CDCC法による3体・4体分解反応の系統的解析

Systematic Analyses of Three- and Four-Body Breakup Reactions in the CDCC Method

Takuma Matsumoto
(Meme Media Laboratory, Hokkaido University)

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

An accurate method is needed to analyze breakup reactions systematically.
Systematic analyses

- Reactions for various nuclei
  - Projectile (light neutron rich nuclei)
    - one-nucleon halo → Three-body breakup
    - two-nucleon halo → Four-body breakup
      → Continuum-Discretized Coupled-Channel

- Target → proton, light and heavy nuclei

- Wide range of incident energy

- Potentials for nucleon + target, core + target (Subsystem)
  - nucleus target
    → Microscopic Optical Potential (K. Minomo)
  - nucleon target (or neutron induced)
    → Effective interaction (JLM)
The Continuum-Discretized Coupled-Channels method (CDCC)

- Developed by Kyushu group about 20 years ago
  
  M.Kamimura, M.Yahiro, Y.Iseri, Y.Sakuragi, H.Kameyama and M.Kawai, PTP Suppl. 89, 1 (1986)
- Fully-quantum mechanical method
- Successful for analyses of nuclear and Coulomb breakup reactions
- Extended to describing four-body reaction system
  

Essence of CDCC

- Breakup continuum states of the projectile are described by a finite number of discretized states
- A set of eigenstates forms a complete set within a finite model space that is important for breakup processes
Breakup Cross Section

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

\[ ^6\text{He} + ^{12}\text{C} \text{ scattering at 240 MeV/nucl.} \]

4-body CDCC calc.

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

How to calculate the continuum breakup cross section
New Smoothing Procedure with $CSM$


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

$$ T(E) = \langle \psi^-(E, \xi)|\chi_C^-(R)|V|\Psi^+(\xi, R)\rangle $$

**Response function**

$$ R(E) = \int d\xi d\xi'\langle \Psi^+(\xi, R)|V^*|\chi_C^-(R)\rangle R G^-(E, \xi, \xi') \langle \chi_C^-(R)|V|\Psi^+(\xi, R)\rangle $$

**Green’s function with Complex-Scaling Method (CDCS Green’s function)**

$$ G^-(E, \xi, \xi') = U^{-\theta} \frac{1}{E - H^\theta - i\epsilon} U^\theta \approx \sum_{\nu} U^{-\theta} \frac{|\Phi^\nu\rangle \langle \tilde{\Phi}^\nu|}{E - E^\theta_\nu} U^\theta $$

$$ G^-(E, \xi, \xi') \approx \sum_{\nu} \sum_{i,j} |\Phi_i\rangle \frac{\langle \Phi_i|U^{-\theta}|\Phi^\nu\rangle \langle \tilde{\Phi}^\nu|U^\theta|\Phi_j\rangle}{E - E^\theta_\nu} \langle \Phi_j| $$

$$ R(E) = \sum_{\nu} \sum_{i,j} \langle \Psi^+(\xi)|V^*|\chi_C^-(R)\Phi_i\rangle \frac{\langle \Phi_i|U^{-\theta}|\Phi^\nu\rangle \langle \tilde{\Phi}^\nu|U^\theta|\Phi_j\rangle}{E - E^\theta_\nu} \frac{\langle \Phi_j\chi_C^-(R)|V|\Psi^+(\xi)\rangle}{E - E^\theta_\nu} $$

**Final state of the projectile**

**T-matrix calculated by CDCC**
New description of differential breakup cross section

\[
\frac{d\sigma}{dE} = \frac{1}{\pi} \text{Im} \sum_{\nu} \sum_{i,j} T^{\text{CDCC}\dagger}_{i} \langle \Phi_{i} | U^{-\theta} | \Phi_{\nu}^{\theta} \rangle \langle \Phi_{\nu}^{\theta} | U^{\theta} | \Phi_{j} \rangle T^{\text{CDCC}}_{j} \frac{E - E_{\nu}^{\theta}}{E - E_{\nu}^{\theta}}
\]

\[^{6}\text{He} + ^{12}\text{C} \text{ scattering at 229.8 MeV}\]
GEM+MOP+CDCC

Gaussian Expansion Method
E. Hiyama, Y. Kino, M. Kamimura, Prog. Part Nucl. Phys. 51, 223.

Microscopic Optical Potential
K. Minomo.

$^6\text{He} + ^{12}\text{C}$ and $^{208}\text{Pb}$ scattering at 240 MeV/A

Nucleus targets
$n - ^{12}\text{C}$ and $^4\text{He} - ^{12}\text{C}$ potentials
$n - ^{208}\text{Pb}$ and $^4\text{He} - ^{208}\text{Pb}$ potentials
$^6\text{He}+^{12}\text{C}$ scattering @ 240 MeV/nucl.

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

Underestimation $\rightarrow$ Inelastic breakup effect $\sim$ 20%

Nuclear Breakup is dominant
$^6\text{He} + ^{208}\text{Pb}$ scattering @ 240 MeV/nucl.

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

- Underestimation → Inelastic breakup effect
- Overestimation ??

Coulomb Breakup is dominant
GEM+JLM+CDCC

Gaussian Expansion Method
E. Hiyama, Y. Kino, M. Kamimura, Prog. Part Nucl. Phys. 51, 223.

JLM effective interaction

Proton Target (neutron induced reaction)
$^6\text{Li} + n, \, ^6\text{He} + p$
$^6$Li: $d + \alpha$ two-body model

$d, s_d = 1$

\[ r, l \quad V_{d\alpha}(r) = V^C(r) + V^{LS}(r) \]

$^4$He + p + n

\[ 3.6989 \]

$^4$He + d

\[ 1.4743 \]

\[ \text{Y. Sakuragi, M. Yahiro and M. Kamimura, Prog. Theor. Phys. 89, 136 (1986)} \]
**JLM effective interaction**


$$v_{j0}(R_{j0}; \rho, E) = \lambda_v V(\rho, E) \exp \left( -R_{j0}/t_R^2 \right) + i\lambda_w W(\rho, E) \exp \left( -R_{j0}/t_I^2 \right)$$

In generally, $t_R = t_I = 1.2$, $\lambda_v = 1.0$ and $\lambda_w = 0.8$ (single channel calculation)

$\rightarrow \lambda_w$ is optimized

**Coupling potential**

$$V_{\gamma'\gamma}(R) = \int ds \rho_{\gamma'\gamma}(s)v_{j0}(R_{j0}; \rho, E)$$

**Transition density of $^6$Li**

$$\rho_{\gamma'\gamma}(s) = \langle \phi_{i'\ell'}^{I'}(r) \varphi_{\alpha} \varphi_{d} | \sum_{k=1}^{6} \delta(s - r_k) \varphi_{i \ell}^{I}(r) \varphi_{\alpha} \varphi_{d} \rangle$$
Elastic cross section of $^6\text{Li}(n, n)$

- Blue: Single channel calc. (without BU effects)
- Red: Full CC

- The optimized $\lambda_w$ is 0.1.
- Breakup effect is significant

Inelastic cross section

$\frac{d\sigma}{d\Omega_{\text{c.m.}}}$ [mb/sr]

$\theta_{\text{c.m.}}$ [deg]

$3^+\text{-resonance (2.186 MeV)}$

$11.5$ MeV

$14.1$ MeV

$18.0$ MeV

$\frac{d\sigma}{d\Omega_{\text{c.m.}}}$ [mb/sr]

$3.6989$ $^4\text{He} + p + n$

$1.4743$ $^4\text{He} + d$

Neutron spectrum of $^6$Li($n$, $n'$)

New results

$^n_p + ^4$He Breakup?

$E_n$ [MeV] $^6$Li

$^{1}\sigma + n + p$ $^{3}\sigma + n + p$ $^{4}$He+d $^{4}$He+p+n

$1.4743$ $3.6989$ $5.37$ $5.65$ $6.0$ $6.5$ $7.0$ $7.5$ $8.0$ $8.5$ $9.0$ $9.5$ $10.0$

$^{1}$S $^{2}$S $^{3}$S $^{1}$D $^{2}$D $^{3}$D

$^6\text{He} + p$ elastic cross section

OP($p-^4\text{He}$)

Normalization of JLM interaction is 0.5 for the imaginary part.
Inelastic Cross Section to $2^+$

Energy spectral of $^6$He

- $2^+$ resonance
- $n + n + ^4$He threshold
- $0^+$ ground state

![Graph showing energy spectrum of $^6$He with peaks at $2^+$ resonance and $n + n + ^4$He threshold]
Inelastic Cross Section

$^6\text{He} + p$ at 25 MeV/A

GEM + JLM + Four-body CDCC well reproduces the elastic and inelastic data

$^6\text{He} + p$ at 40 MeV/A
$^6\text{Li}: n + p + \alpha$ three-body model

$^6\text{He}$ (T=1) $\rightarrow$ $^6\text{Li}$ (T=0)
Elastic cross section $^6\text{Li}(n, n)$

Red: Four-body CDCC
Blue: Three-body CDCC

$\lambda_w = 0.3$
$\lambda_w = 0.1$

$\rightarrow$ Neutron spectrum
Summary

- Systematic analyses for three-body and four-body breakup reactions
  - Development of the CDCC method
    - Four-body breakup system
    - Calculation of breakup cross section with CSM
  - Using microscopic optical potentials for nucleus targets and JLM effective interactions for nucleon targets

Future Plan

- Three-body BU
- Four-body BU

Neutron drip line

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- Three-body BU
- Four-body BU

Neutron drip line