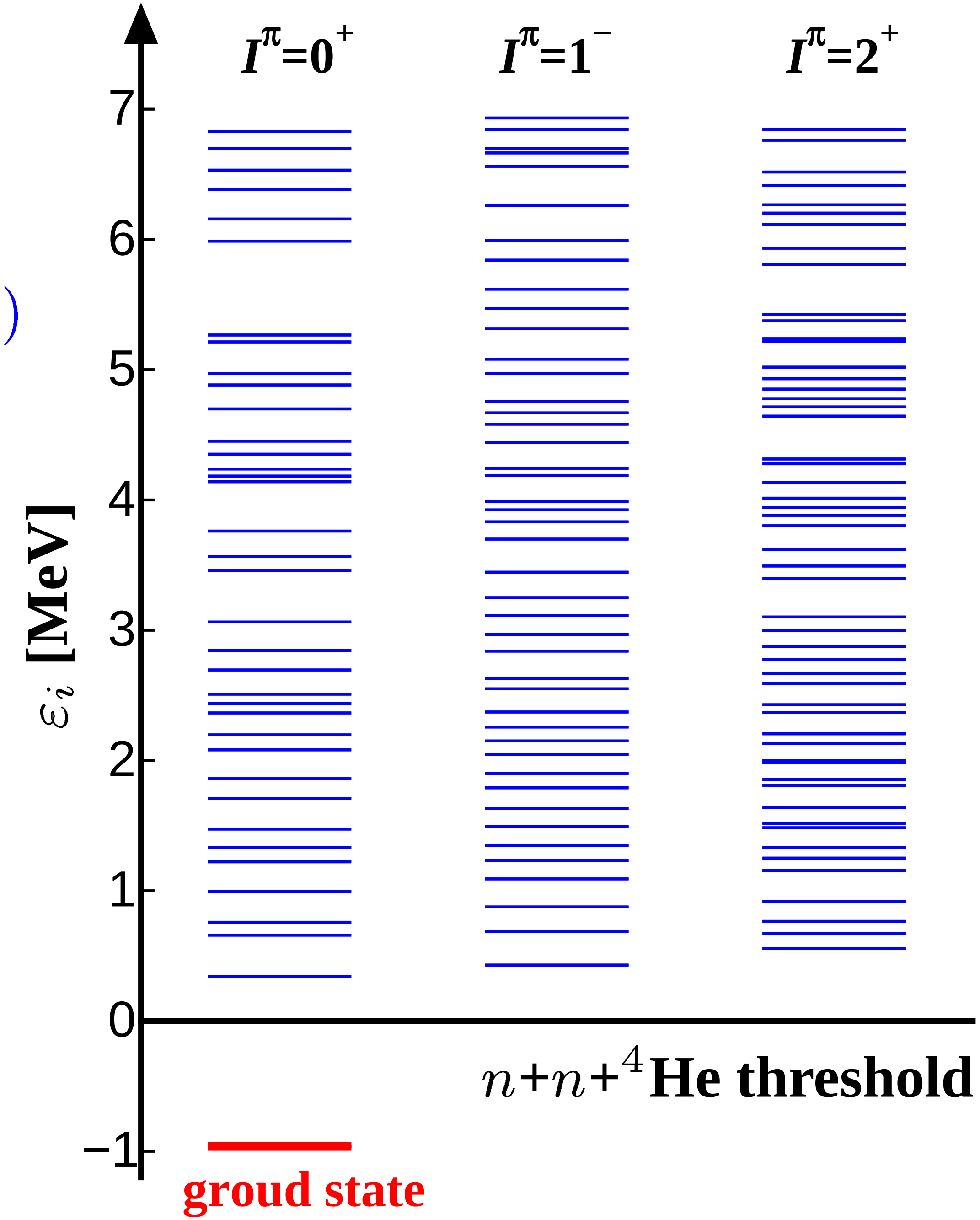
Bound and Discretized Continuum states of 6He

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

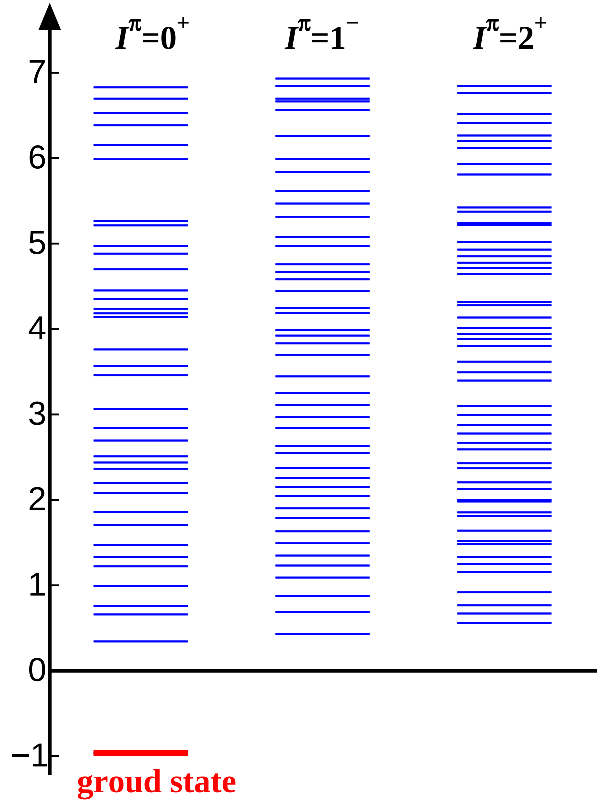
$$H = T_y + T_r + V_{n\alpha}(y_1) + V_{n\alpha}(y_2) + V_{nn}(y_3)$$

— V_{nn} : **BonnA**
— $V_{n\alpha}$: **Kanada pot.**





CDCC Equation



Total Wave Function

$$\Psi_{JM}(\xi, \mathbf{R}) = \Phi_0(\xi)\chi^J_{0J}(\mathbf{R}) + \sum_\gamma \left[\hat{\Phi}_{nI}(\xi) \otimes \chi^J_{nIL}(\mathbf{R})\right]_{JM}$$

Coupled-Channels Equation for χ_γ

$$\{T_R + U_{\gamma\gamma}(R) - E_\gamma\}\,\chi^J_{nIL}(R) = -U_{\gamma\gamma'}(R)\chi^J_{n'I'L'}(R)$$

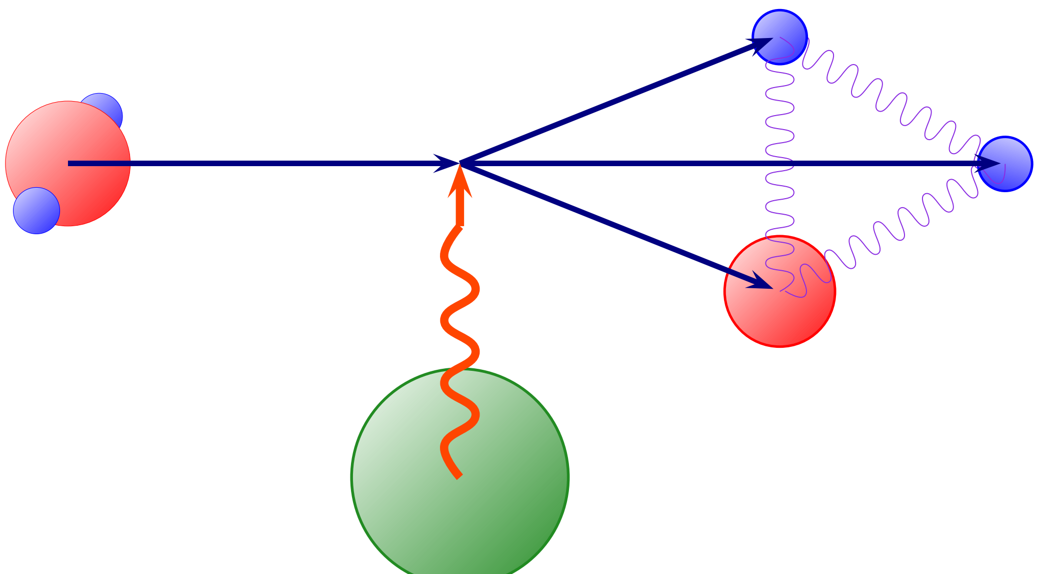
Asymptotic boundary condition

$$\chi^J_{nIL}(R) \sim u^{(-)}_L(R) - \hat{S}^J_{nIL}\, u^{(+)}_L(R)$$

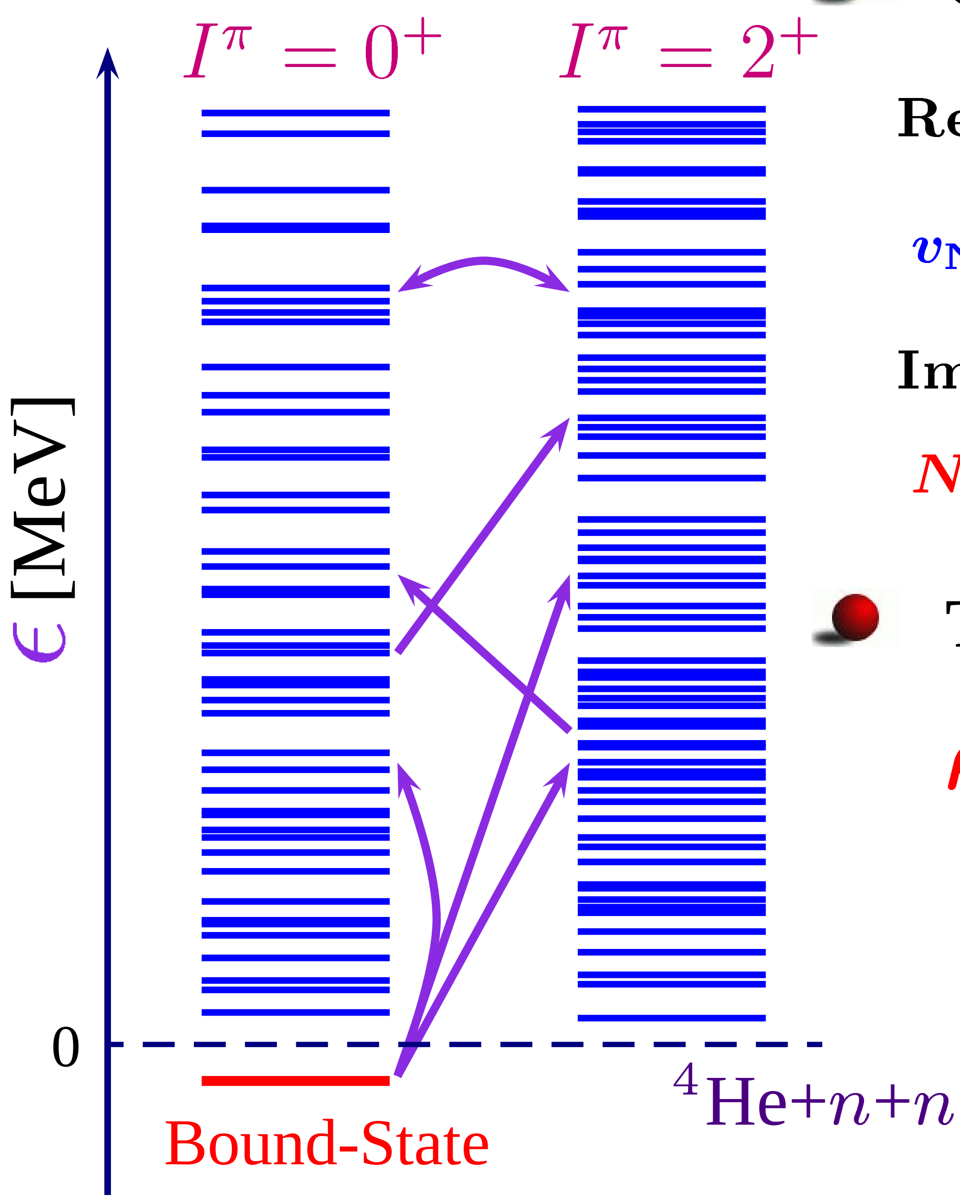
^{6}He Nuclear Breakup

System : ^{6}He+^{12}C scattering at 18 and 229.8 MeV

Coulomb barrier $<< E_{\rm in}$



Breakup Continuum States of 6He



- **Coupling Potential : Double-Folding**

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

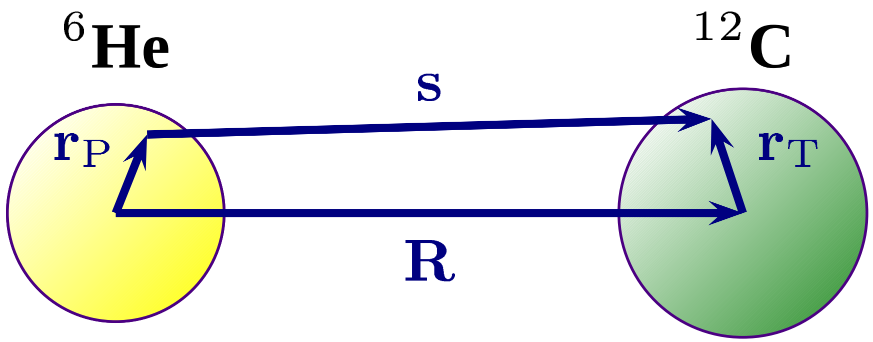
v_NN **is taken as DDM3Y**

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

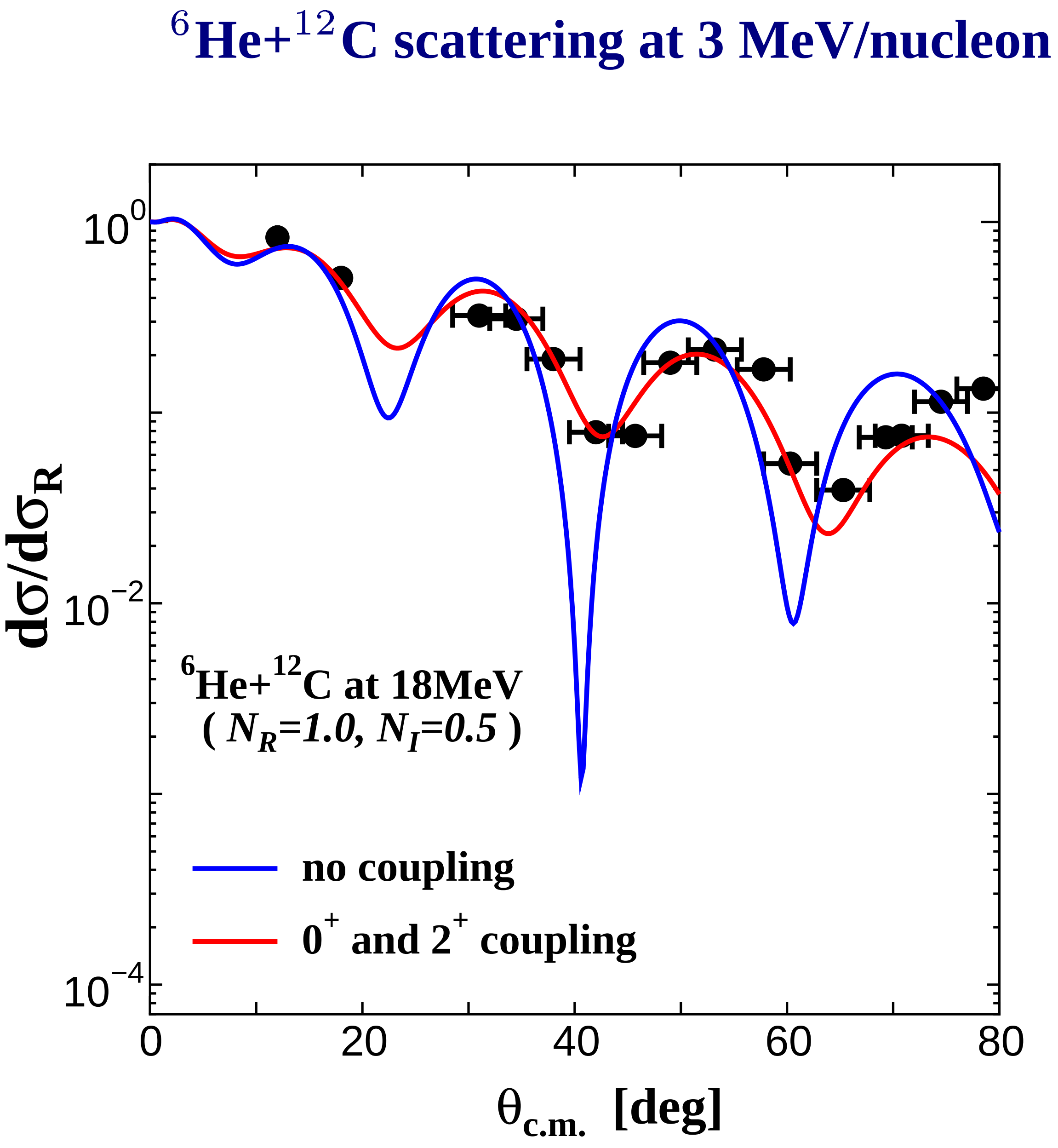
N_I **is optimized to reproduce the experimental data**

- **Transition Density**

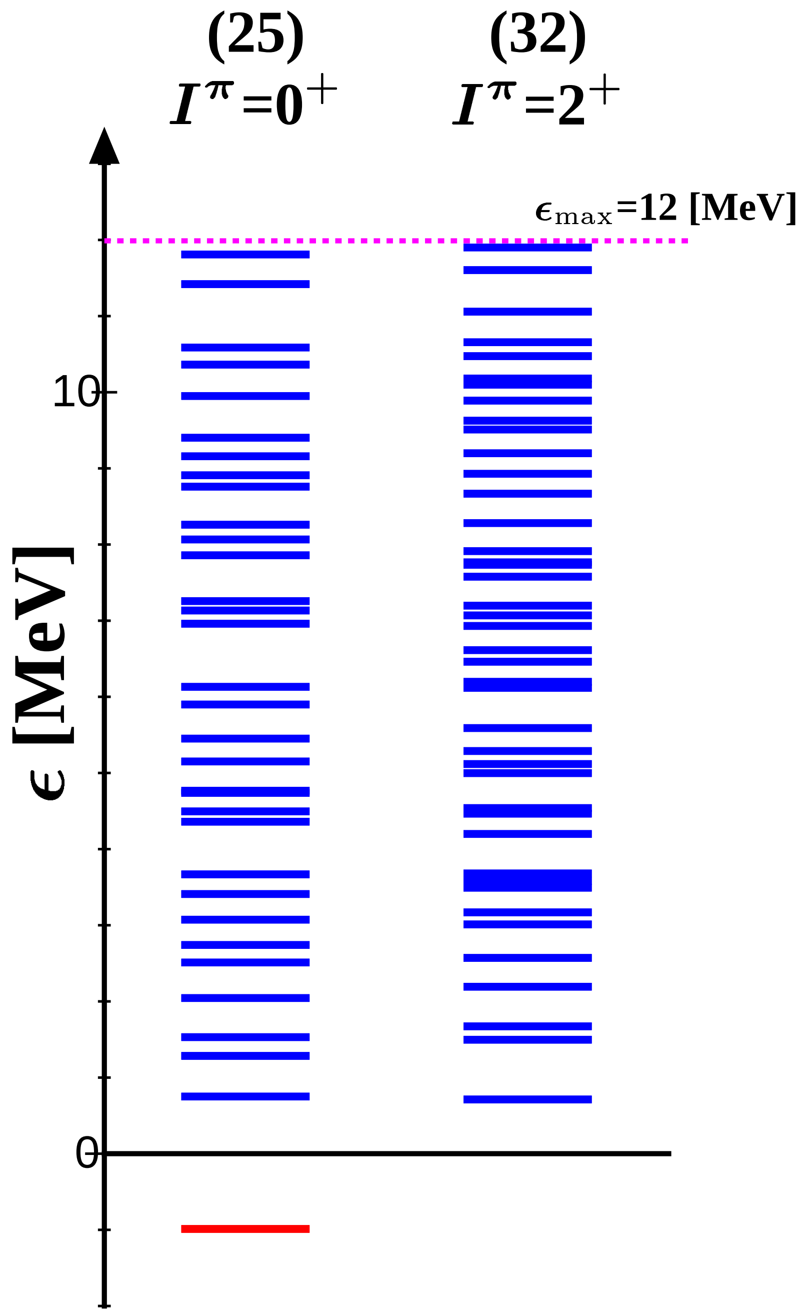
$$\rho_{\gamma\gamma'}(\mathbf{r}_\mathrm{P}) = \langle \Phi_\gamma | \delta(\mathbf{r}_\mathrm{P} - \mathbf{t}) | \Phi_{\gamma'} \rangle$$



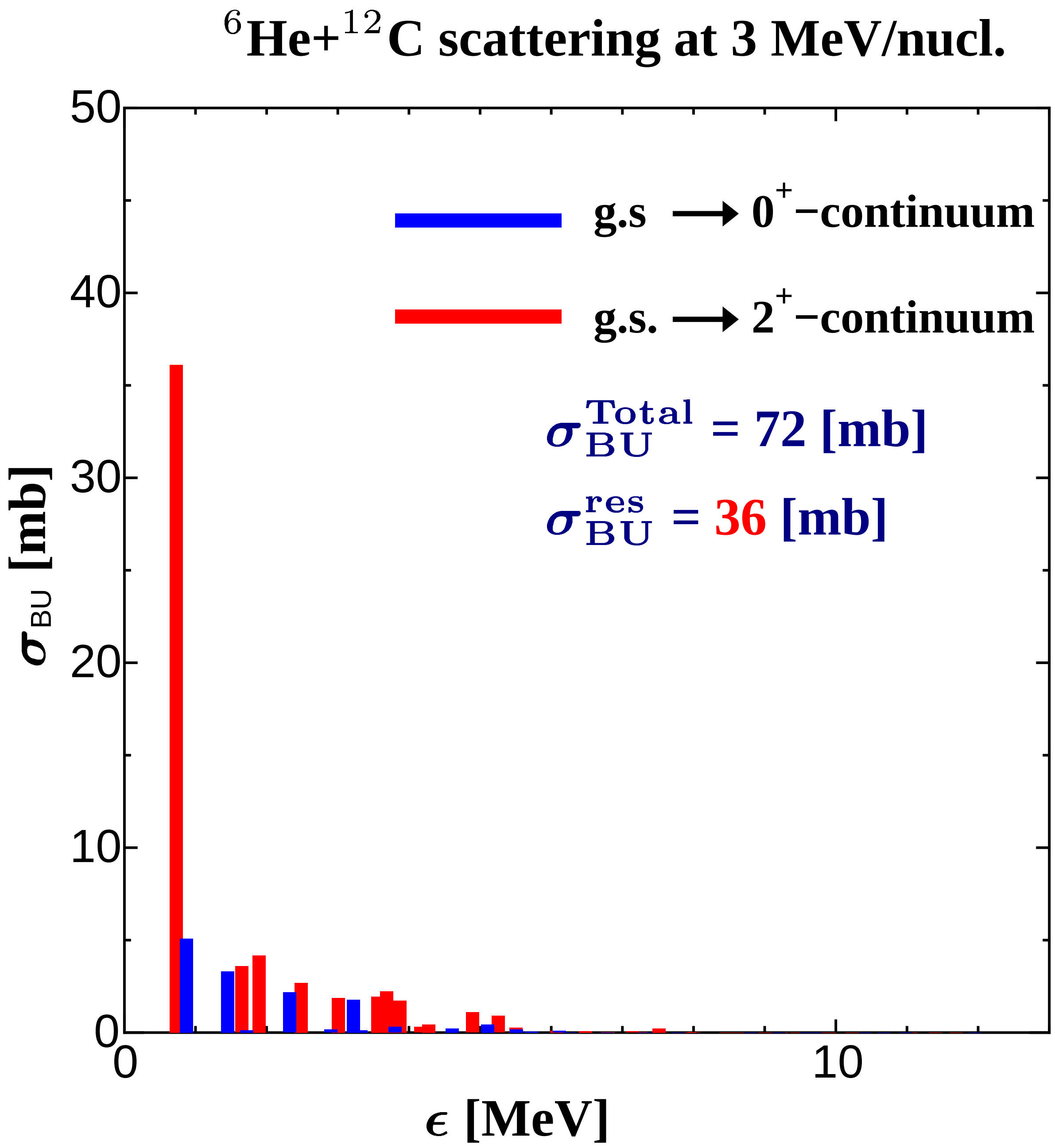
Elastic Cross Section (6He+12C @ 3MeV/A)

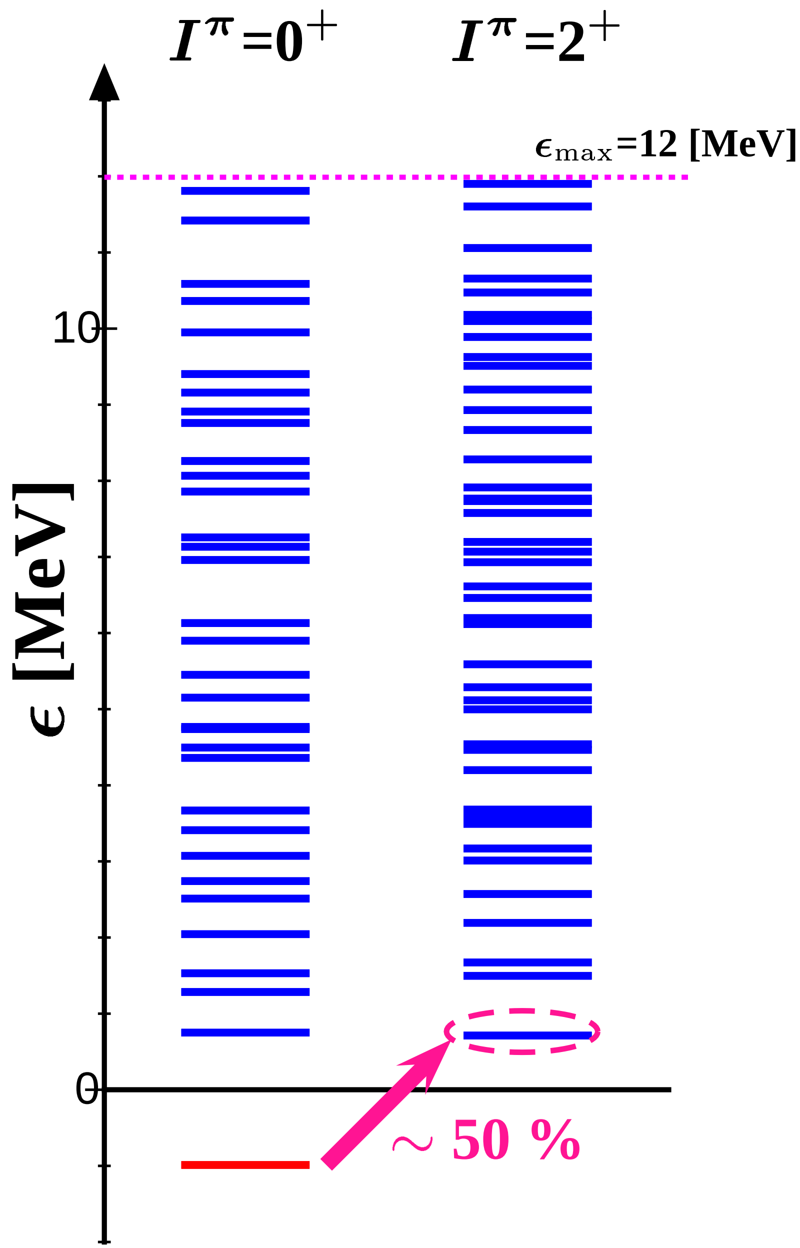


M. Milin *et al.*, Nucl. Phys. A730, 285 (2004).



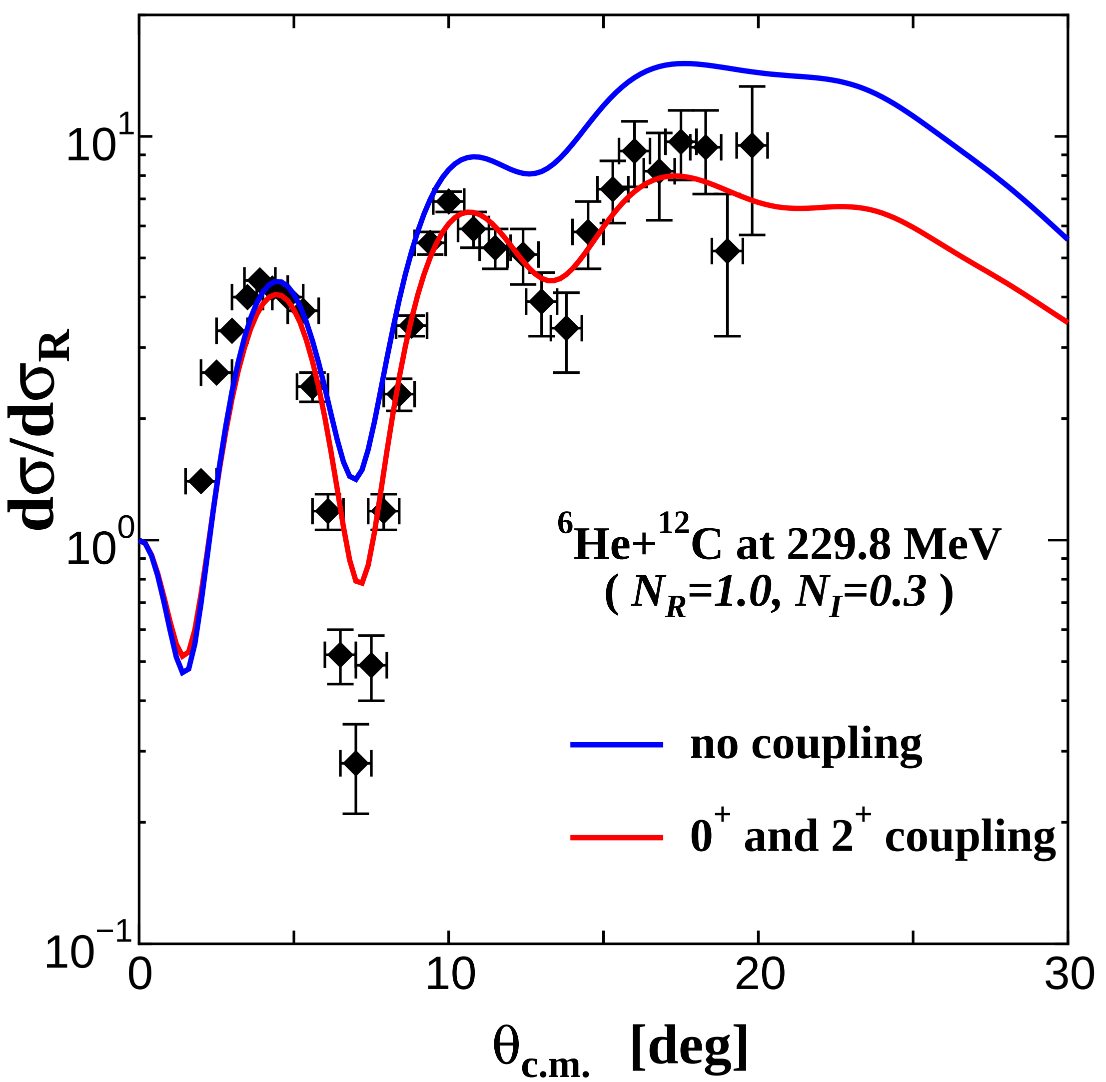
Breakup Cross Section (6He+12C @ 3MeV/A)

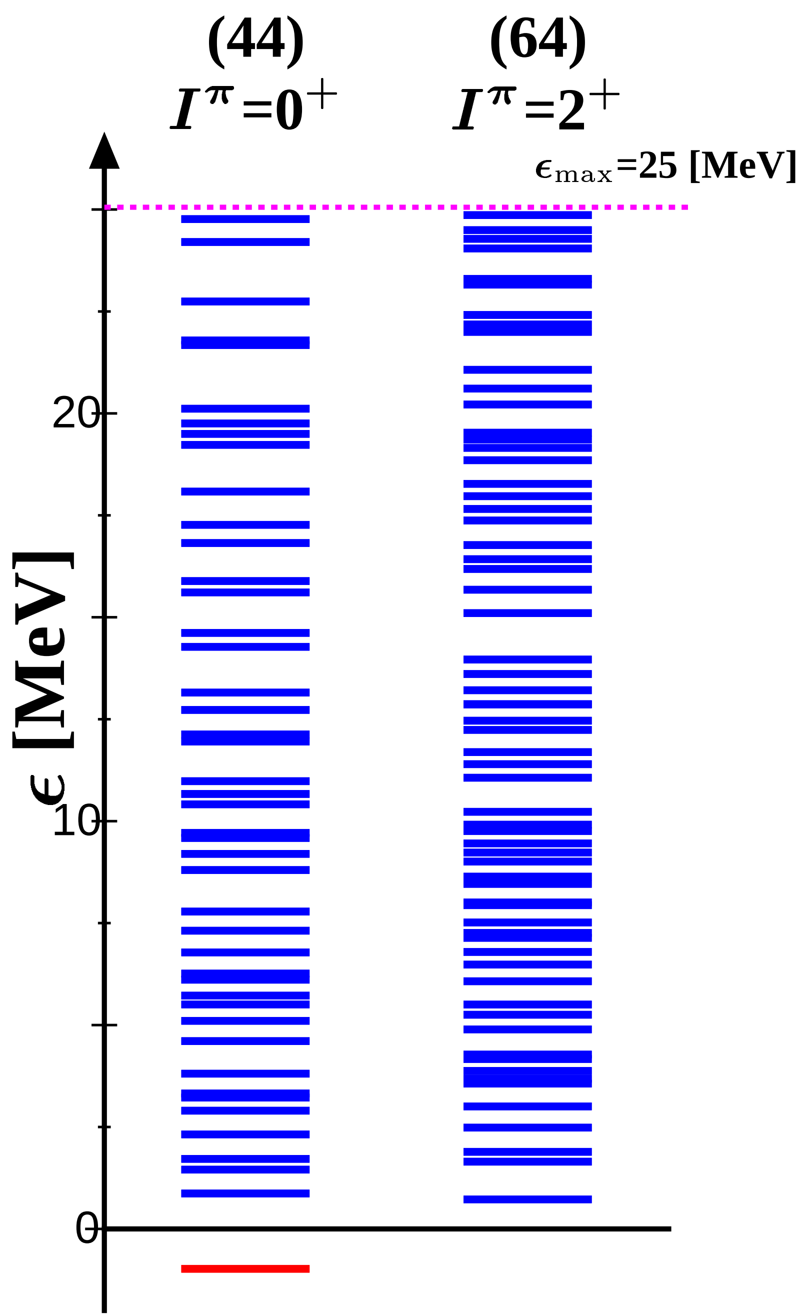




Elastic Cross Section (6He+12C @ 38.3MeV/A)

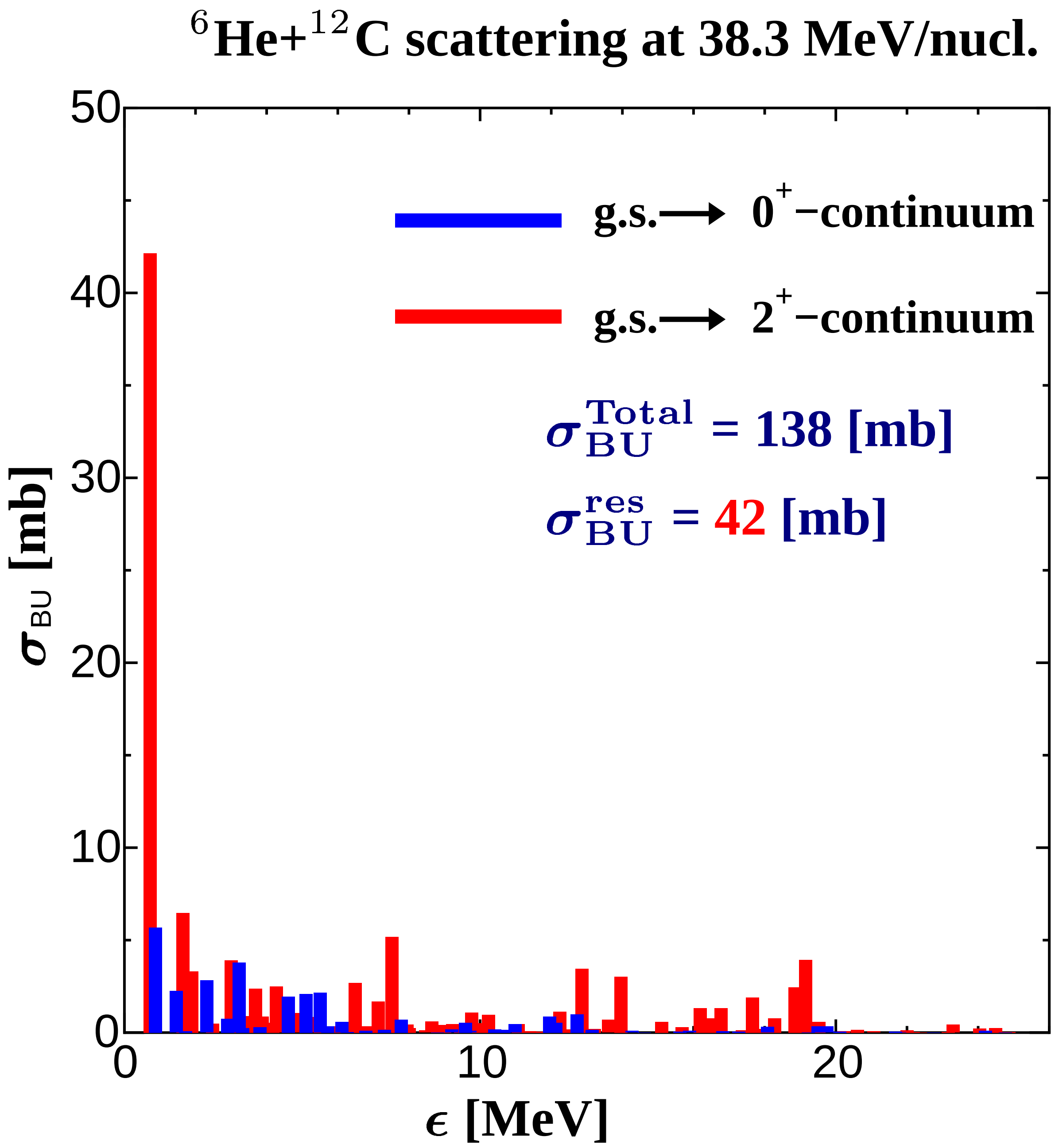
^{6}He+^{12}C scattering at 38.3 MeV/nucleon

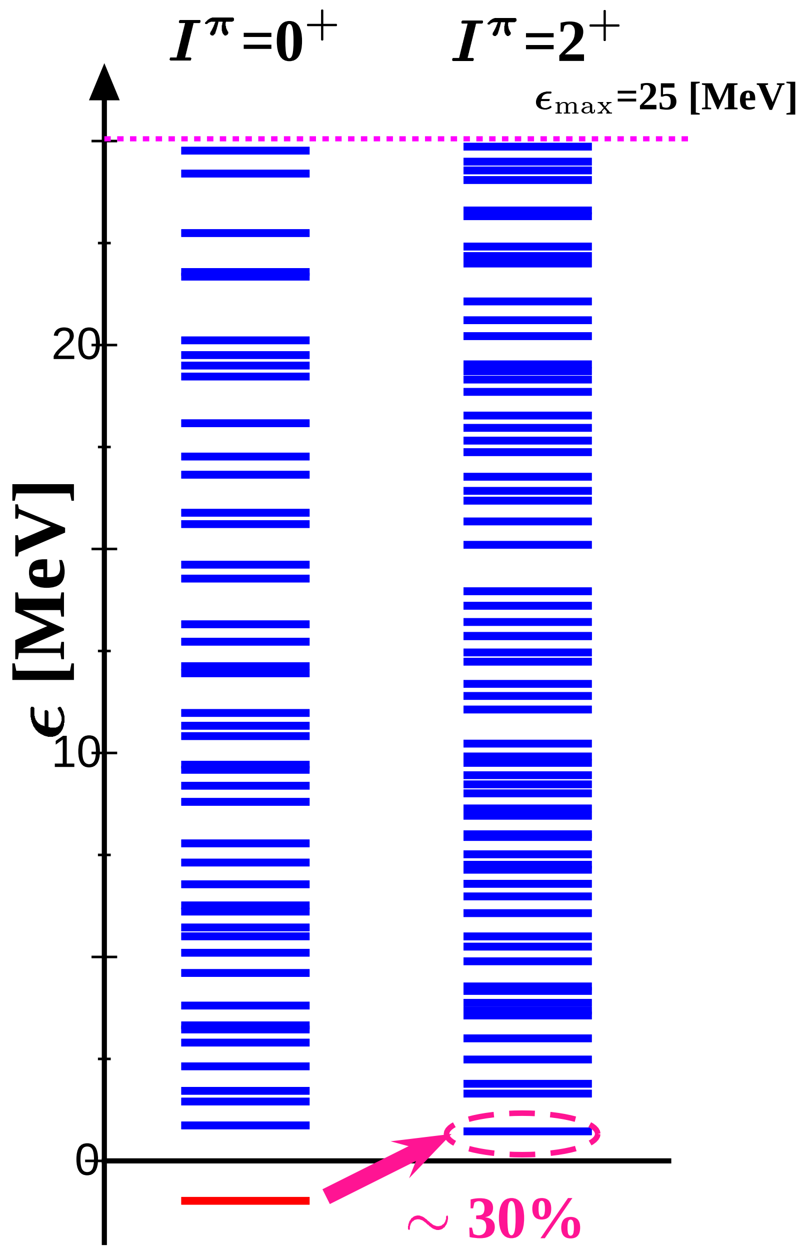




V. Lapoux *et al.*, Phys. Rev. C 66, 034608 (2002).

Breakup Cross Section (6He+12C @ 38.3MeV/A)

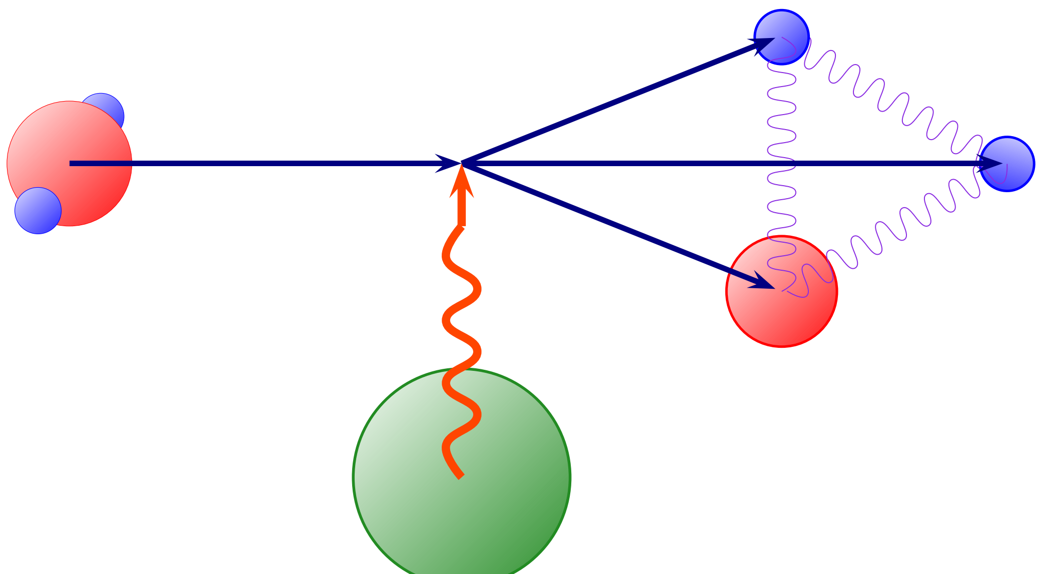




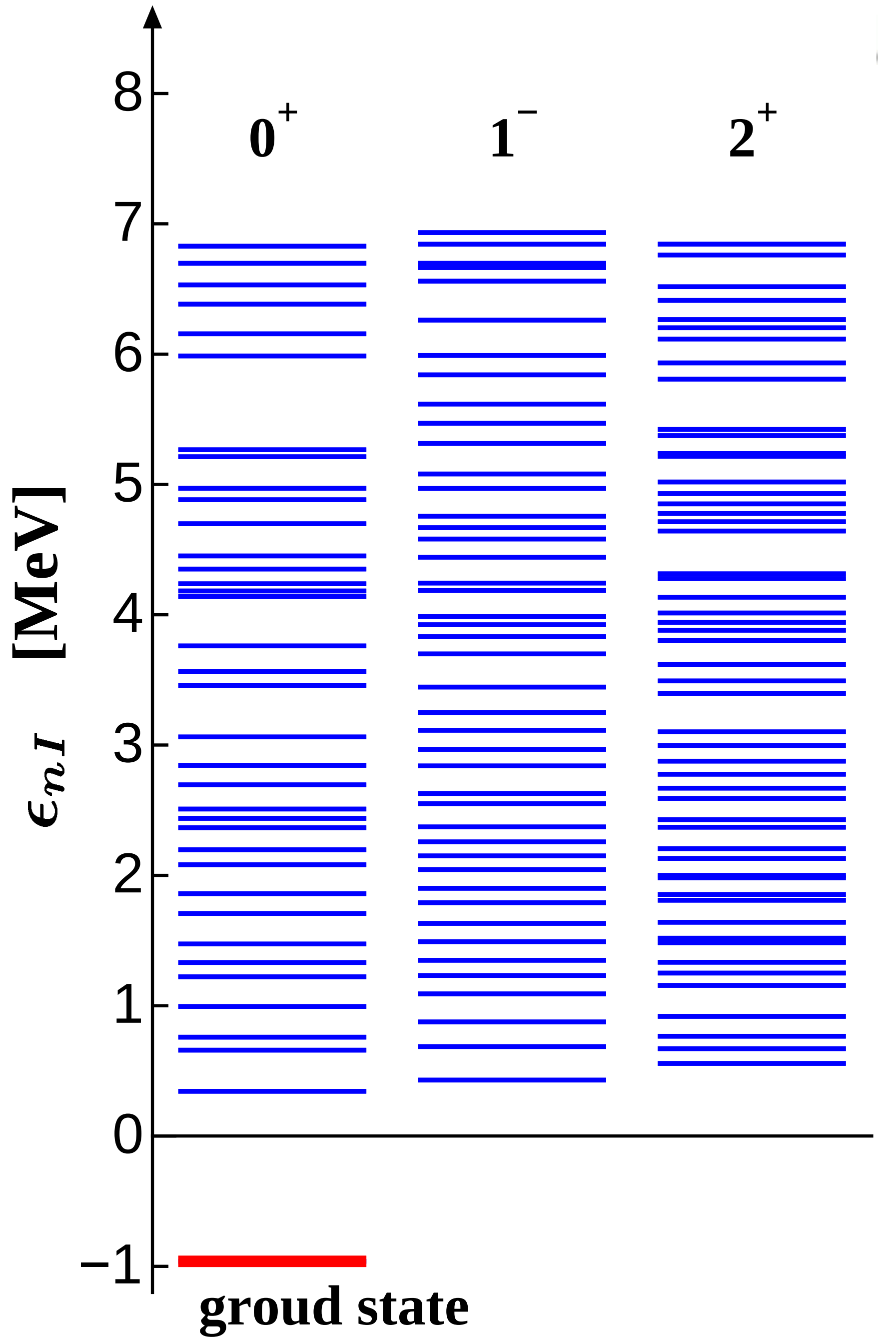
^{6}He Nuclear and Coulomb Breakup

System : ^{6}He+^{209}Bi scattering at 19 and 22.5 MeV

Coulomb barrier $\approx E_{\rm in}$



Breakup Continuum States of 6He



- **Coupling Potential : Cluster-Folding**

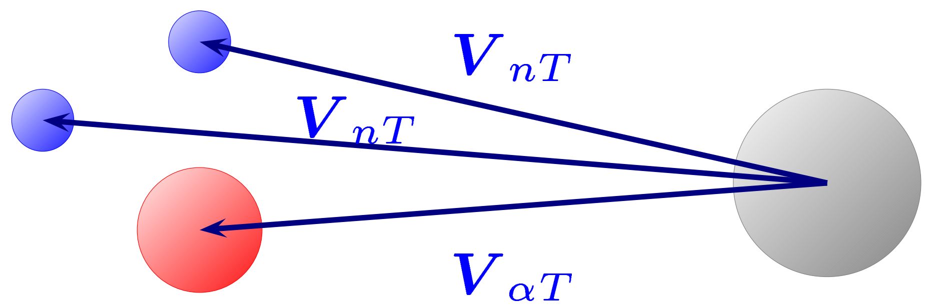
^{4}He–^{209}Bi potential : $V_{\alpha T}(\boldsymbol{r}_\alpha)$

· **Barnet and Lilley, PRC 9, 2010.**

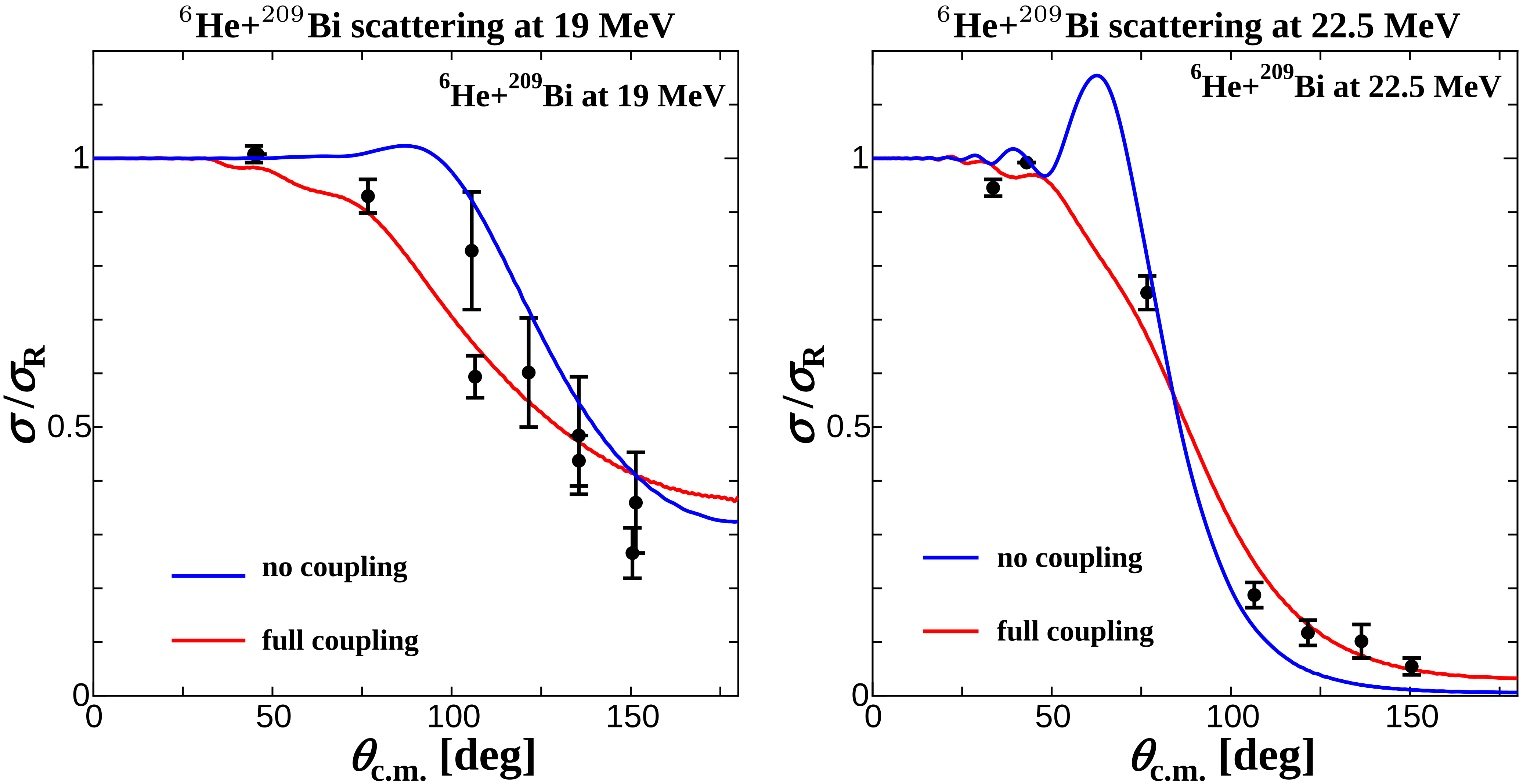
n–^{209}Bi potential : $V_{nT}(\boldsymbol{r}_n)$

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

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

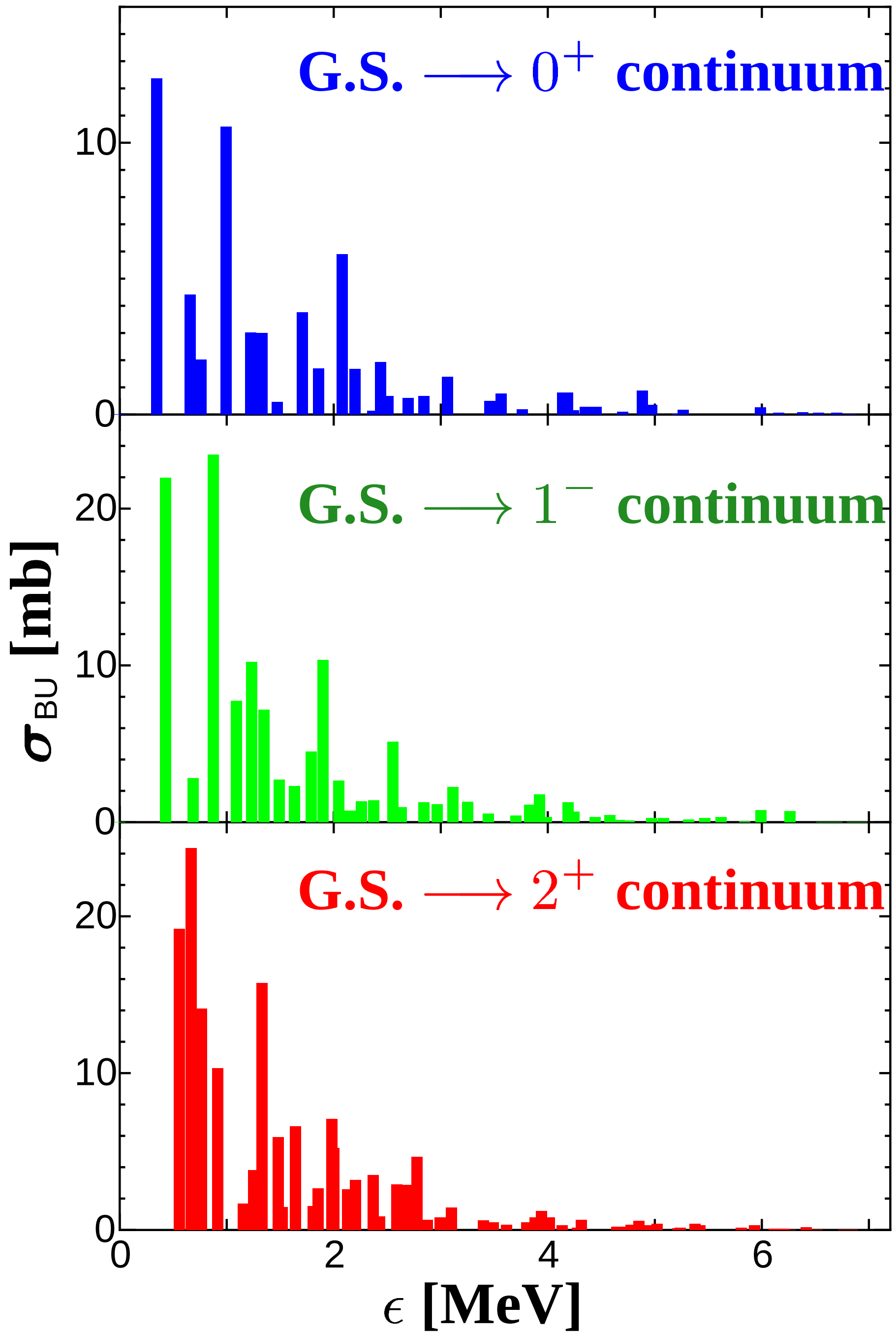


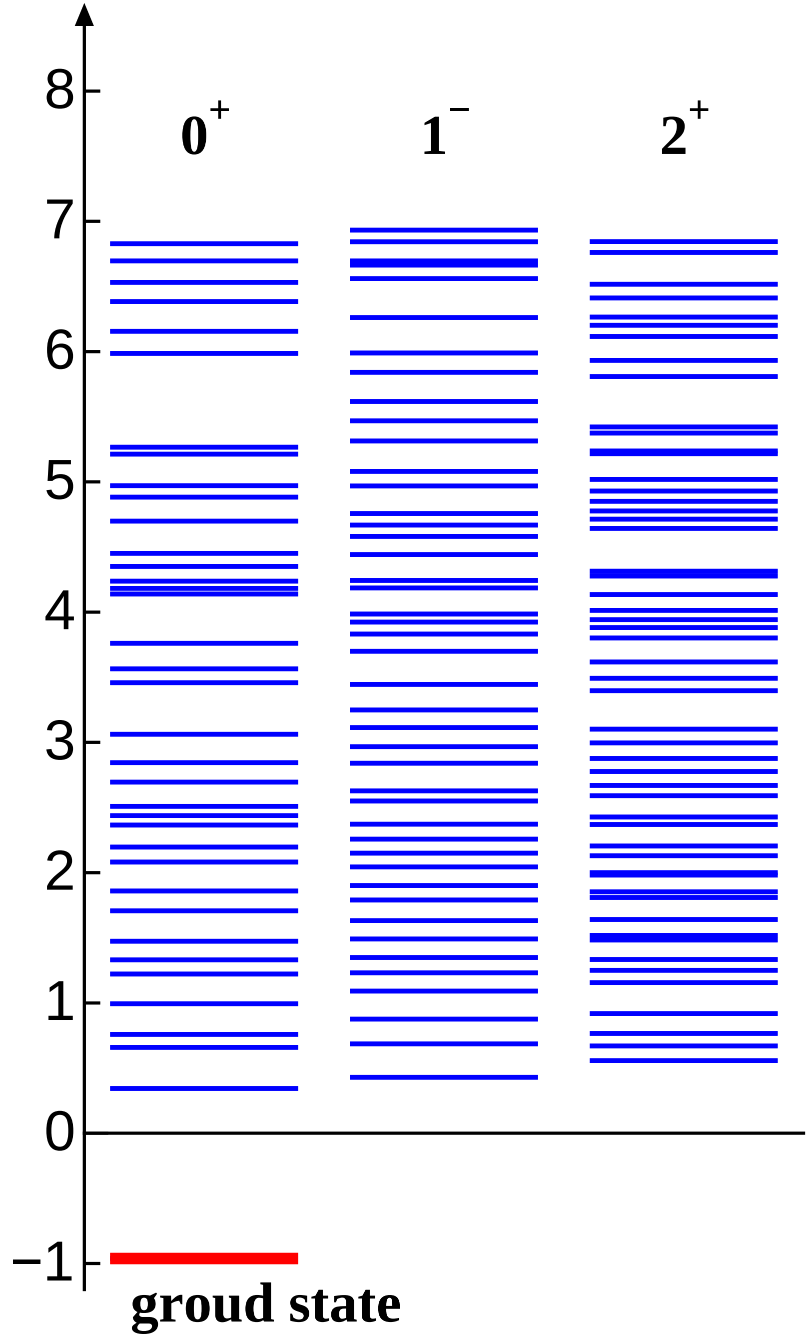
Angular Distribution of Elastic Cross Section



The four-body CDCC calculation well reproduces the data.

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



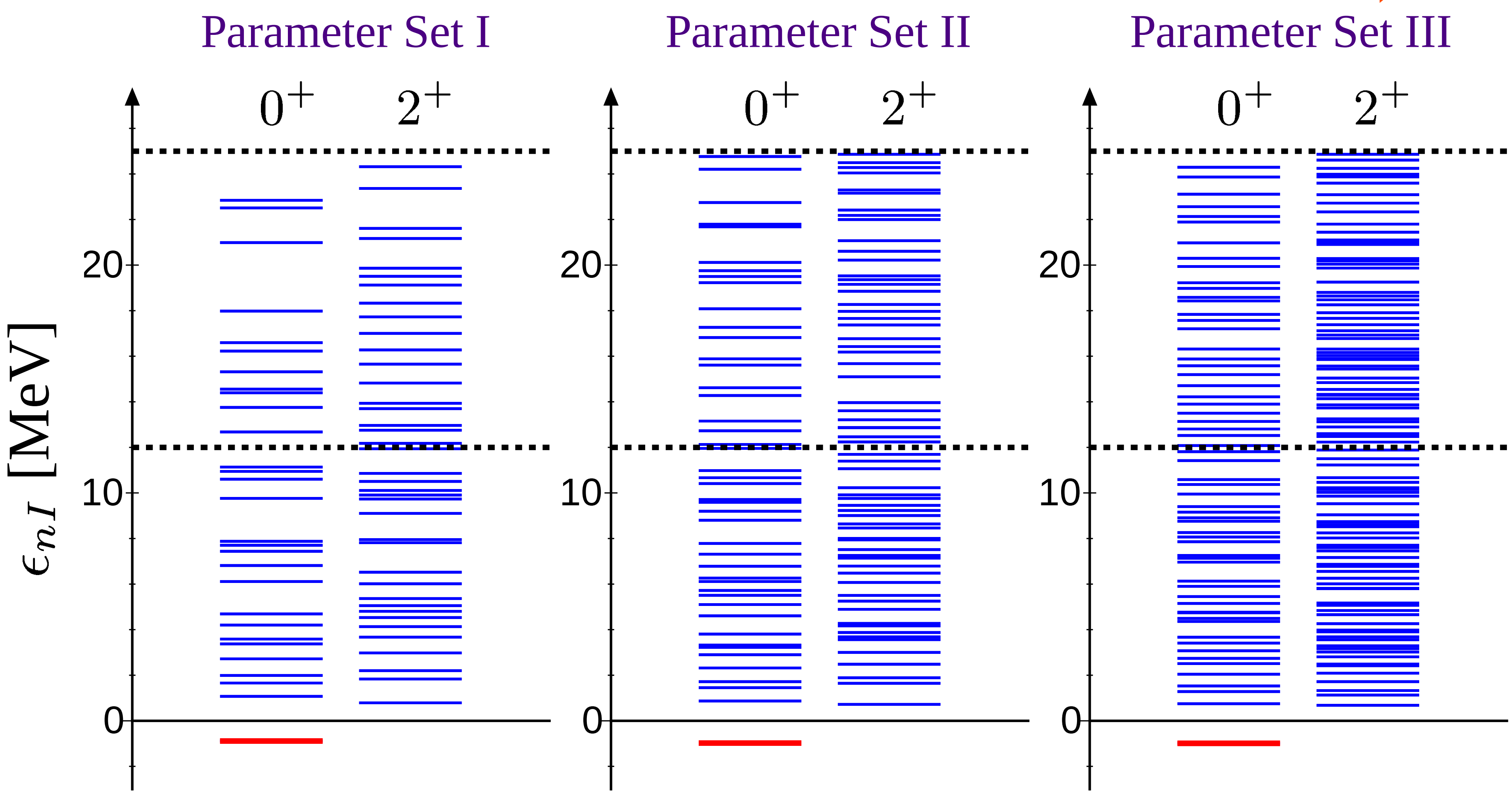


Summary

- **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 method 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.**

Convergence of Four-Body CDCC Solution I

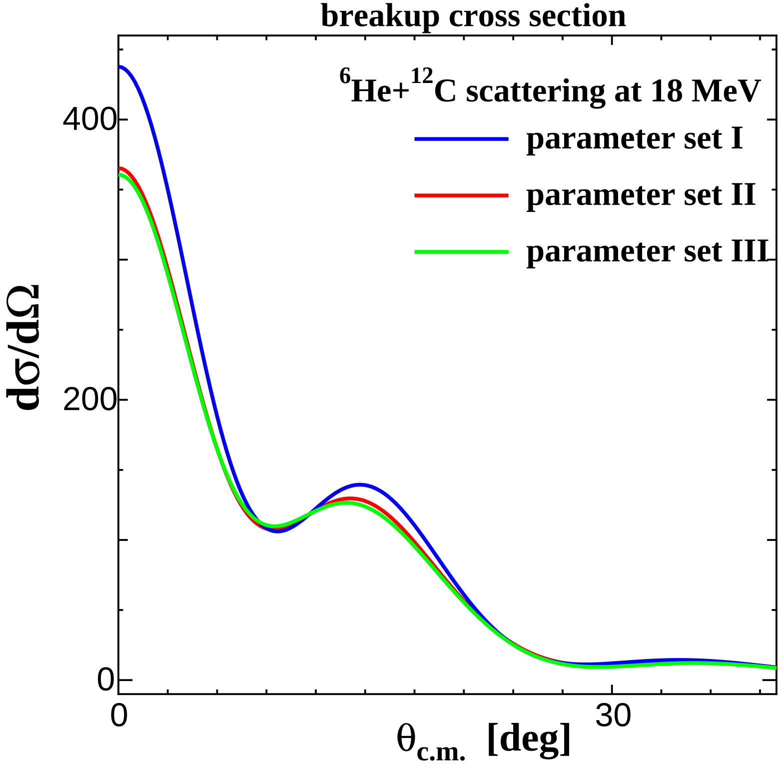
increase the number of the Gaussian basis functions

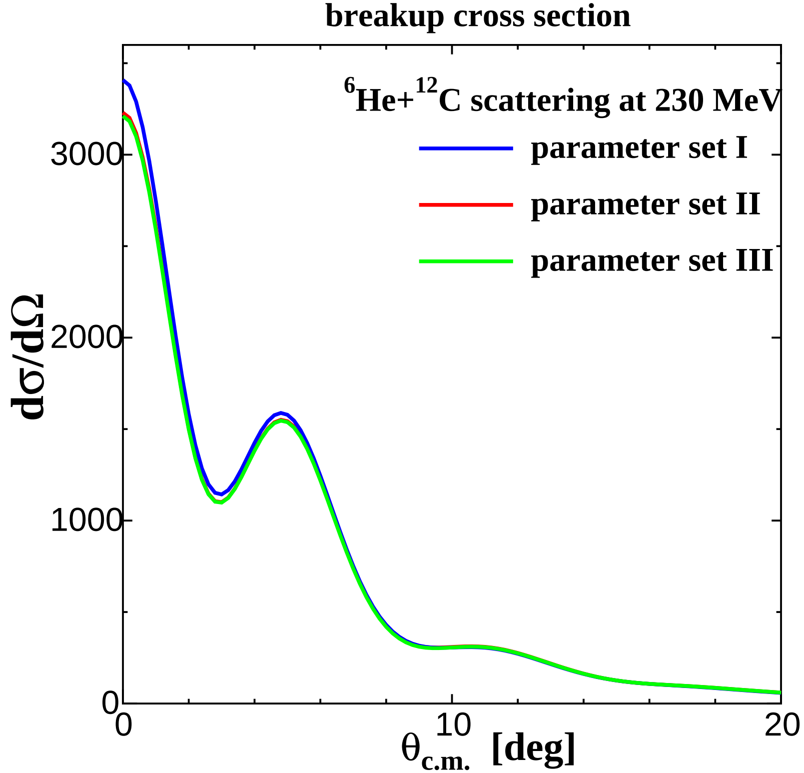


Convergence of Four-Body CDCC Solution II

Total Breakup Cross Section

	18 MeV	229.8 MeV
parameter set I	0^+: 17 state, 2^+: 21 state	0^+: 28 state, 2^+: 39 state
parameter set II	0^+: 25 state, 2^+: 32 state	0^+: 44 state, 2^+: 64 state
parameter set III	0^+: 32 state, 2^+: 42 state	0^+: 60 state, 2^+: 85 state





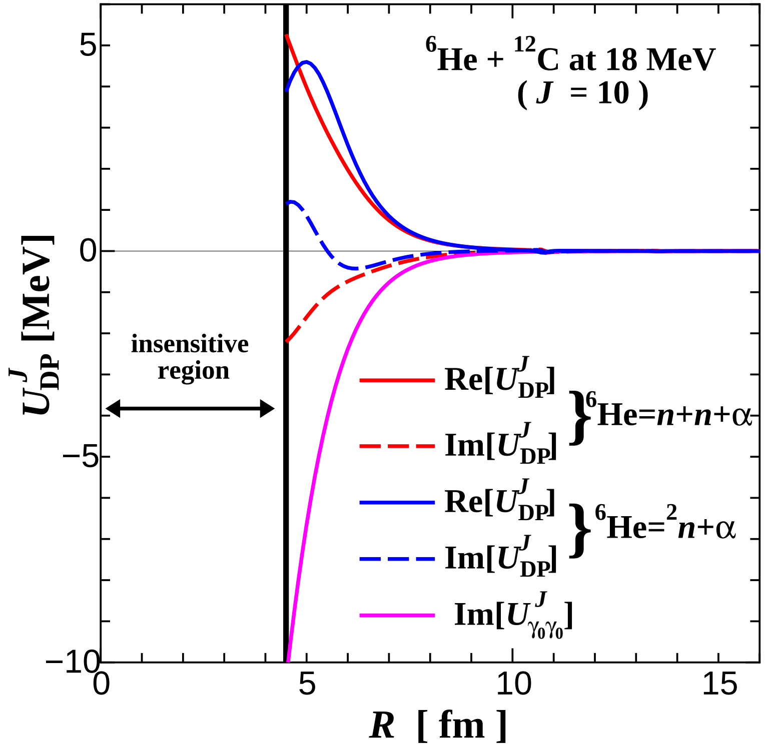
Dynamical Polarization Potential

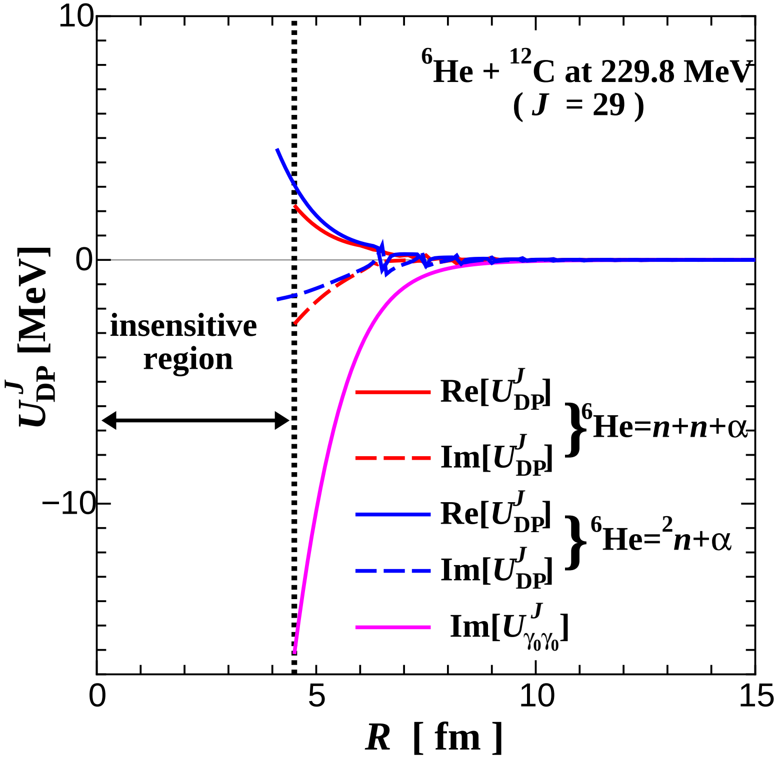
Coupled-Channels Equation

$$[T_R + V_{\gamma_0\gamma_0}(\mathbf{R}) - (E - \epsilon_{\gamma_0})]\,\chi_{\gamma_0}(\mathbf{R}) = -\sum_{\gamma\neq\gamma_0} V_{\gamma_0\gamma}(\mathbf{R})\chi_\gamma(\mathbf{R})$$

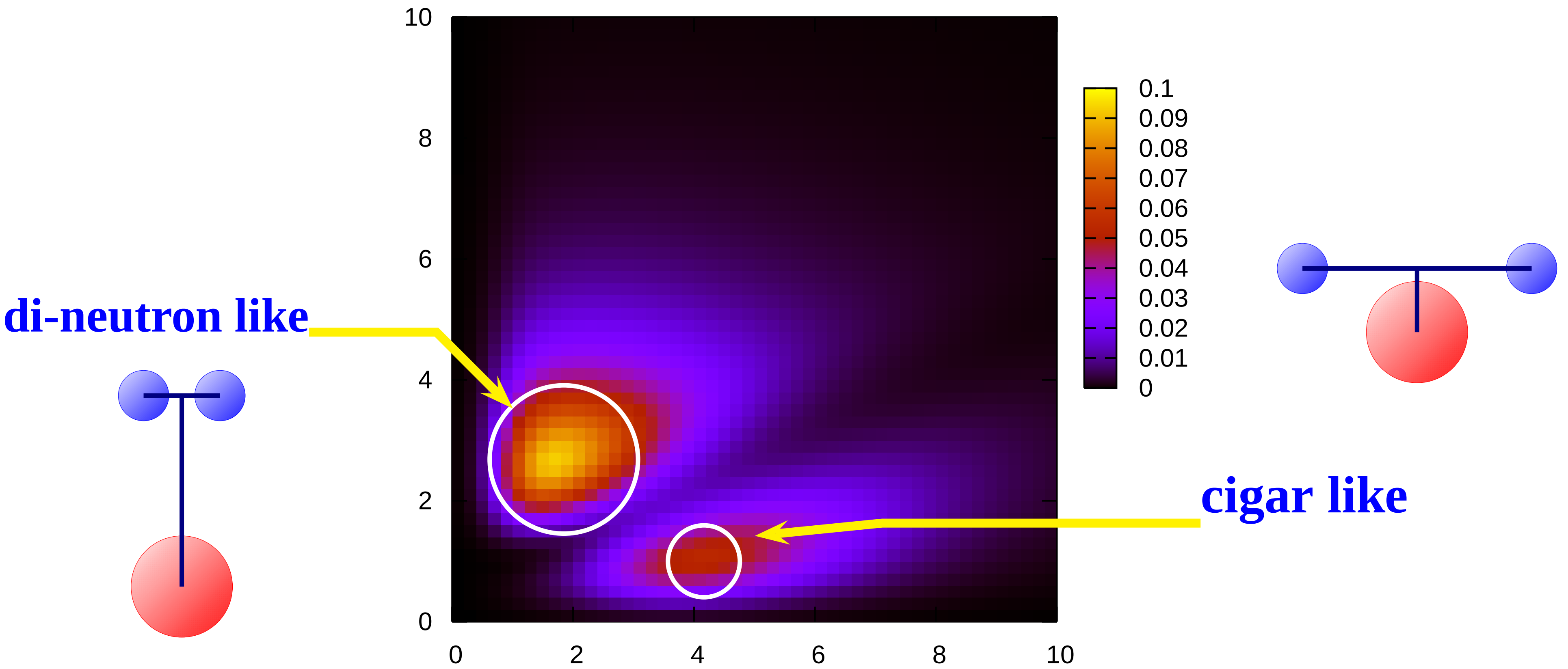
$$[T_{\mathbf{R}} + V_{\gamma_0\gamma_0}(\mathbf{R}) + U_{\mathrm{DP}}(\mathbf{R}) - (E - \epsilon_0)]\,\chi^{(J)}_{\gamma_0}(\mathbf{R}) = 0$$

$$U_{\mathrm{DP}}(\mathbf{R}) = \frac{\sum_{\gamma\neq\gamma_0} V_{\gamma_0\gamma}(\mathbf{R})\chi_\gamma(\mathbf{R})}{\chi_{\gamma_0}(\mathbf{R})}$$

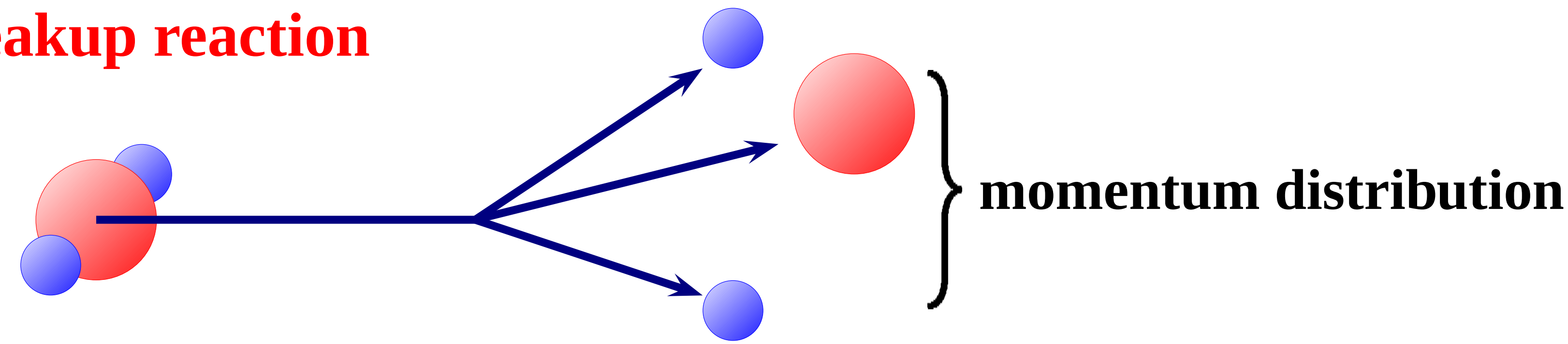




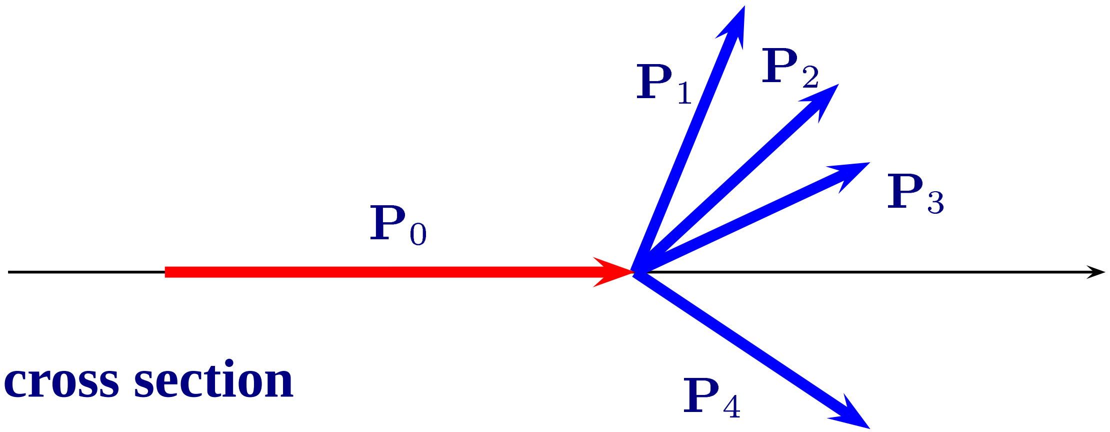
Three-Body Breakup Cross Section



^{6}He breakup reaction



Quintuple Differential Cross Section



- **Quituple differential cross section**

$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 d\Omega_3 dE_1 dE_2} \sim \frac{2\pi}{\hbar}\frac{\mu_R}{P_0}\boldsymbol{\rho}(\boldsymbol{E_1},\boldsymbol{E_2})\left|\sum_{Im} T_{Im}(\mathbf{k},\mathbf{K},\mathbf{P})\right|^2$$

- T**-matrix**

$$\begin{aligned} T_{Im}(\mathbf{k},\mathbf{K},\mathbf{P}) &= \sum_{LJM}\langle \Phi_{Im}\chi^J_{LIM}|U|\Psi_{JM}\rangle \\ &\approx \sum_{LJM}\sum_n \langle \Phi_{Im}|\hat{\Phi}_{Im}\rangle\langle\hat{\Phi}_{Im}\chi^J_{LIM}|U|\Psi_{JM}\rangle \\ &\approx \sum_n F_{nIm}(\mathbf{k},\mathbf{K})\hat{T}^{\mathbf{CDCC}}_{Im} \end{aligned}$$