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

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「微視的核反応理論による物理」
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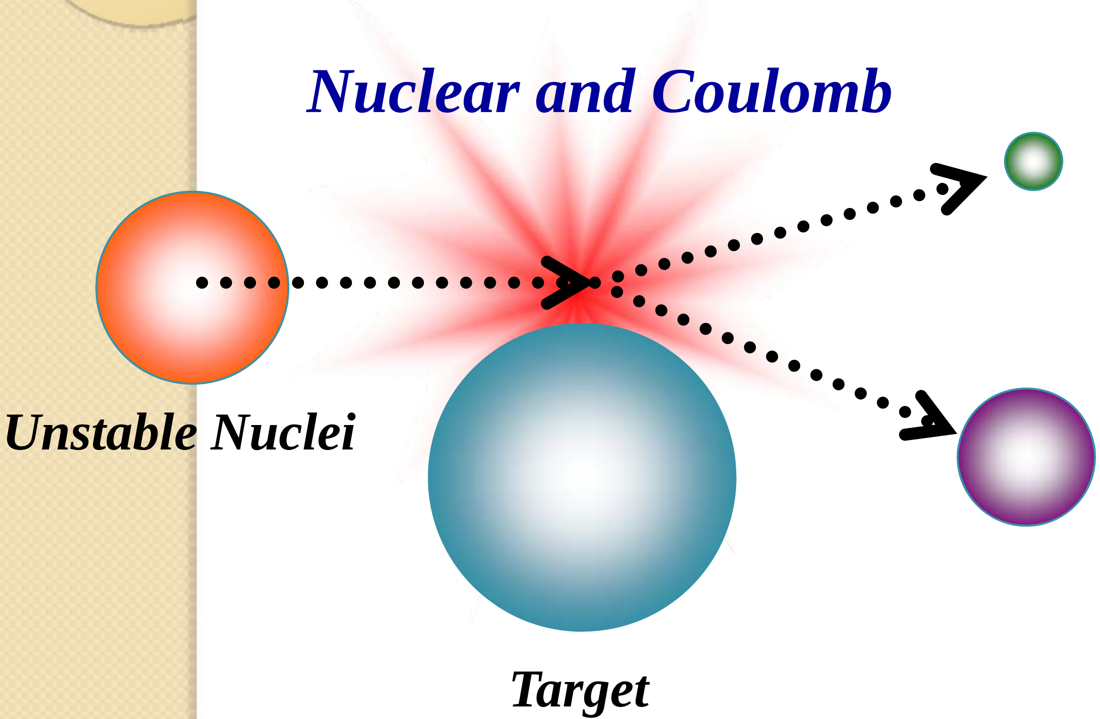
Background

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

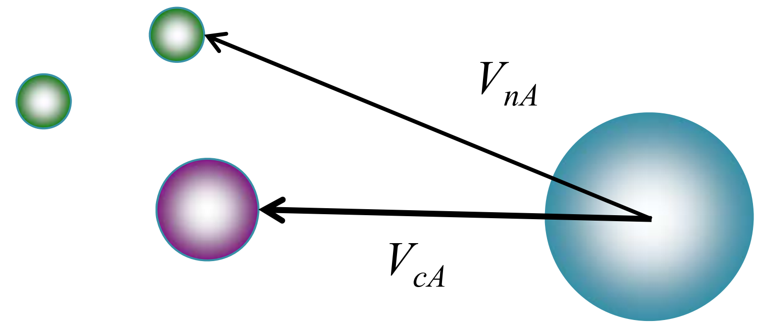


- **Inelastic cross section**
- **Breakup cross section**
- **Momentum distribution of emitted particles**

Structure information

- **An accurate method is needed to analyze breakup reactions systematically.**

Introduction



- **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)

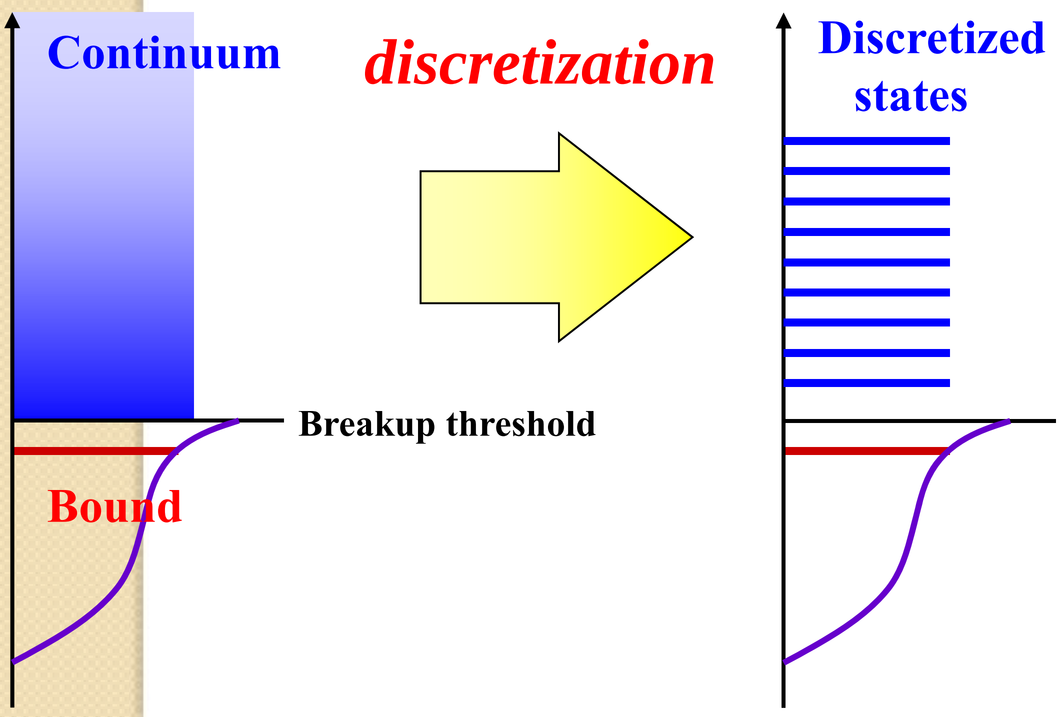
      → Effective interaction (JLM)

Continuum-Discretized Coupled-Channels

- **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**

    T.M., E. Hiyama, K. Ogata, Y. Iseri, M. Kamimura, S. Chiba, M. Yahiro, PRC 70, 061601 (2004).
- **Essence of CDCC**



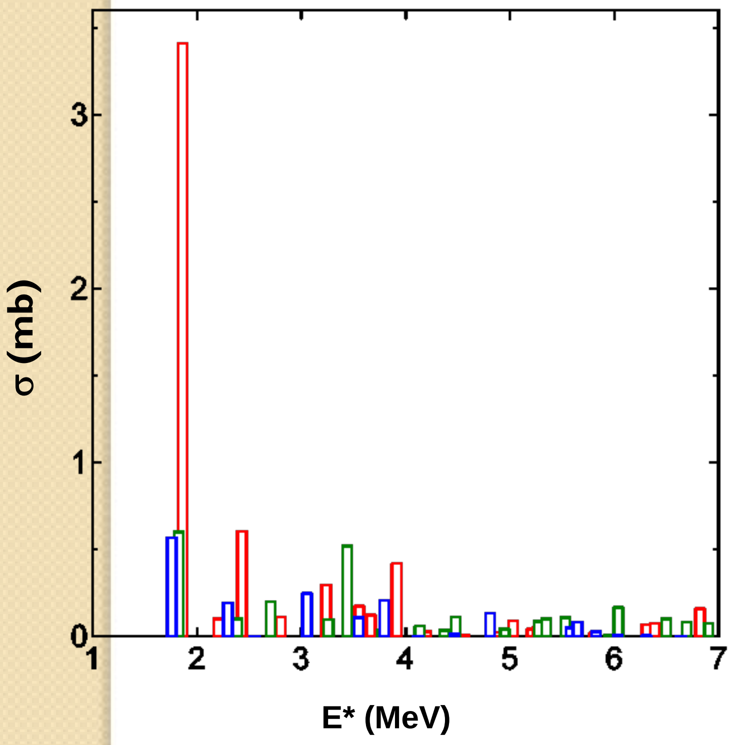
- **Breakup continuum states of the projectile are described by a finite number of discretized states**
- **A set of eigenstates forms a complete set within a finite model space that is important for breakup processes**

Breakup Cross Section

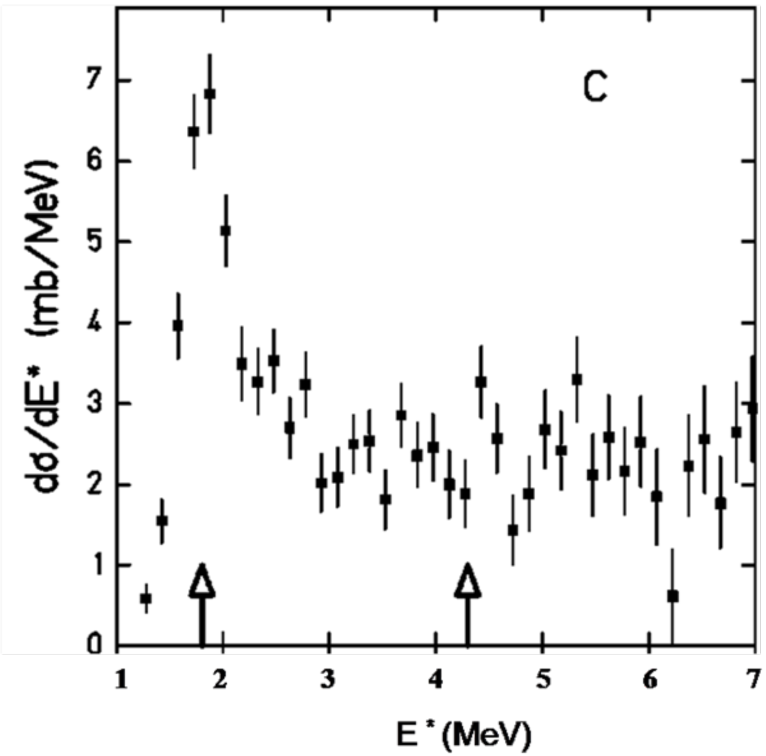
Breakup cross sections calculated by CDCC are discrete in the internal energy of the projectile.

$^{6}He+^{12}C$ 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*

T.M., K. Kato, and M. Yahiro, PRC82, 051602 (2010).

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

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

Final state of the projectile

Response function

$$\mathcal{R}(E) = \int d\xi d\xi' \langle\Psi^{(+)}(\xi,\mathbf{R})|V^*|\chi_C^{(-)}(\mathbf{R})\rangle_{\mathbf{R}}\mathcal{G}^{(-)}(E,\xi,\xi')\langle\chi_C^{(-)}(\mathbf{R})|V|\Psi^{(+)}(\xi,\mathbf{R})\rangle_{\mathbf{R}}$$

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

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

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

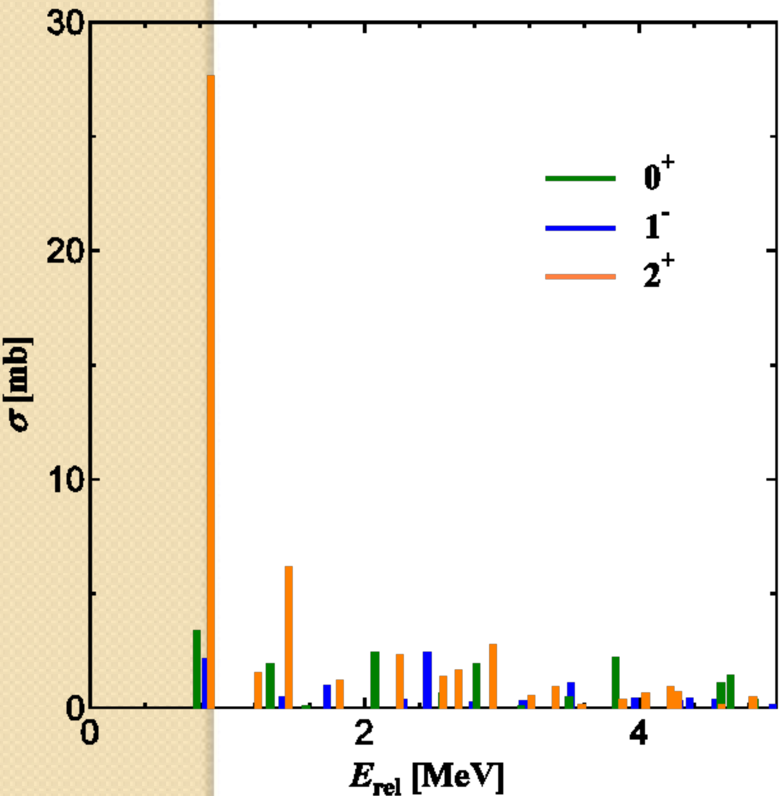
$$\mathcal{R}(E) = \sum_\nu\sum_{i,j}\langle\Psi^{(+)}|V^*|\chi_C^{(-)}\Phi_i\rangle\frac{\langle\Phi_i|U^{-\theta}|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|U^\theta|\Phi_j\rangle}{E-E_\nu^\theta}\langle\Phi_j\chi_C^{(-)}|V|\Psi^{(+)}\rangle$$

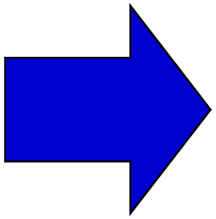
T-matrix calculated by CDCC

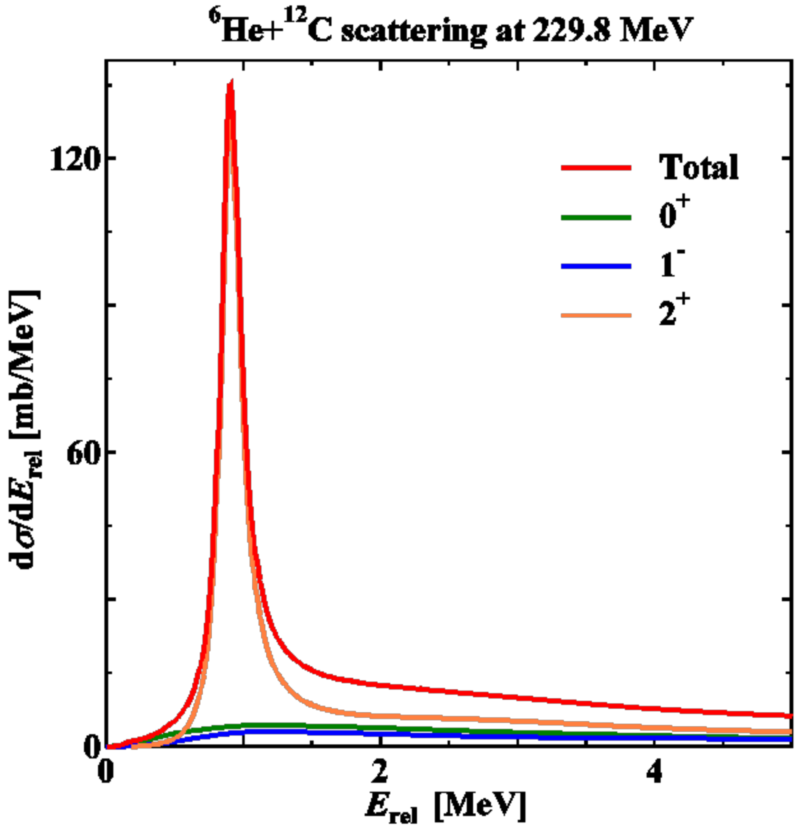
Differential Breakup Cross Section

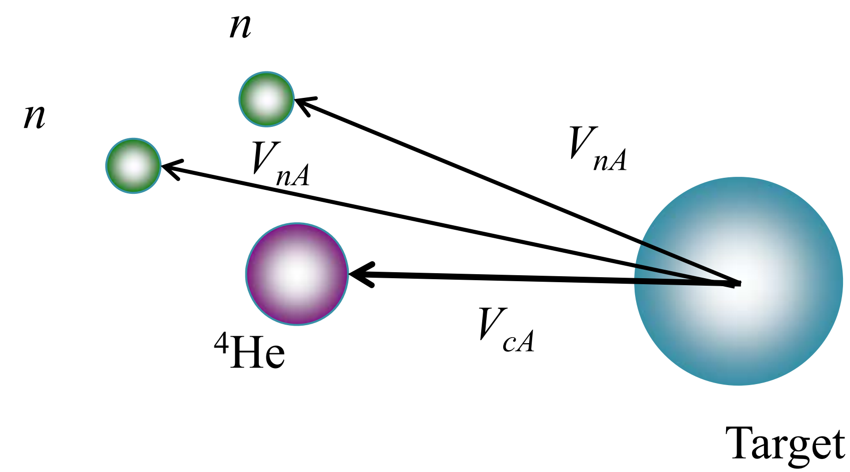
New description of differential breakup cross section

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









GEM+MOP+CDCC

Gaussian Expansion Method

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

Microscopic Optical Potential

K. Minomo.

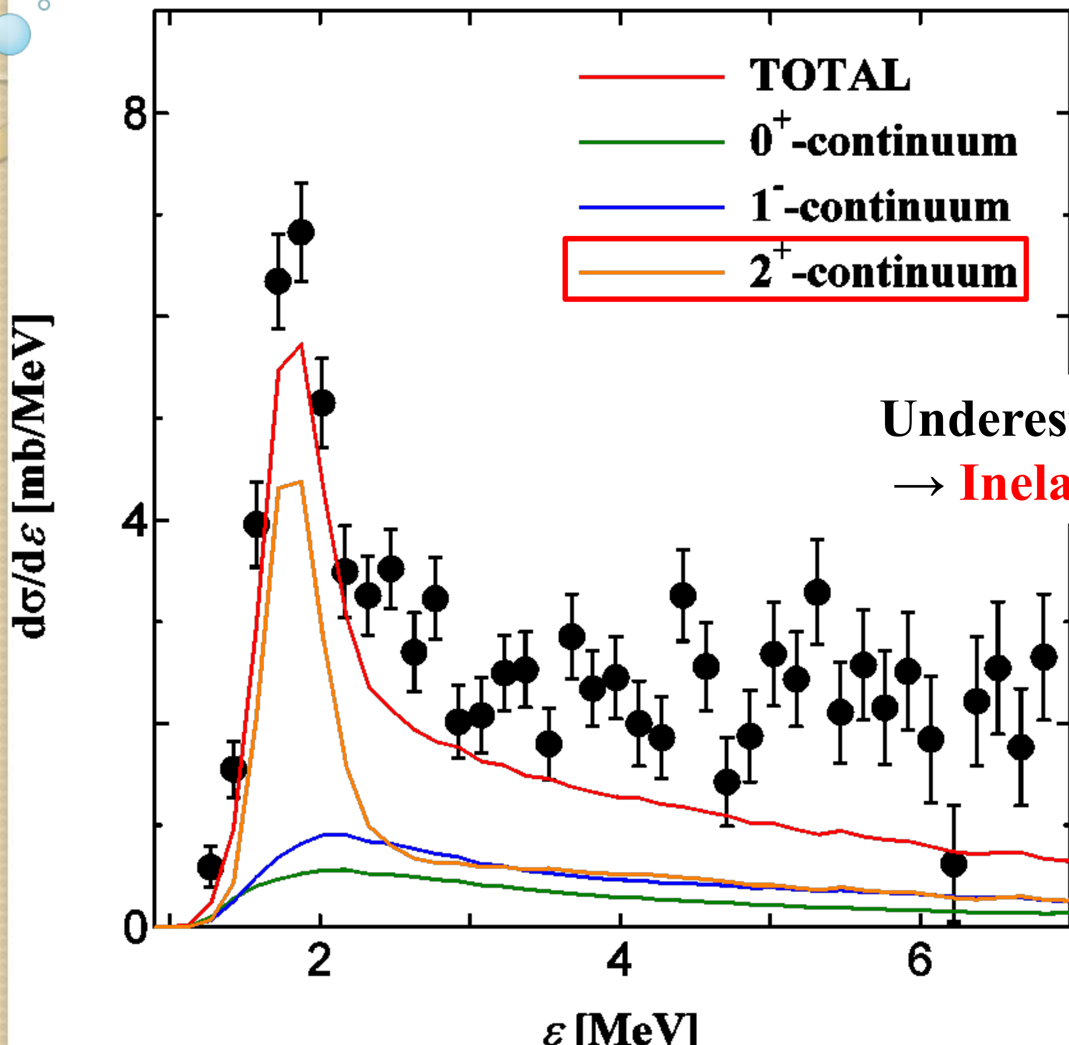
^{6}He + ^{12}C and ^{208}Pb scattering at 240 MeV/A

Nucleus targets

n - ^{12}C and ^{4}He -^{12}C potentials

n – ^{208}Pb and ^{4}He – ^{208}Pb potentials

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

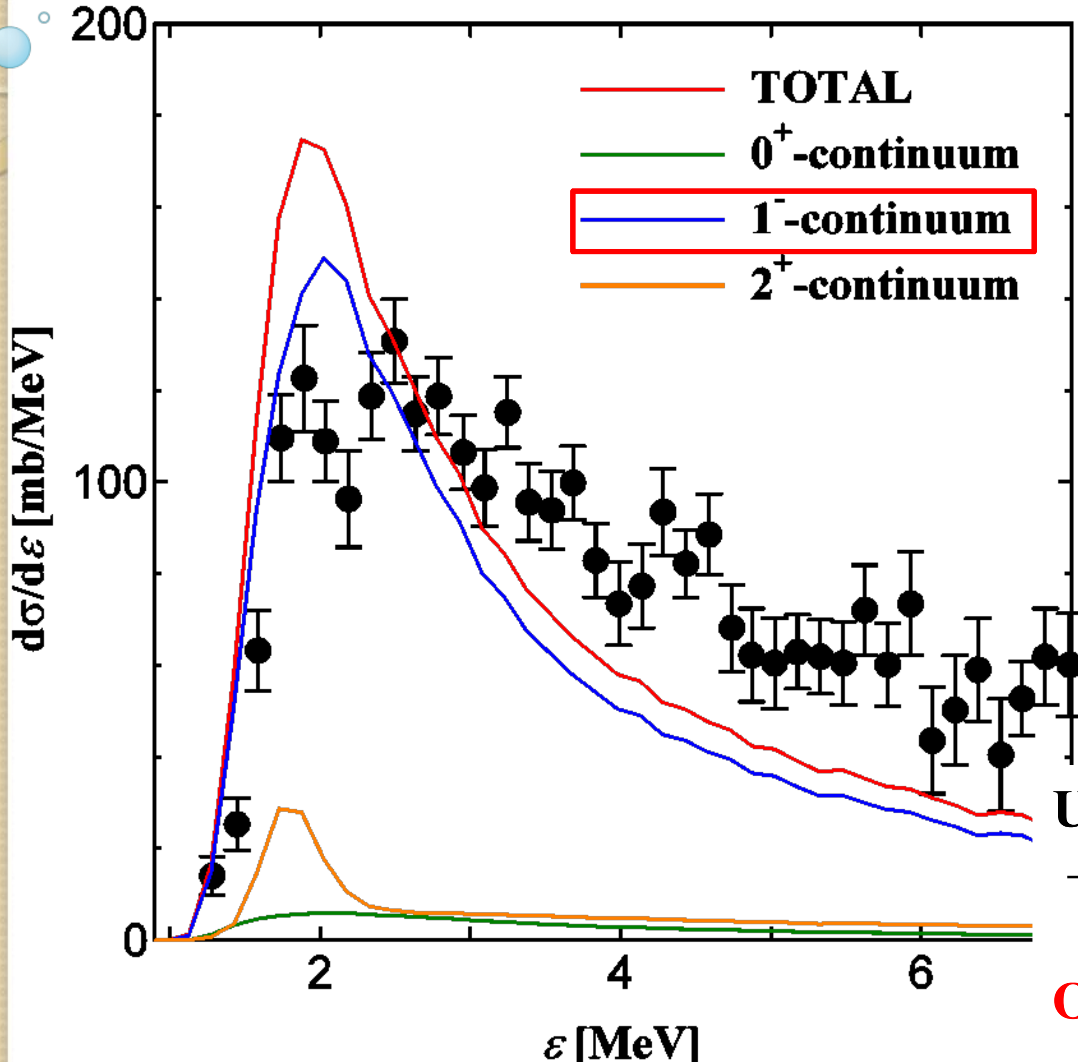


Nuclear Breakup is dominant

Underestimation
→ **Inelastic breakup effect ~ 20%**

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

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



Coulomb Breakup is dominant

Underestimation

→ Inelastic breakup effect

Overestimation ???

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

GEM+JLM+CDCC

Gaussian Expansion Method

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

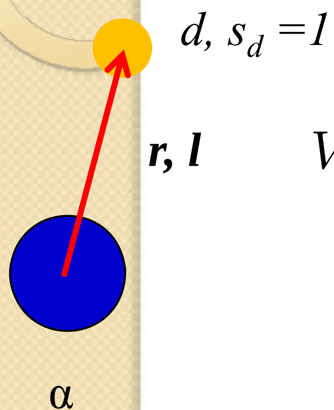
JLM effective interaction

J.-P. Jeukenne, A. Lejeune, and C. Mahaux, Phys. Rev. C16, 80.

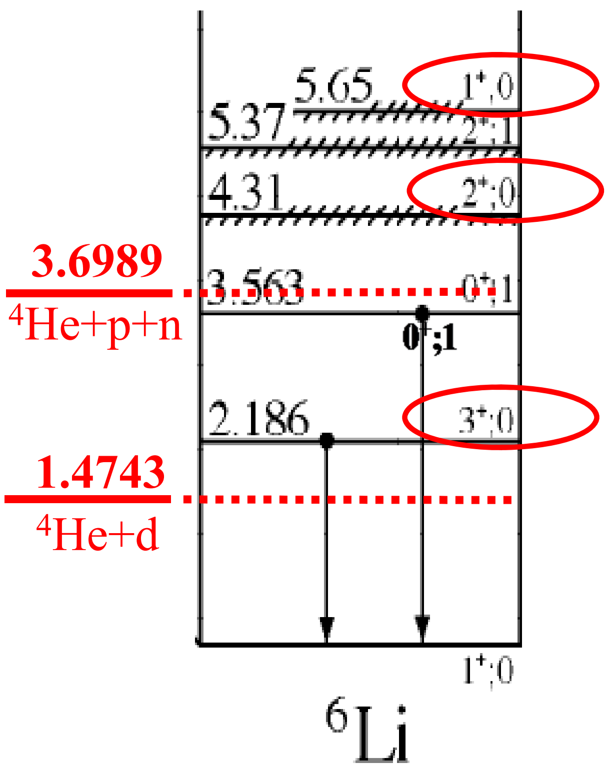
Proton Target (neutron induced reaction)

^{6}Li + *n*, ^{6}He + *p*

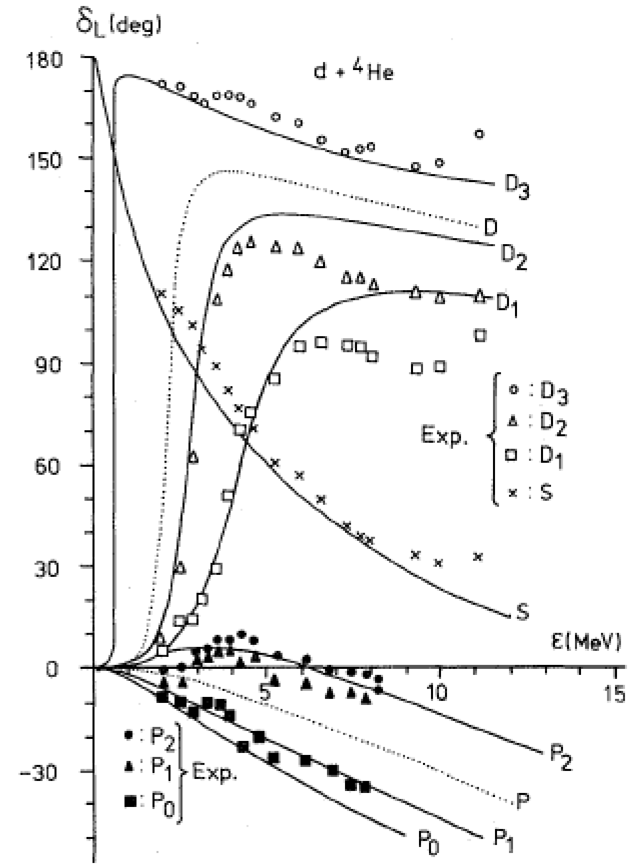
^{6}Li: $d + \alpha$ two-body model



$$V_{d\alpha}(r) = V^{C}(r) + V^{LS}(r)$$



d +^{4}He scattering phase shift



Y. Sakuragi, M. Yahiro and M. Kamimura, Prog. Theor. Phys. 89, 136 (1986)

JLM effective interaction

JLM interaction (J.-P. Jeukenne, A. Lejeune, and C. Mahaux, Phys. Rev. C16, 80 (1977))

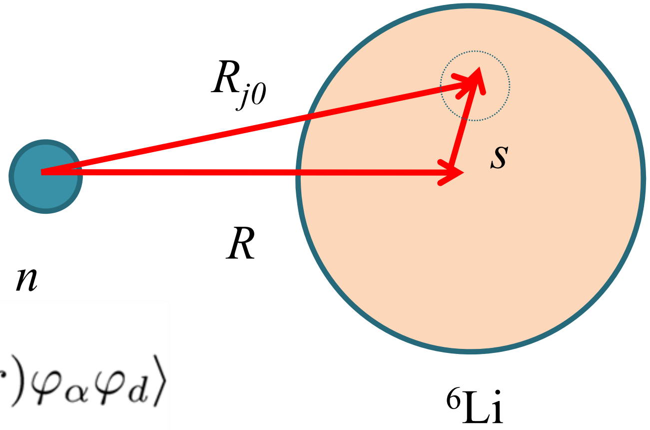
$$\begin{aligned} v_{j0}(R_{j0};\rho,E) &= \lambda_v V(\rho,E)\exp\left(-R_{j0}/t_R^2\right) \\ &\quad + i\lambda_w W(\rho,E)\exp\left(-R_{j0}/t_I^2\right) \end{aligned}$$

In generally, $t_R = t_I$=1.2, λv = 1.0 and λw = 0.8 (single channel calculation)

→ λw is optimized

Coupling potential

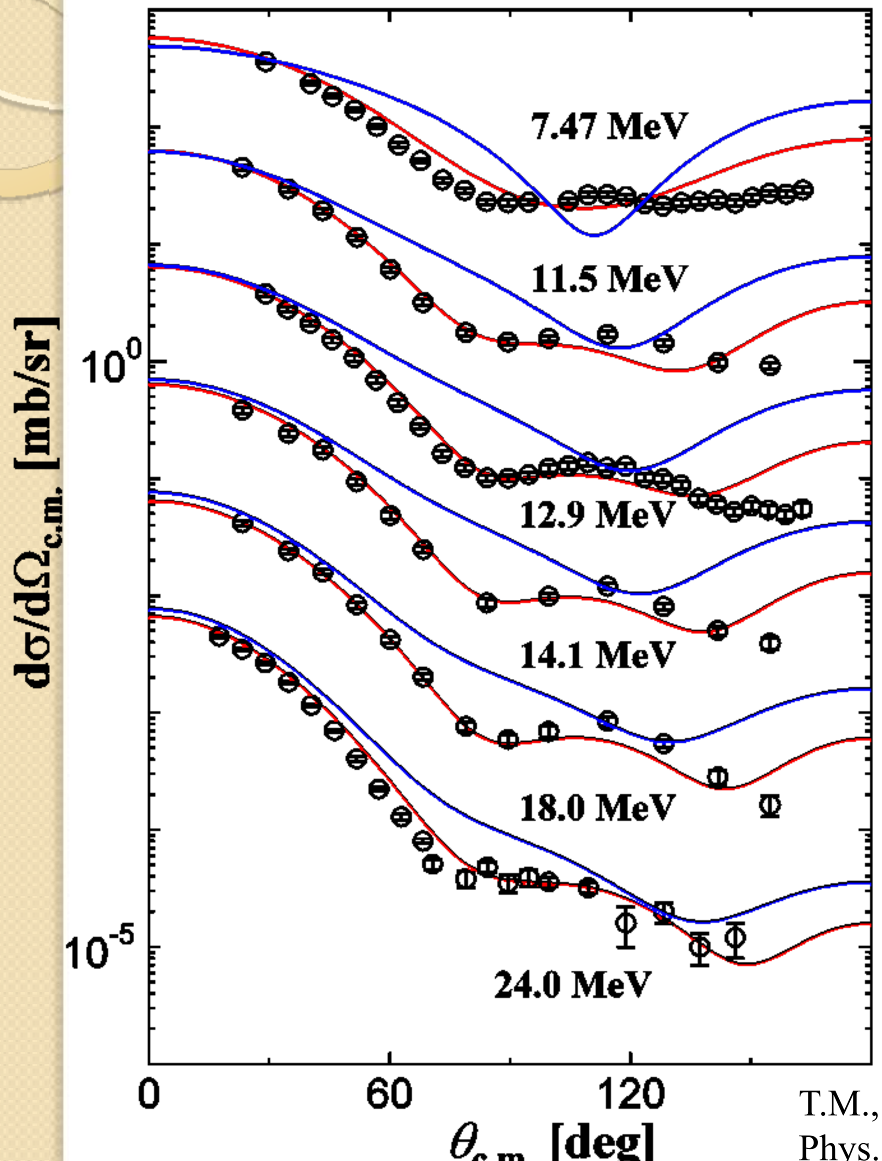
$$V_{\gamma'\gamma}(R) = \int ds \rho_{\gamma'\gamma}(s) v_{j0}(R_{j0};\rho,E)$$



Transition density of ^{6}Li

$$\rho_{\gamma'\gamma}(s) = \langle \phi^{I'}_{i'\ell'}(r)\varphi_\alpha\varphi_d | \sum_{k=1}^{6} \delta(s - r_k) | \phi^{I}_{i\ell}(r)\varphi_\alpha\varphi_d \rangle$$

Elastic cross section of ^{6}Li(n, n)



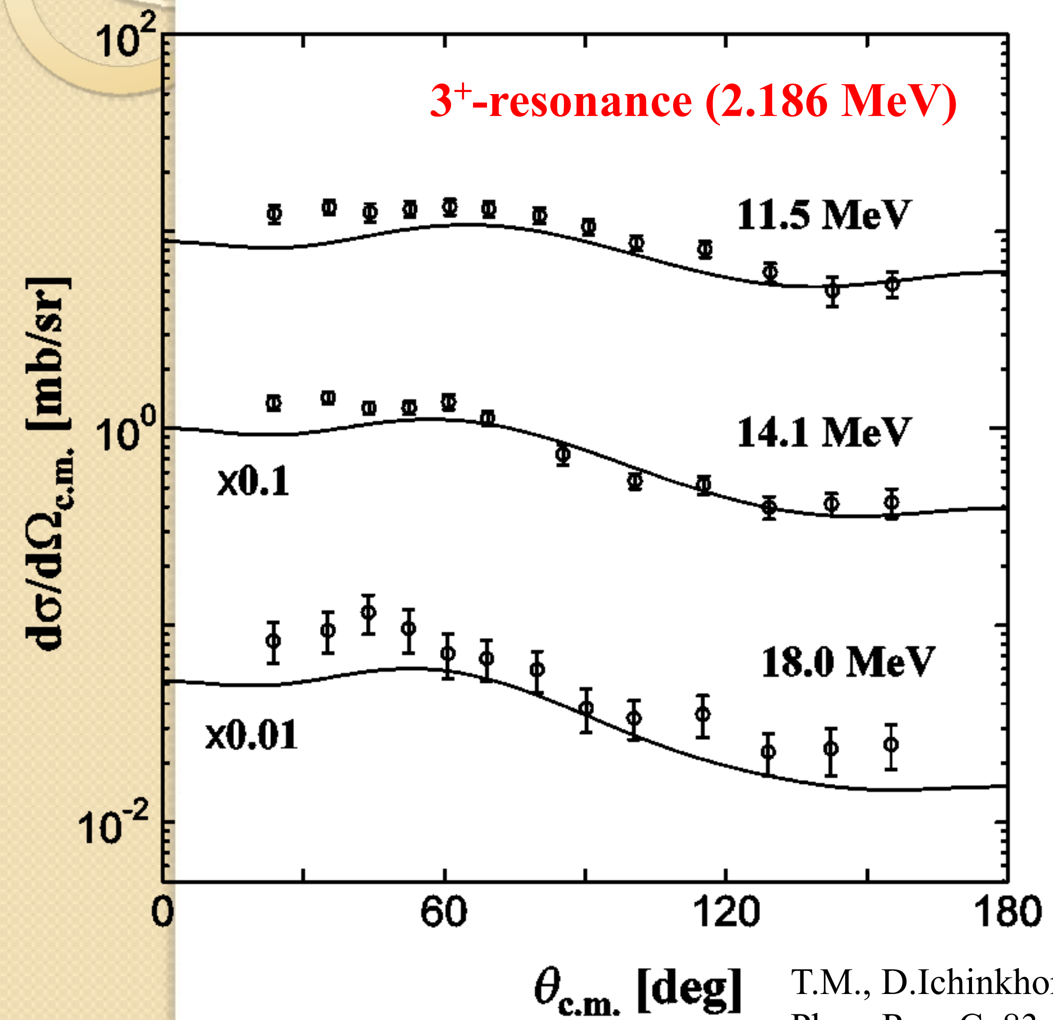
Blue:
Single channel calc.
(without BU effects)

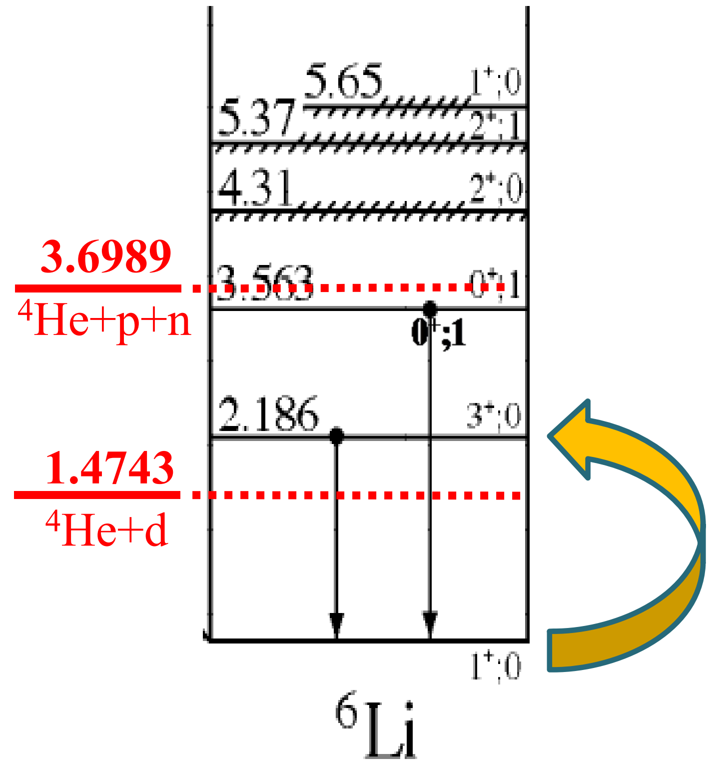
Red: Full CC

- The optimized λ_w is 0.1.
- Breakup effect is significant

T.M., D.Ichinkhoroloo, Y. Hirabayashi, K. Kato, and S. Chiba, Phys. Rev. C. 83. 064611 (2011)

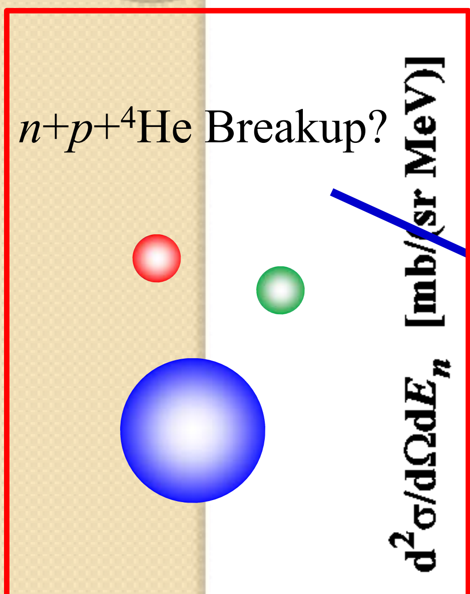
Inelastic cross section



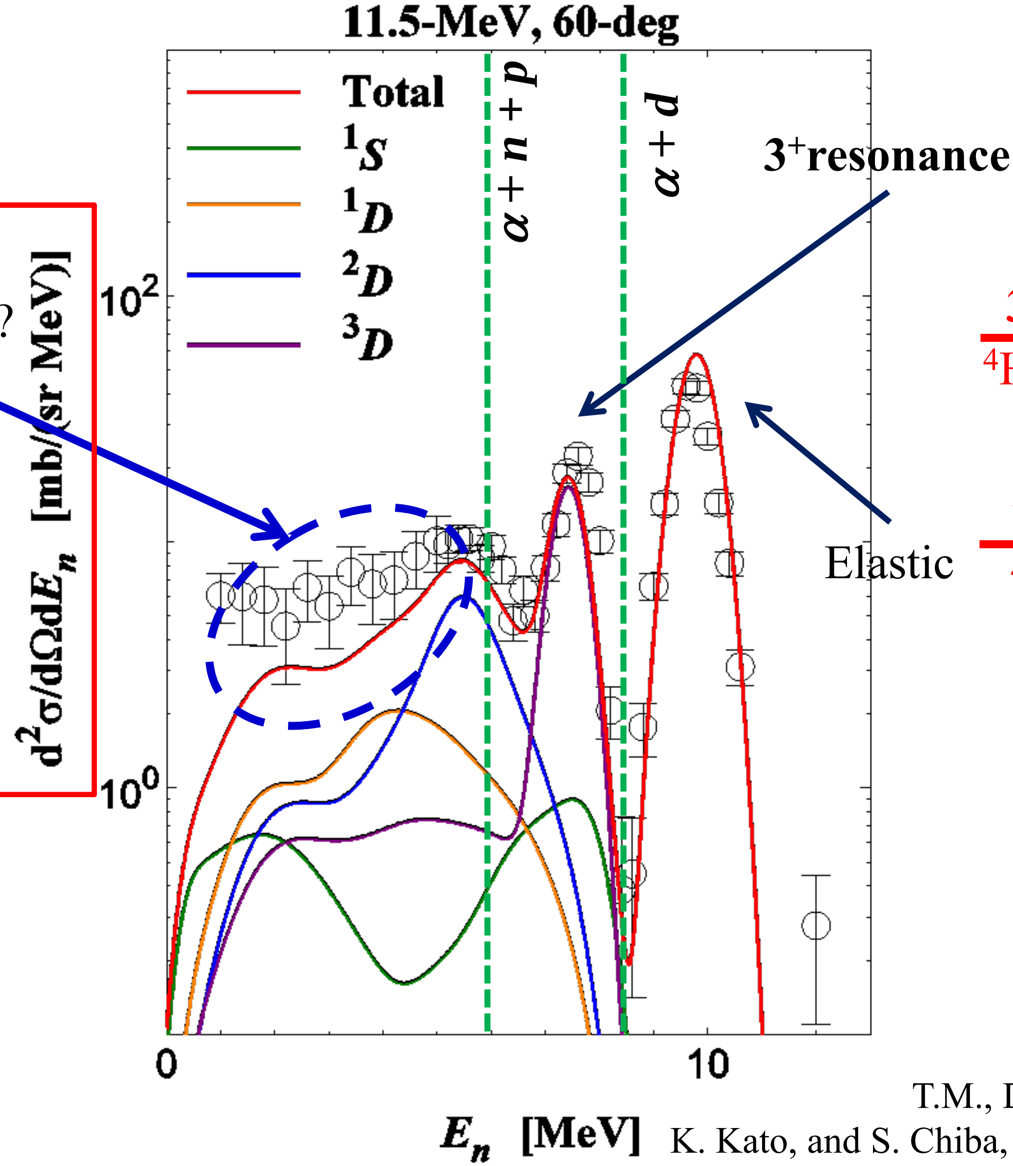


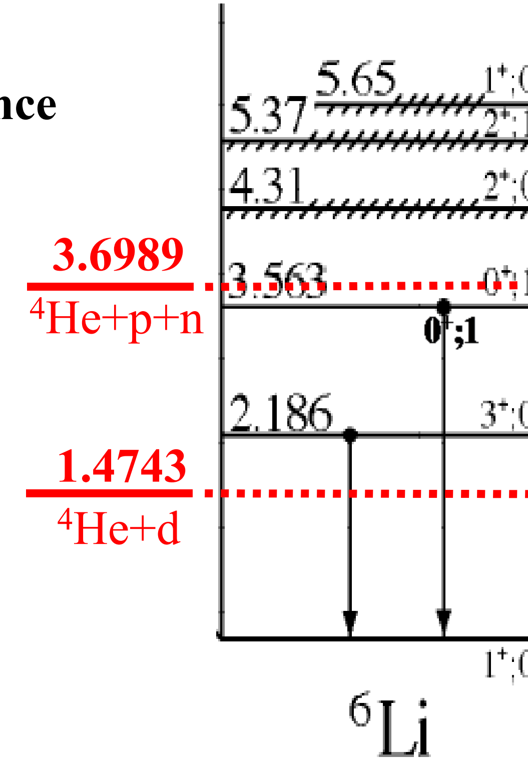
T.M., D.Ichinkhoroloo, Y. Hirabayashi, K. Kato, and S. Chiba, Phys. Rev. C. 83. 064611 (2011)

Neutron spectrum of ^{6}Li(n, n')



New results

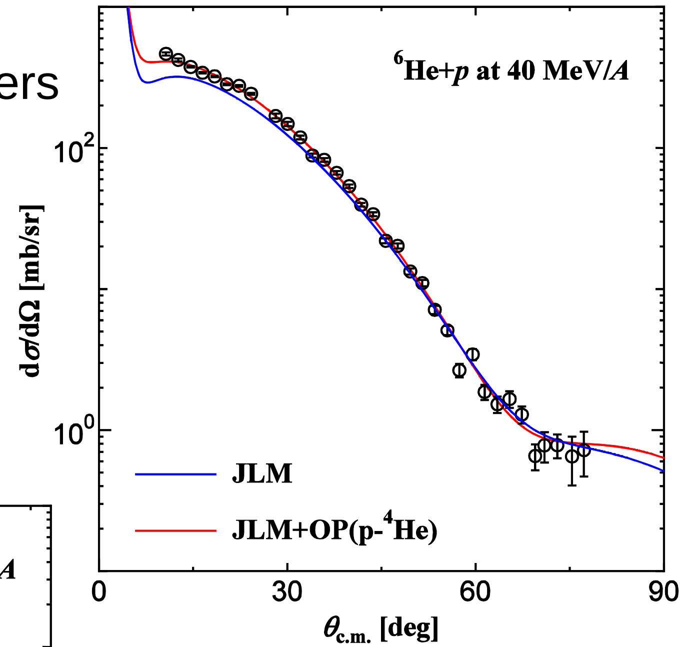


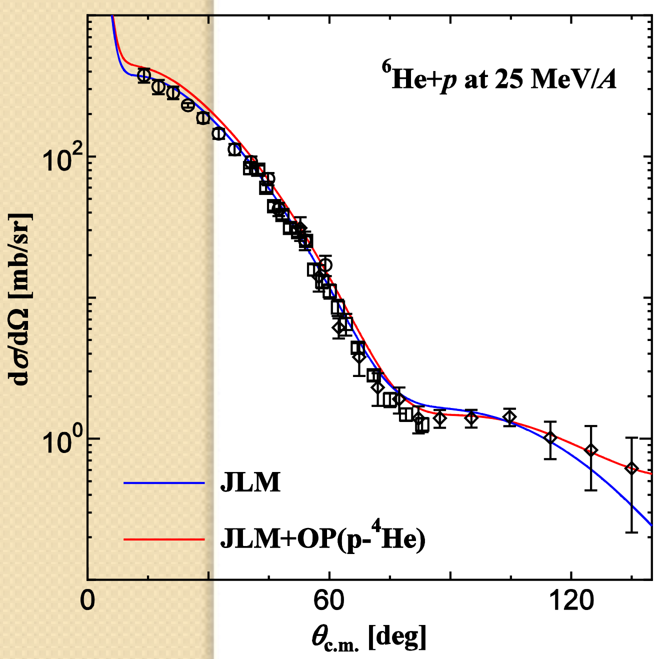


T.M., D.Ichinkhoroloo, Y. Hirabayashi, K. Kato, and S. Chiba, Phys. Rev. C. 83. 064611 (2011)

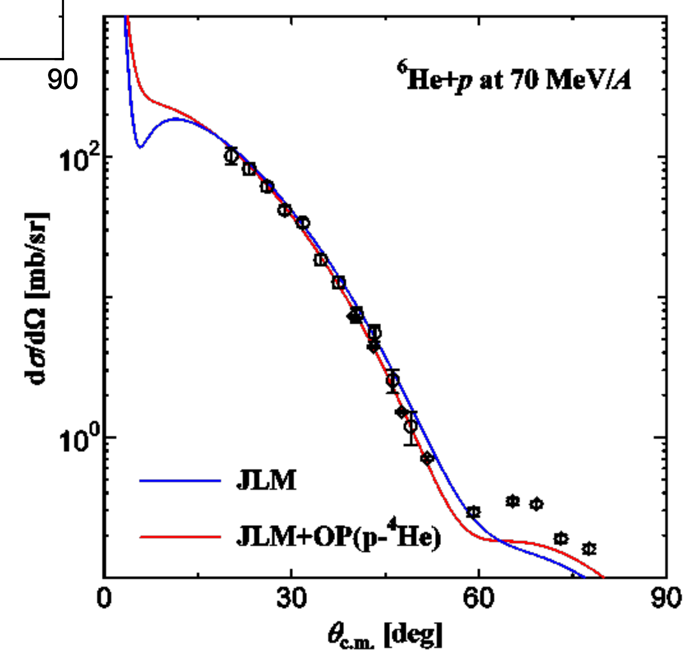
^{6}He + p elastic cross section

OP(p-^{4}He)
:Optical Potential parameters taken from **NPA 674, 77 (2000) D. Gupta *et al*.**





Normalization of JLM interaction is 0.5 for the imaginary part.



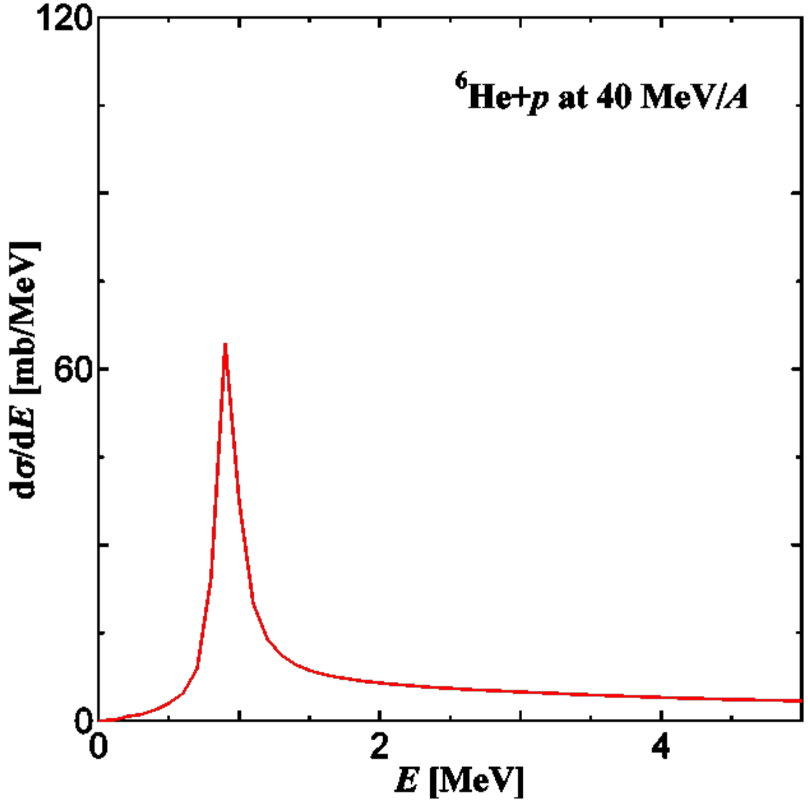
Inelastic Cross Section to 2^+

Energy spectral of ^{6}He

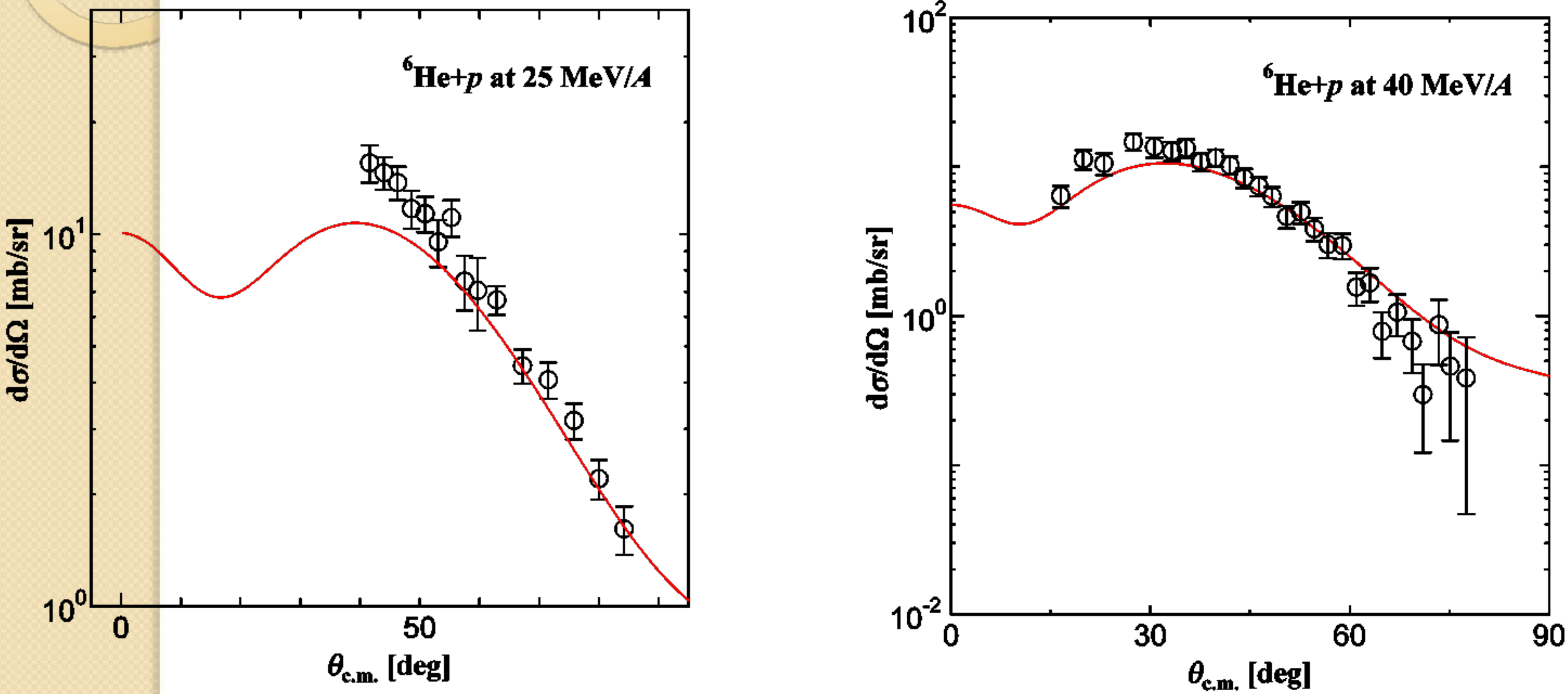
2^+ resonance

n + n + ^{4}He threshold

0^+ ground state



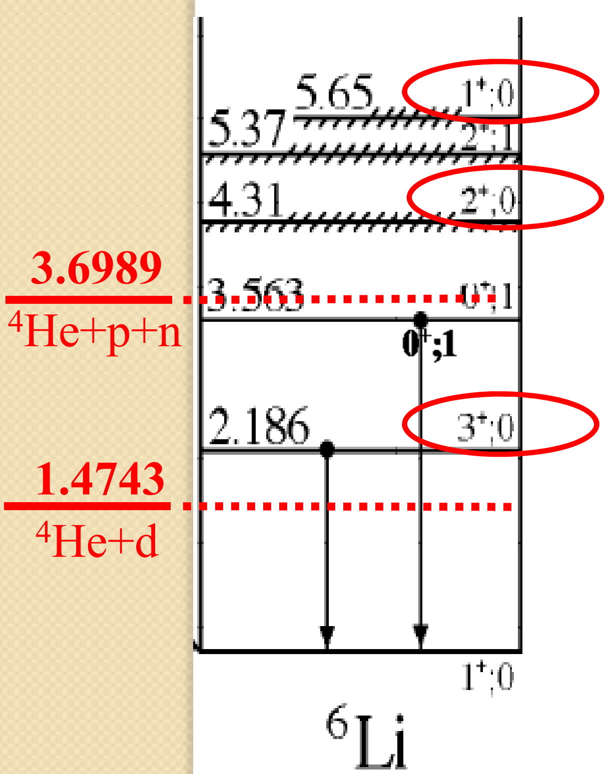
Inelastic Cross Section

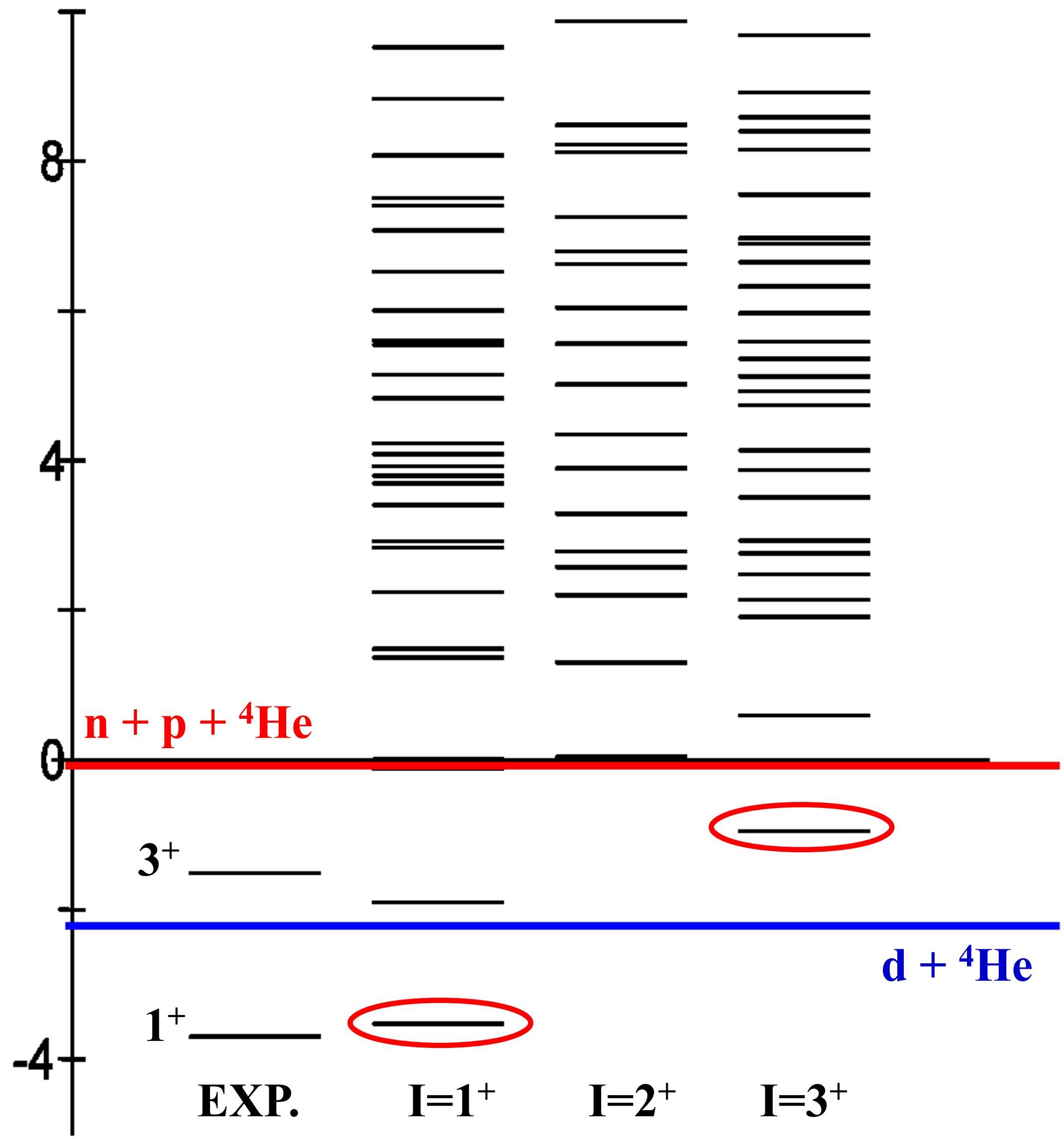


GEM + JLM + Four-body CDCC well reproduces the elastic and inelastic data

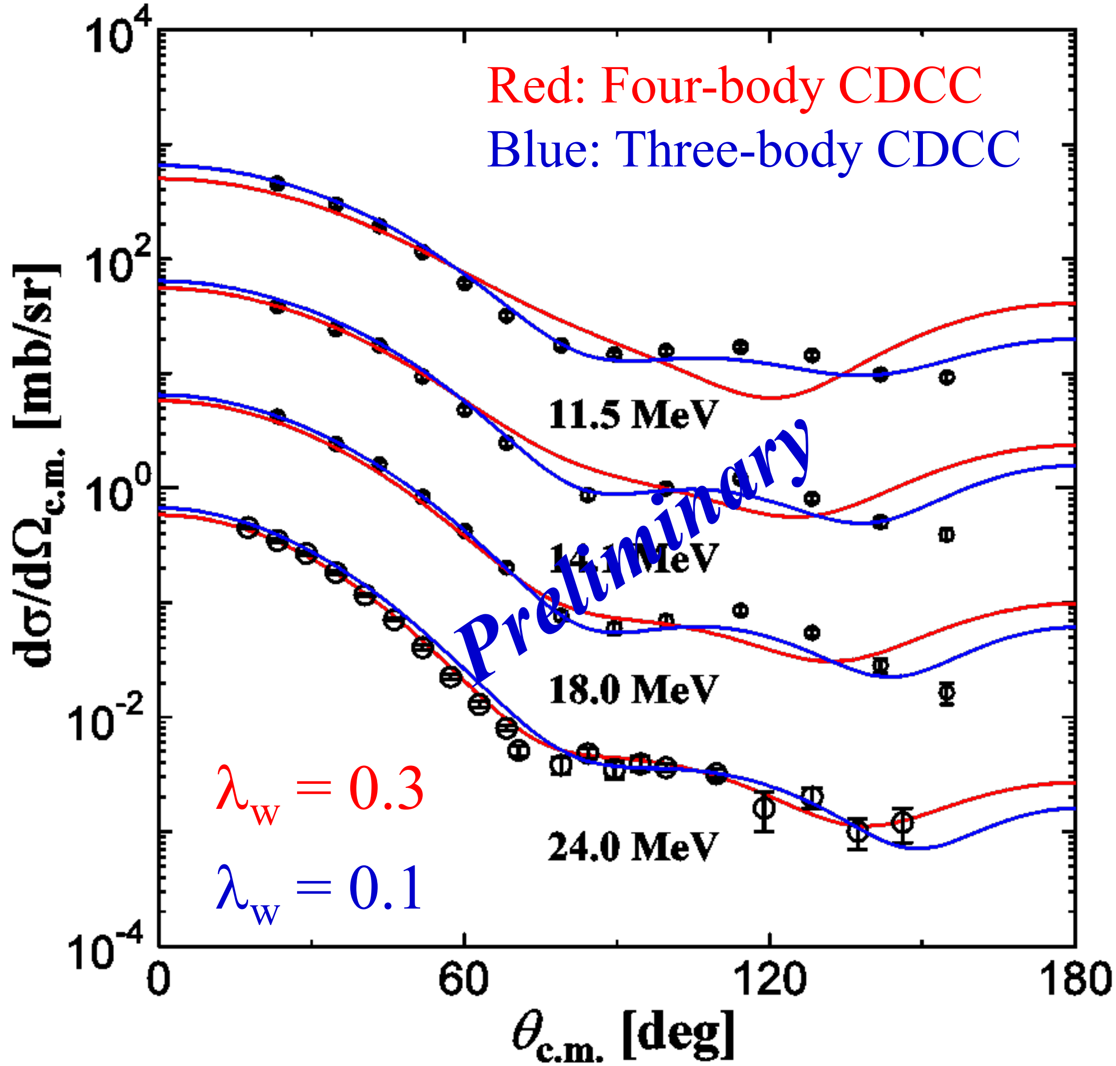
^{6}Li: $n + p + \alpha$ three-body model

^{6}He (T=1) → ^{6}Li (T=0)





Elastic cross section $^{6}Li(n, n)$



→ **Neutron spectrum**

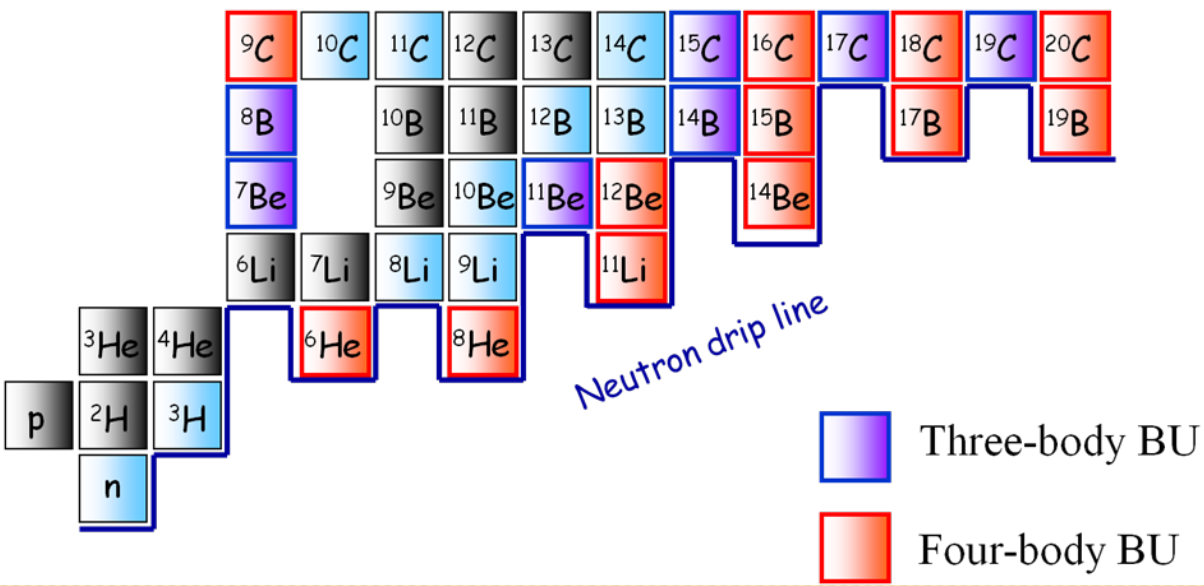
Summary

- 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



Collaborators