New Description of Four-body Breakup Reactions

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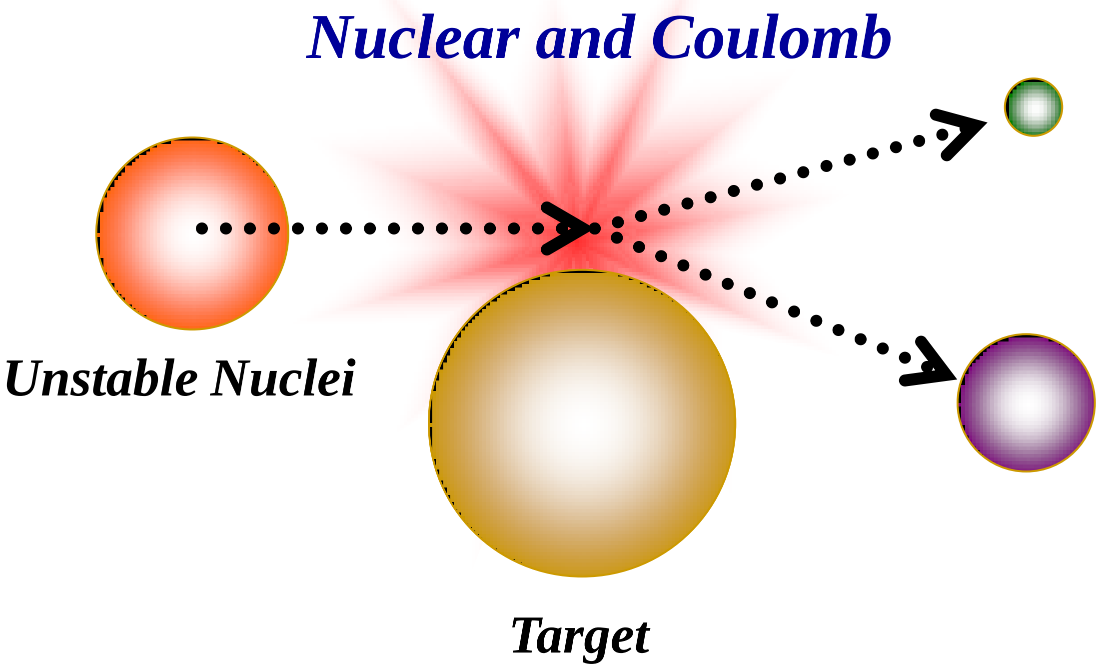
Introduction

- **The unstable nuclear structure can be efficiently investigated via the breakup reactions.**



- **Inelastic cross section**
- **Breakup cross section**
- **Momentum distribution of emitted particles**

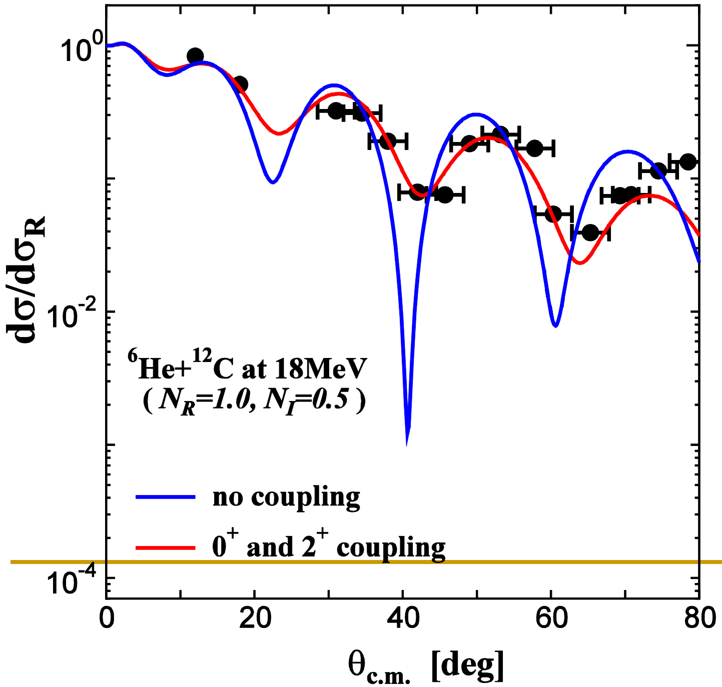
Structure information

- **An accurate method of treating breakup processes is needed.**

Continuum-Discretized Coupled-Channels

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

    M. Kamimura, et al., PTP Suppl. 89, 1 (1986)
  - **Successful for analyses of nuclear and Coulomb breakup reactions**
  - **Continuum breakup states are described by a finite number of discretized states**
  - **Extended to describing four-body breakup (Three-body projectile)**



- **^{6}He induced reaction is a typical example of four-body breakup systems.**
- **^{6}He is described as n+n+^{4}He three-body model**
- **CDCC calculation well reproduce experimental data for *elastic scattering***

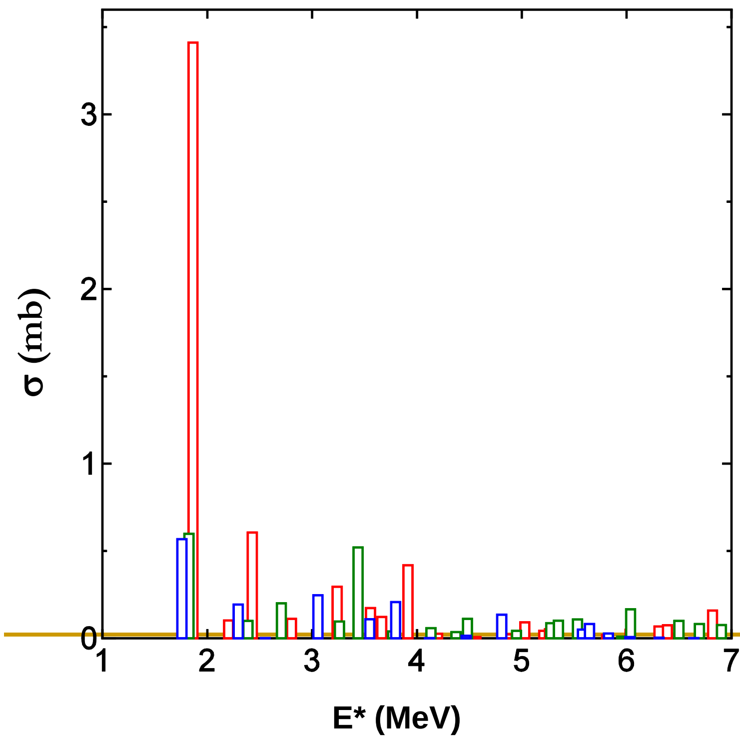
Breakup Cross Section

How to calculate the continuum breakup cross section

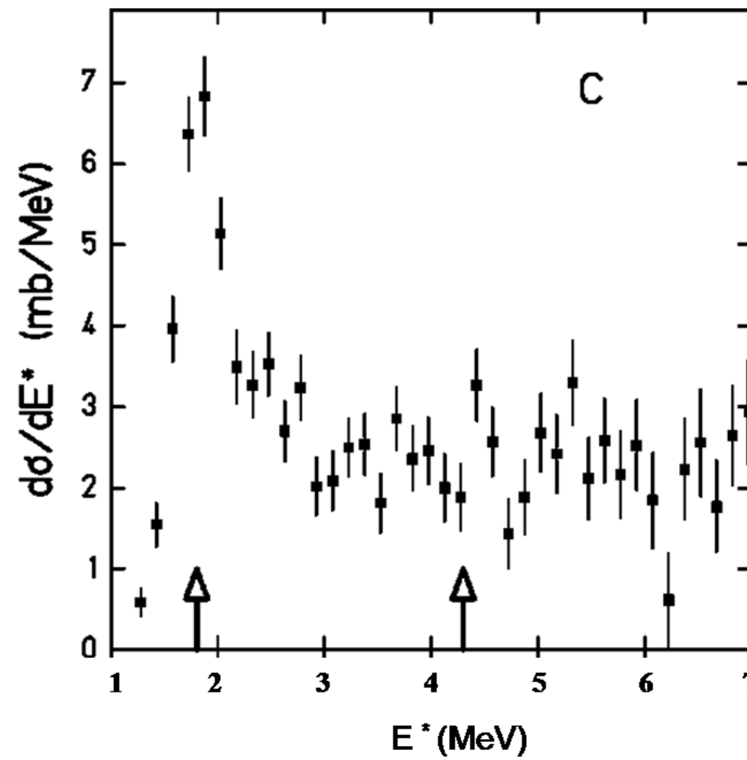
Breakup cross sections calculated by CDCC are discrete in the internal energy of the projectile.

$^{6}He+^{12}C$ scattering at 240 MeV/nucl.

4-body CDCC calc.



PRC59, 1252(1999), T. Aumann *et al*.



New Smoothing Procedure with *CSM*

Final state of the projectile

$$\begin{aligned} T(E) &= \langle \psi^{(-)}(E,\xi)\chi_{\rm C}^{(-)}(\mathbf{R})|V|\Psi^{(+)}(\xi,\mathbf{R})\rangle \\ &\approx \sum_n \langle \psi^{(-)}(E,\xi)|\Phi_n\rangle\langle\Phi_n\chi_{\rm C}^{(-)}(\mathbf{R})|V|\Psi^{(+)}(\xi,\mathbf{R})\rangle \\ &\approx \sum_n \langle \psi^{(-)}(E,\xi)|\Phi_n\rangle T_n^{\rm CDCC} \end{aligned}$$

A set of discretized states

Differential breakup cross section

$$\frac{d\sigma}{dE} = \int T^\dagger(E')T(E')\delta(E-E')dE' = \frac{1}{\pi}{\rm Im}\mathcal{R}(E)$$

Response function

$$\mathcal{R}(E) = \sum_{i,j} T_i^{\rm CDCC\dagger}\langle\Phi_i|\mathcal{G}^{(-)}|\Phi_j\rangle T_j^{\rm CDCC}$$

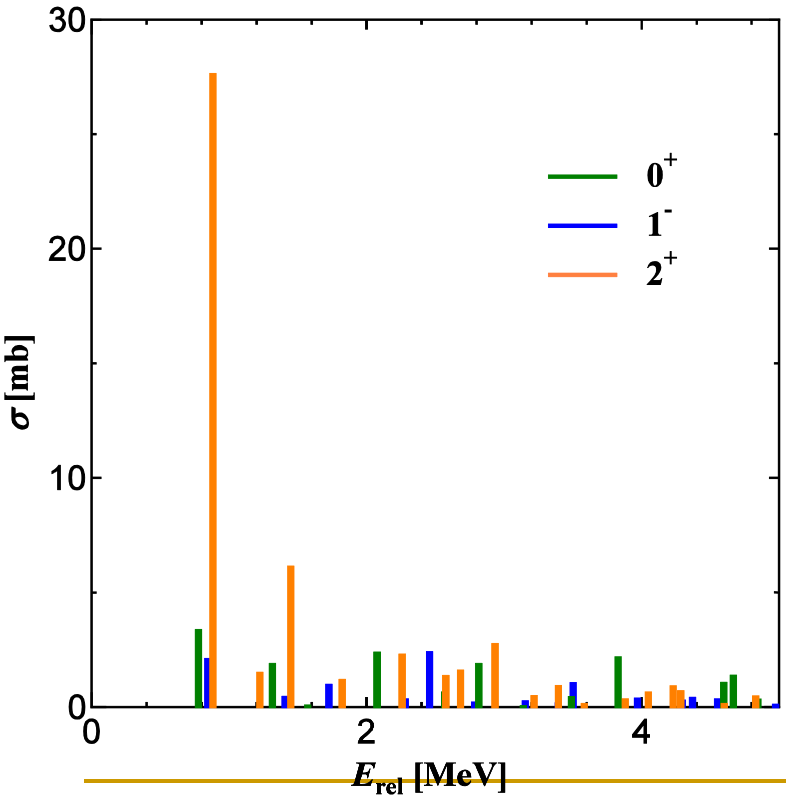
Green's function with Complex-Scaling Method (CDCS Green's function)

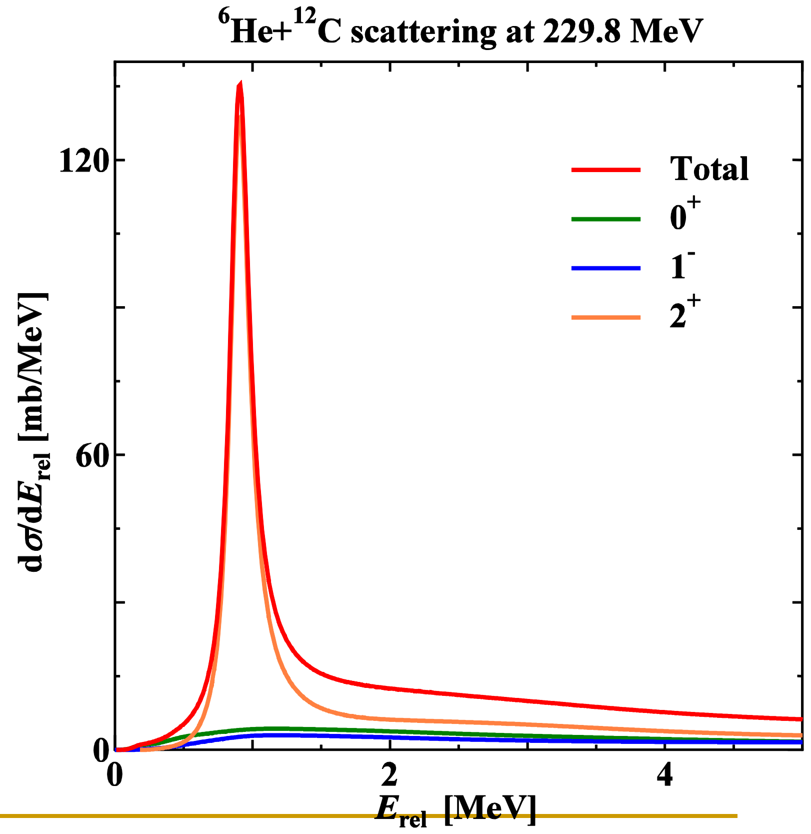
$$\mathcal{G}^{(-)} = U^{-\theta}\frac{1}{E-h^\theta-i\epsilon}U^\theta \approx \sum_\nu U^{-\theta}\frac{|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|}{E-E_\nu^\theta}U^\theta$$

Differential Breakup Cross Section

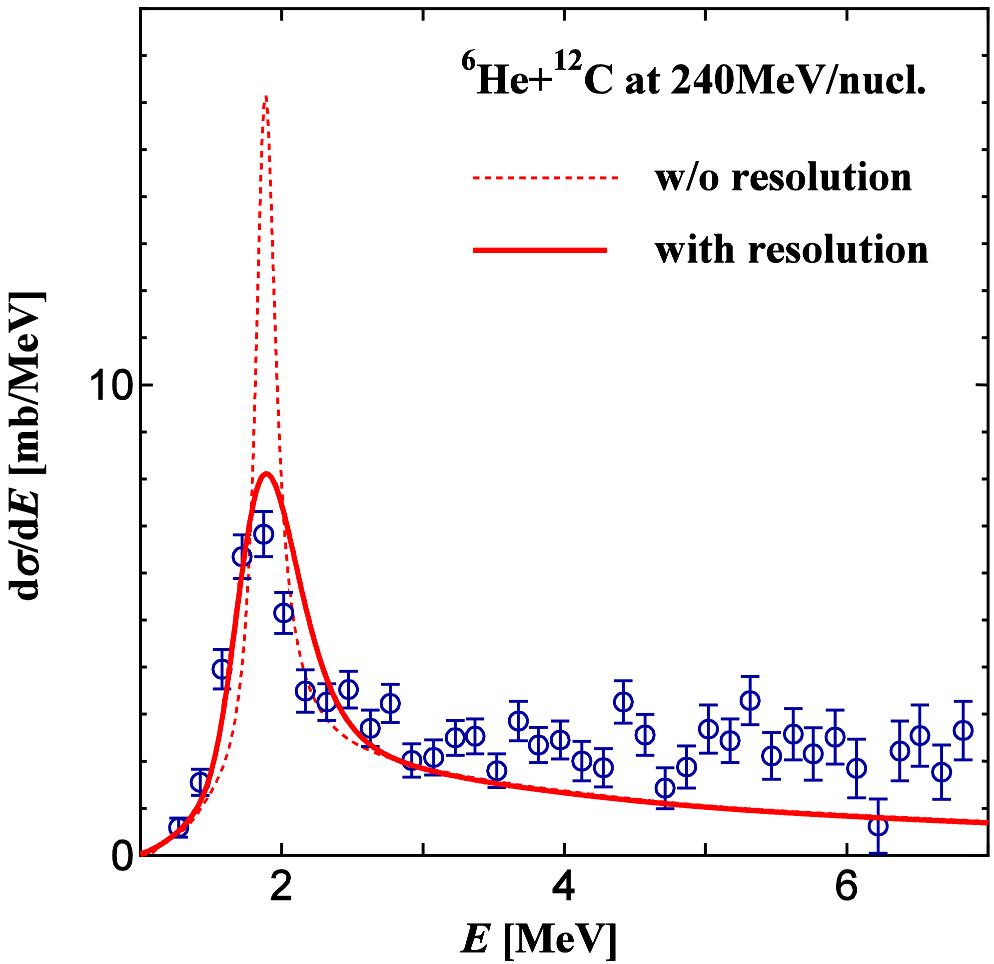
New description of differential breakup cross section

$$\frac{d\sigma}{dE} = \frac{1}{\pi}\mathrm{Im}\sum_{\nu}\sum_{i,j} T_i^{\mathrm{CDCC}\dagger}\frac{\langle\Phi_i|U^{-\theta}|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|U^\theta|\Phi_j\rangle}{E-E_\nu^\theta}T_j^{\mathrm{CDCC}}$$





$^{6}He+^{12}C$ scattering @ 240 MeV/nucl.



Coupling potential:

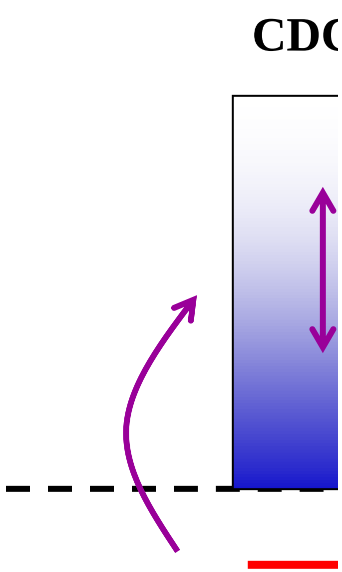
- **N-^{12}C potential folded with ^{6}He transition densities**
- **Without Coulomb breakup**

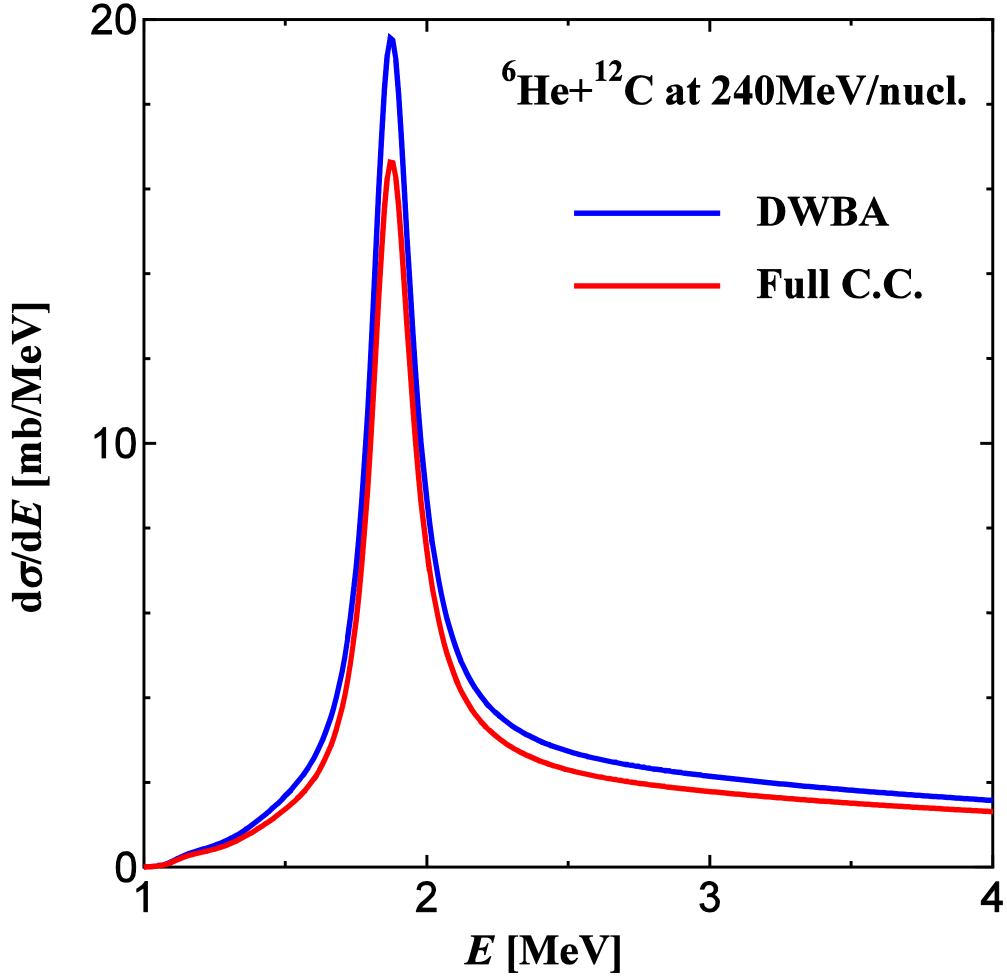
Calculation:

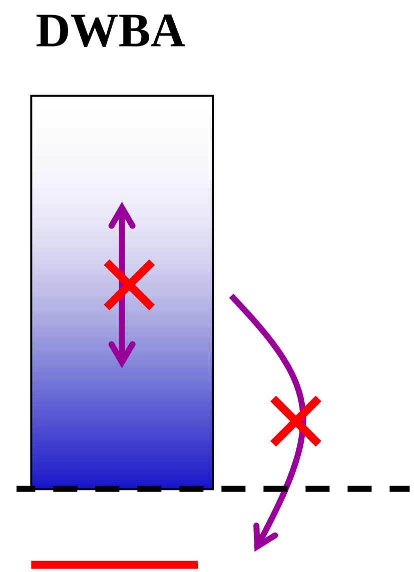
- **non-relativistic**
- **Coupled-channel calculation**

Exp. data from PRC59, 1252 (1999), T. Aumann *et al.*

Coupling Effects



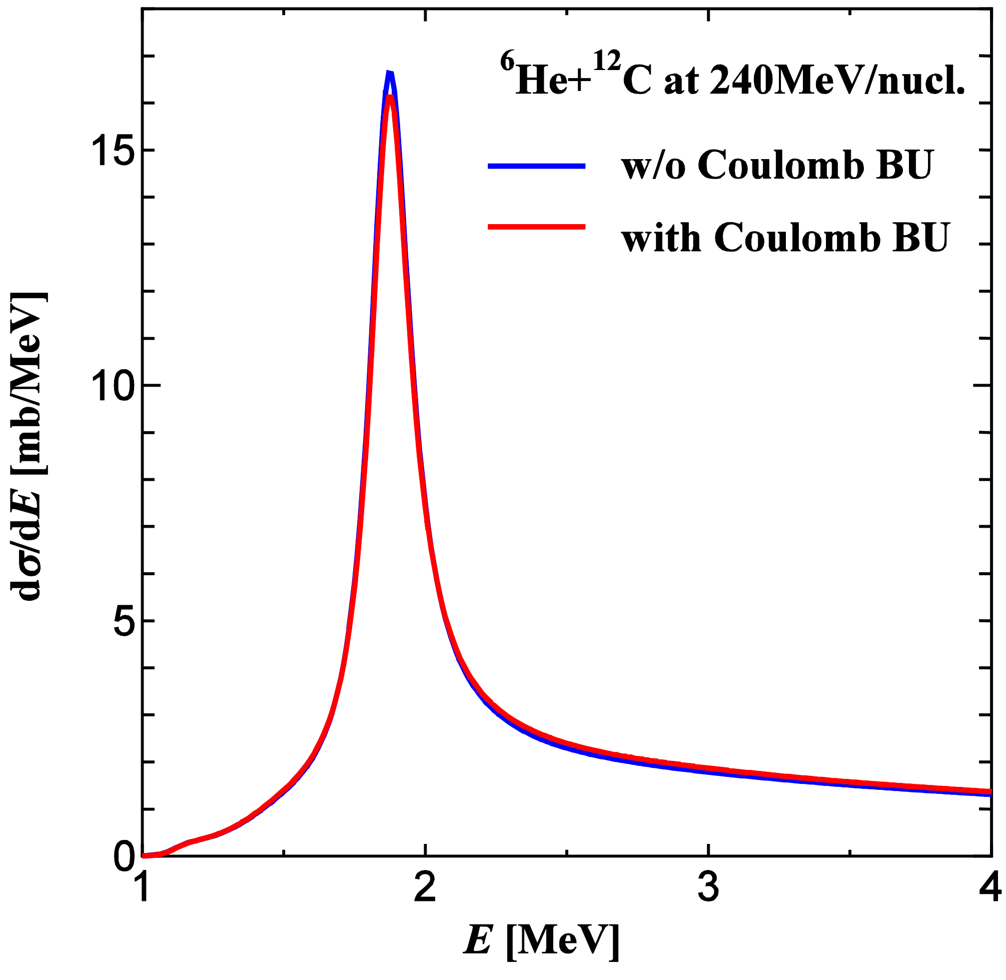




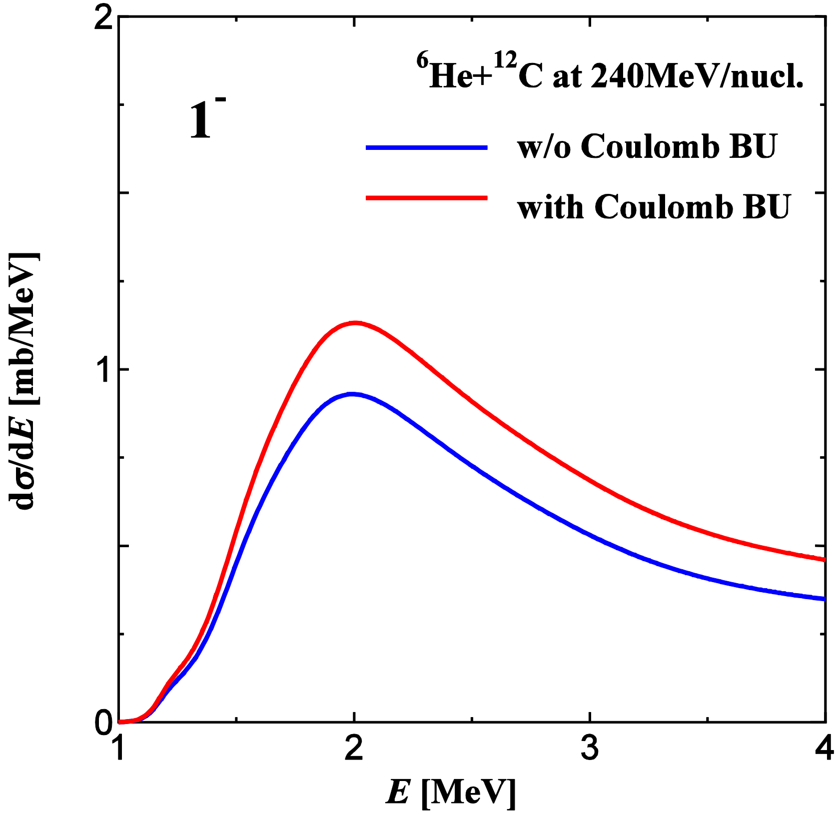
Including all coup ... **uum-continuum and**
(continuum-conti ... **nd couplings**

DWBA overestimates the breakup cross section calculated by CDCC.
Continuum-continuum coupling effects are not negligible.

Coulomb Breakup Effects

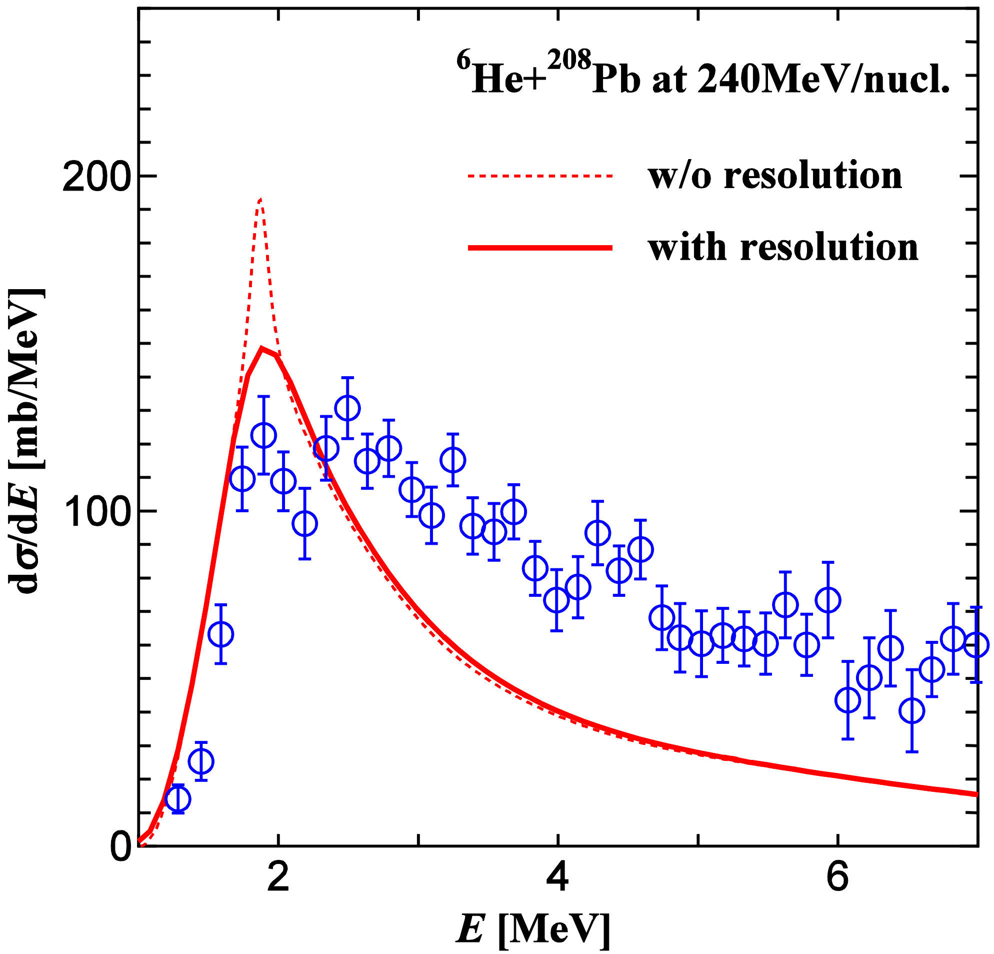


Coulomb breakup effects are negligible.
The effects increase the breakup cross section to 1^{-} continuum.



The Main component of nuclear breakup effects is 2^{+}-continuum states.
For heavy targets, Coulomb breakup is dominant.

^{6}He+^{208}Pb scattering @ 240 MeV/nucl.



Coupling potential:

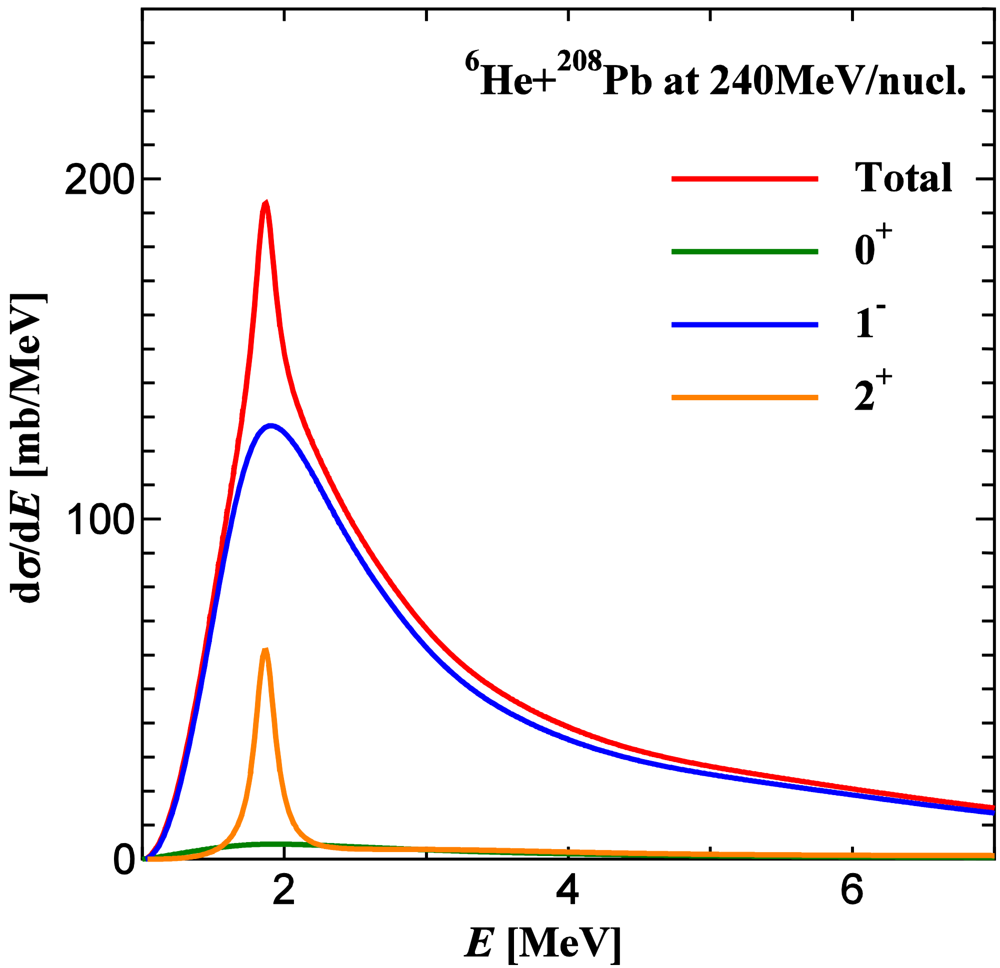
- **N-^{12}C potential folded with ^{6}He transition densities**
- **With Coulomb breakup**

Calculation:

- **non-relativistic calculation.**
- **Distorted Wave Born Approx.**

Exp. data from PRC59, 1252 (1999), T. Aumann *et al.*

Nuclear and Coulomb Breakup



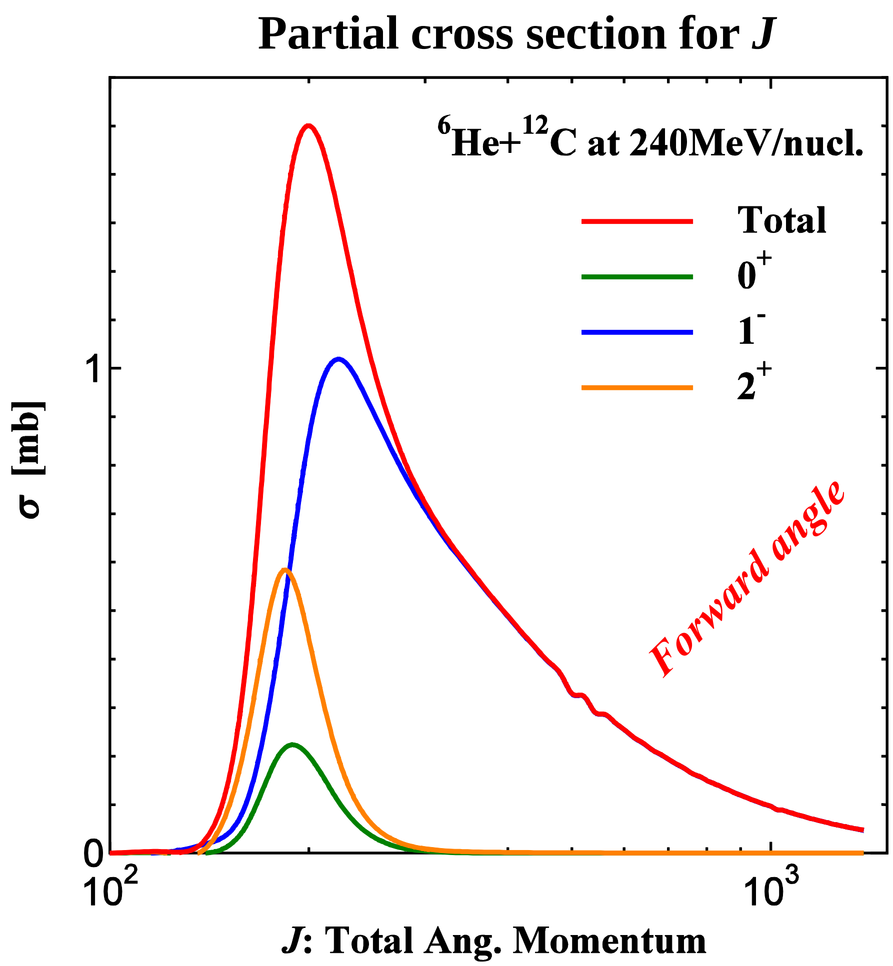
- **Breakup to 1^{-} state is dominant.**
  → Coulomb breakup

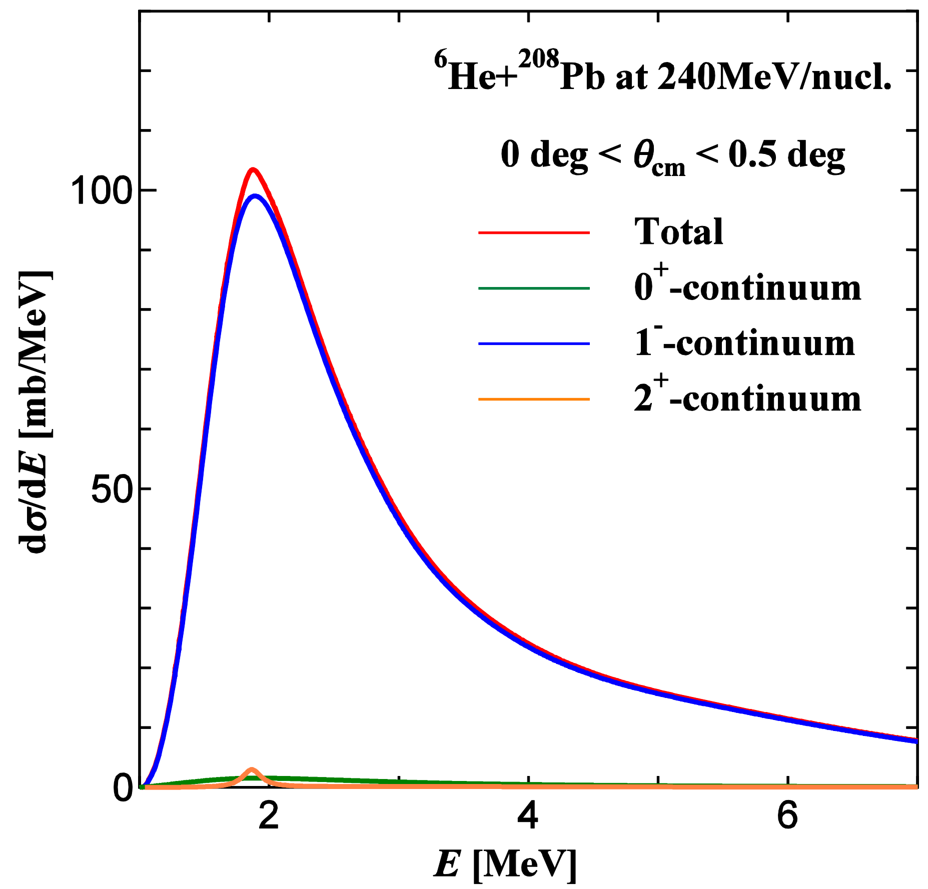
- **Nuclear breakup effects are also significant for 2^{+} resonance.**

Both Nuclear and Coulomb breakup effects should be taken into account.

How to exclude nuclear breakup

Forward Angles





Summary

- **In order to calculate continuum breakup cross sections, we propose a new method with *the complex scaling method*.**

- **The calculated cross section for nuclear and Coulomb breakup can *directly* compare with experimental data.**

- **^{6}He+^{12}C@240MeV/nucl. (CDCC calculation)**
  - **Coulomb breakup effects are negligible.**
  - **Continuum-continuum coupling effects are small but not negligible.**

- **^{6}He+^{208}Pb@240MeV/nucl. (DWBA calculation)**
  - **Coulomb breakup effects are significant.**
  - **At forward angles, nuclear breakup effects are negligible.**