CDCC法による
少数多体反応系の記述

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Introduction

- Structure + Reaction + Effective interaction
  - Structure (Few-body Model)
  - Reaction (Continuum-Discretized Coupled-Channels)
  - Effective interaction

- Microscopic Coupled-Channels Calculation (Furumoto)

  - ^{6}He + ^{12}C, ^{6}He + p (Double folding and Single folding)
    - ^{6}He $\rightarrow$ n + n + ^{4}He

  - n + ^{6}Li, p, n + ^{7}Li (Single Folding)
    - ^{6}Li $\rightarrow$ d + ^{4}He $\rightarrow$ n + p + ^{4}He
    - ^{7}Li $\rightarrow$ t + ^{4}He

MCC with Double Folding Model

Schroedinger Equation

$$\left[T_R + h_{\rm P} + h_{\rm T} + \sum_{i\in {\rm P}, j\in {\rm T}} \bar{v}_{ij}(\rho, E) - E \right] \Psi \;=\; 0$$

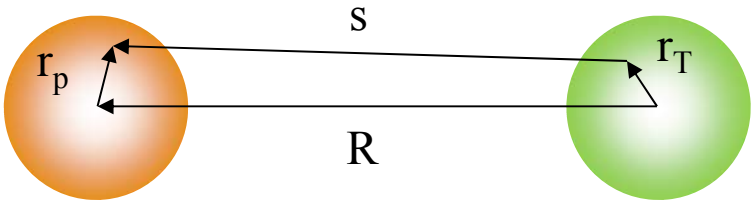
Coupling potential

$$V_{\gamma\gamma'}(\vec{R}) \;=\; \int \rho^{\rm P}_{\gamma\gamma'}(\vec{r}_{\rm P}) \rho^{\rm T}_{00}(\vec{r}_{\rm T}) \bar{v}(\bar{\rho}, E, \vec{s}) d\vec{r}_{\rm P} d\vec{r}_{\rm T}$$

Density dependence

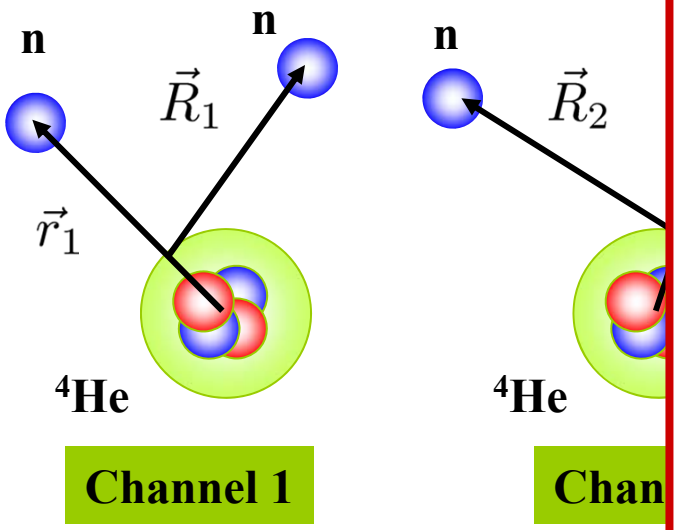
$$\bar{\rho} \;=\; \bar{\rho}_{\rm P}(\vec{r}_{\rm P} - \vec{s}/2) + \bar{\rho}_{\rm T}(\vec{r}_{\rm T} + \vec{s}/2)$$

$$\bar{\rho}_{\rm P}(\vec{r}_{\rm P}) \;=\; \frac{\rho^{\rm P}_{\gamma\gamma}(\vec{r}_{\rm P}) + \rho^{\rm P}_{\gamma'\gamma'}(\vec{r}_{\rm P})}{2}$$



Ground and breakup states of ^{6}He

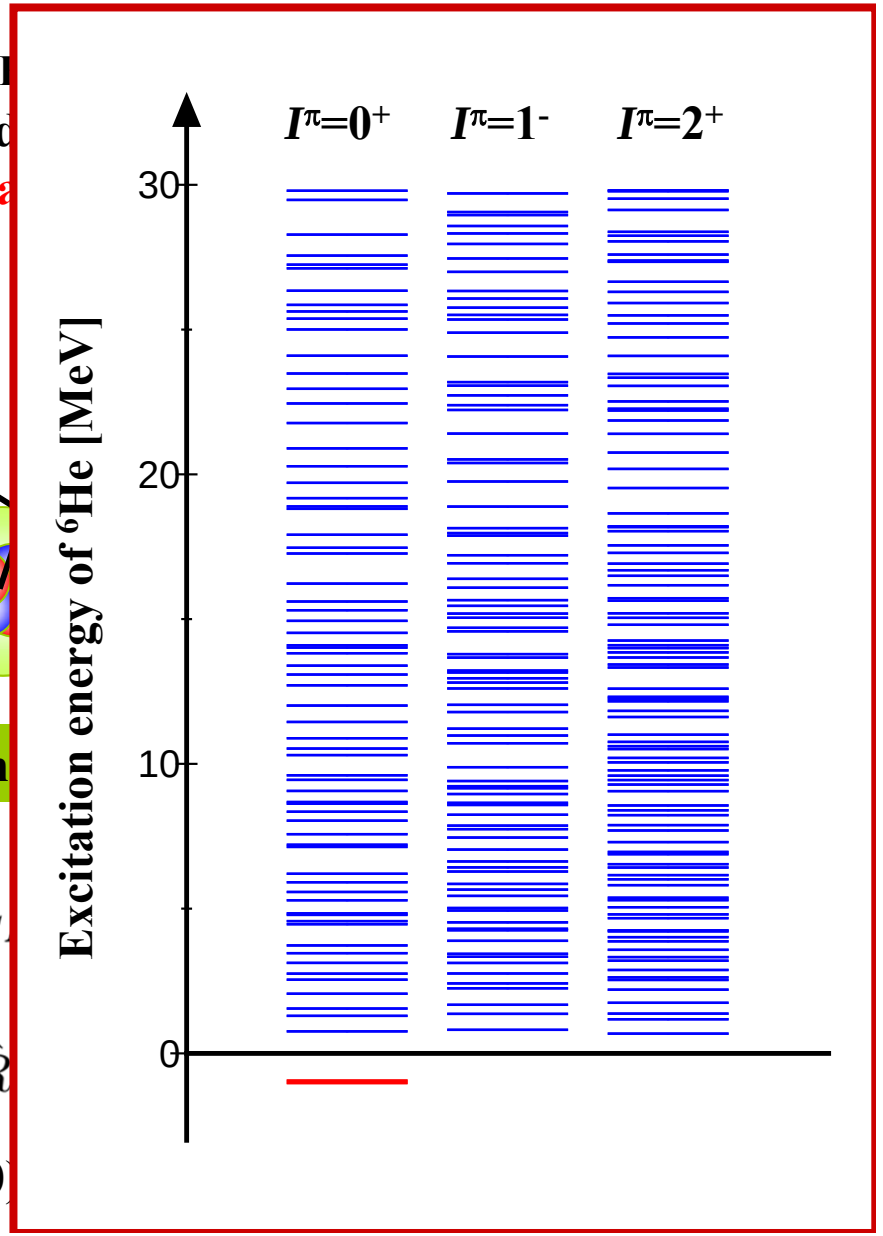
- **Gaussian Expansion Method** : E. I
  - ✓ **An accurate method** of solving few-bod
  - ✓ A variational method with **Gaussian ba**
  - ✓ Take all the sets of **Jacobi coordinates**



$$\Phi_{Im}(\vec{r},\vec{R}) = \sum_c \sum_{ij} \sum_{\ell LS\Lambda} A_{ij\ell LS}$$

$$\times \left[\left[Y_\ell(\hat{r}_c) \otimes Y_L(\hat{R}\right.\right.$$

V_{nn}: D. Gogny, et al., PLB32, 591 (1970)

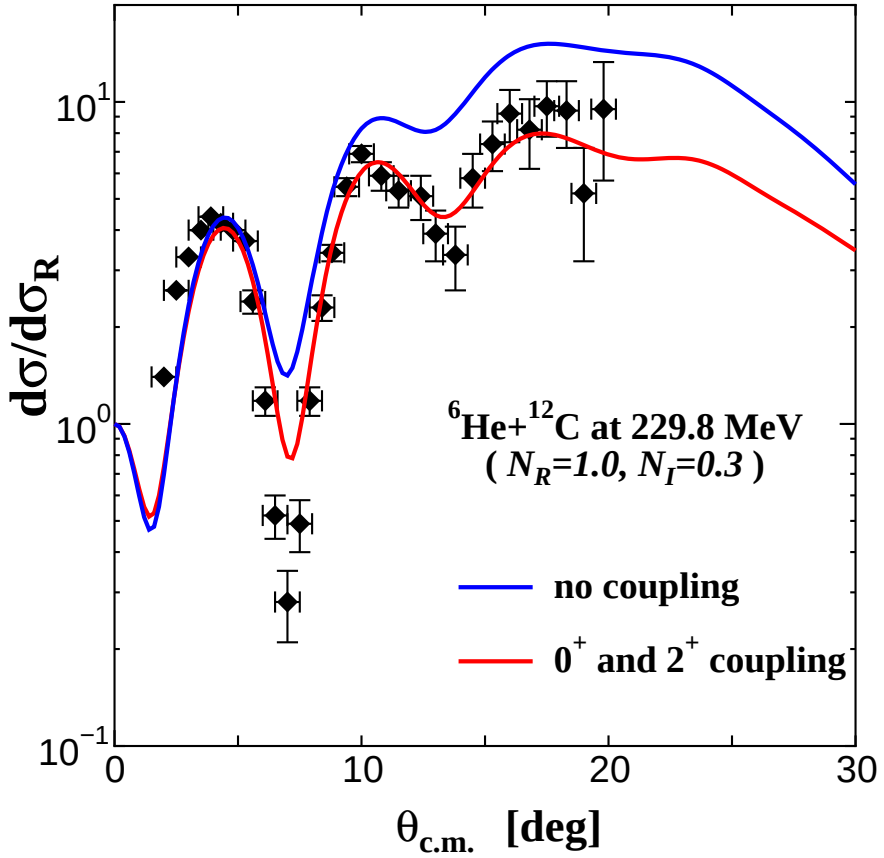


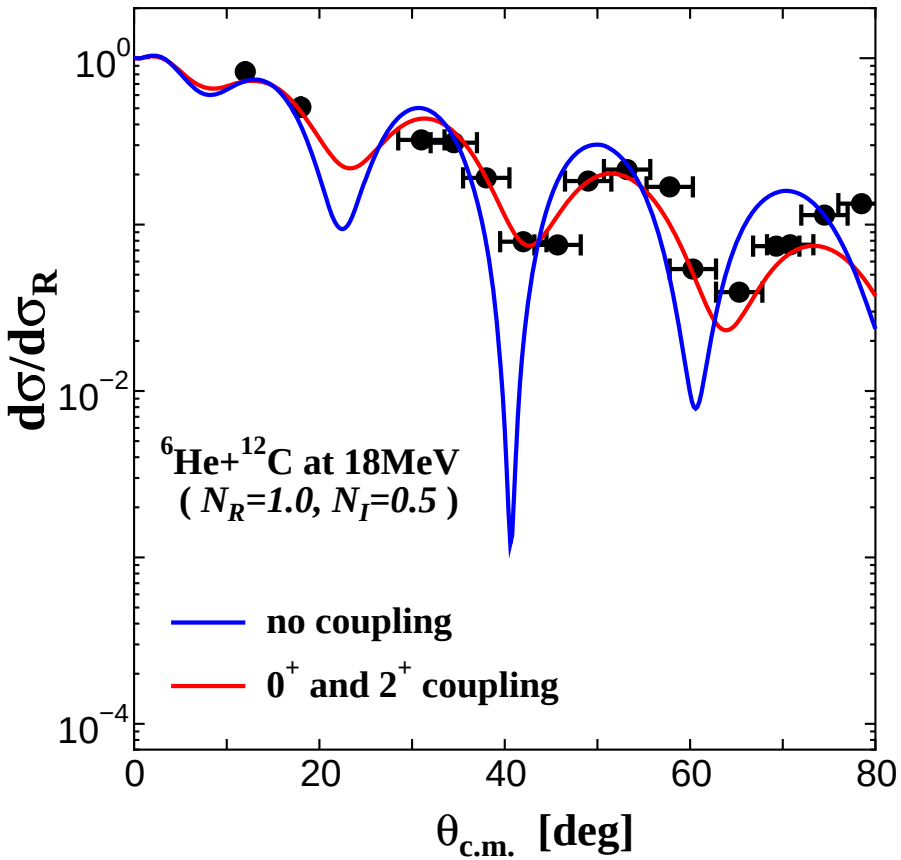
MCC Calculation of ^{6}He + ^{12}C scattering

DDM3Y[1] $v_{NN}(E,\rho,s) = g(E,s)\,f(E,\rho)$

Imaginary part = N_I x Real part

$$g(E,s) = \left(7999\frac{e^{-4s}}{4s} - 2134\frac{e^{-2.5s}}{2.5s}\right) + \hat{J}(E)\delta(s) \qquad f(E,\rho) = C(E)[1+\alpha(E)\,e^{-\beta(E)\rho}].$$





[1] El-Azab Farid M and Satchler G R 1985 *Nucl. Phys. A* ***438 525***

[2] T.M. Hiyama, Ogata, Iseri, Kamimura, Chiba, and Yahiro, Phys. Rev. C**70**, 061601 (2004).

Double Folding Potential

Coupling potential

$$V_{\gamma\gamma'}(\vec{R}) = \int \rho^{\mathrm{P}}_{\gamma\gamma'}(\vec{r}_{\mathrm{P}})\rho^{\mathrm{T}}_{00}(\vec{r}_{\mathrm{T}})\bar{v}(\bar{\rho}, E, \vec{s})d\vec{r}_{\mathrm{P}}d\vec{r}_{\mathrm{T}}$$

Simple formula of effective interaction

DDM3Y $v_{\mathrm{NN}}(E,\rho,s) = g(E,s)f(E,\rho) \quad f(E,\rho) = C(E)[1+\alpha(E)\,\mathrm{e}^{-\beta(E)\rho}].$

$$\bar{v}(\bar{\rho}, E, \vec{s}) = \bar{v}_{\mathrm{P}}(\bar{\rho}_{\mathrm{P}}, E)\bar{v}_{\mathrm{T}}(\bar{\rho}_{\mathrm{T}}, E)\bar{v}(E, \vec{s})$$

$$V_{\gamma\gamma'}(\vec{R}) = \int d\vec{r}_{\mathrm{P}}\rho^{\mathrm{P}}_{\gamma\gamma'}(\vec{r}_{\mathrm{P}})\bar{v}_{\mathrm{P}}(\bar{\rho}_{\mathrm{P}}, E)\int d\vec{r}_{\mathrm{T}}\rho^{\mathrm{T}}_{00}(\vec{r}_{\mathrm{T}})\bar{v}_{\mathrm{T}}(\bar{\rho}_{\mathrm{T}}, E)\bar{v}(E, \vec{s})$$

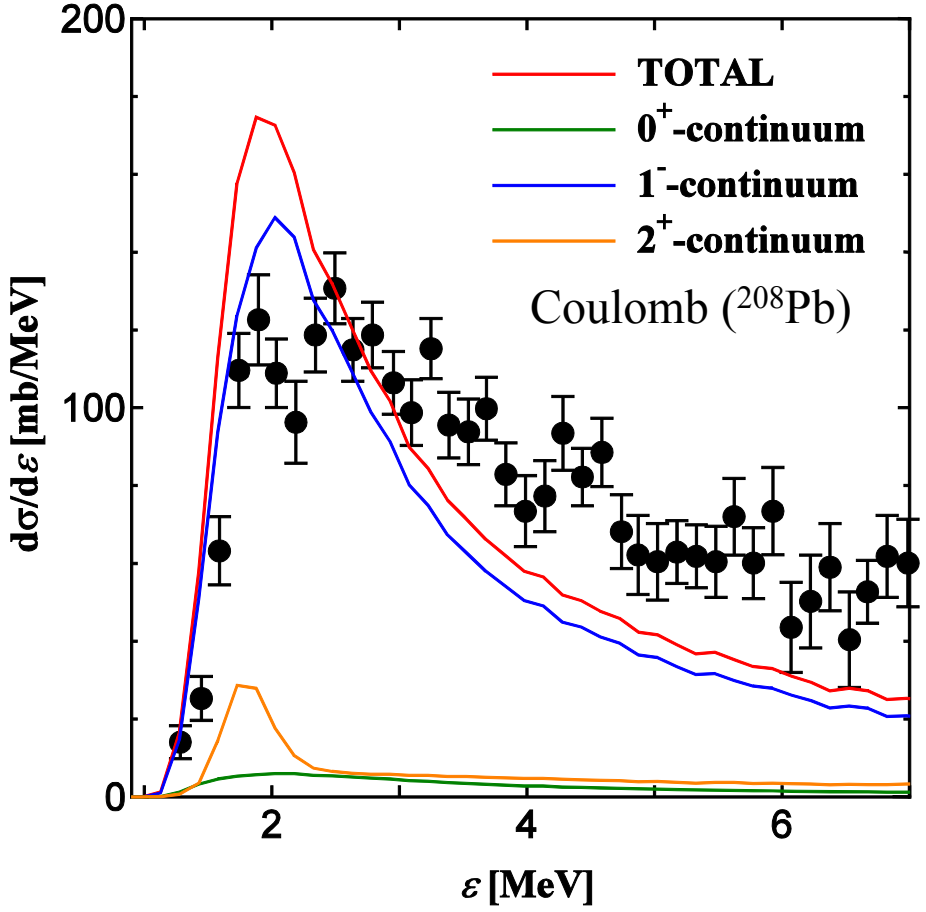
$$= \int d\vec{r}_{\mathrm{P}}\rho^{\mathrm{P}}_{\gamma\gamma'}(\vec{r}_{\mathrm{P}})\bar{v}_{\mathrm{P}}(\bar{\rho}_{\mathrm{P}}, E)V_{\mathrm{T}}(\vec{r}_{\mathrm{P}}, \vec{R})$$

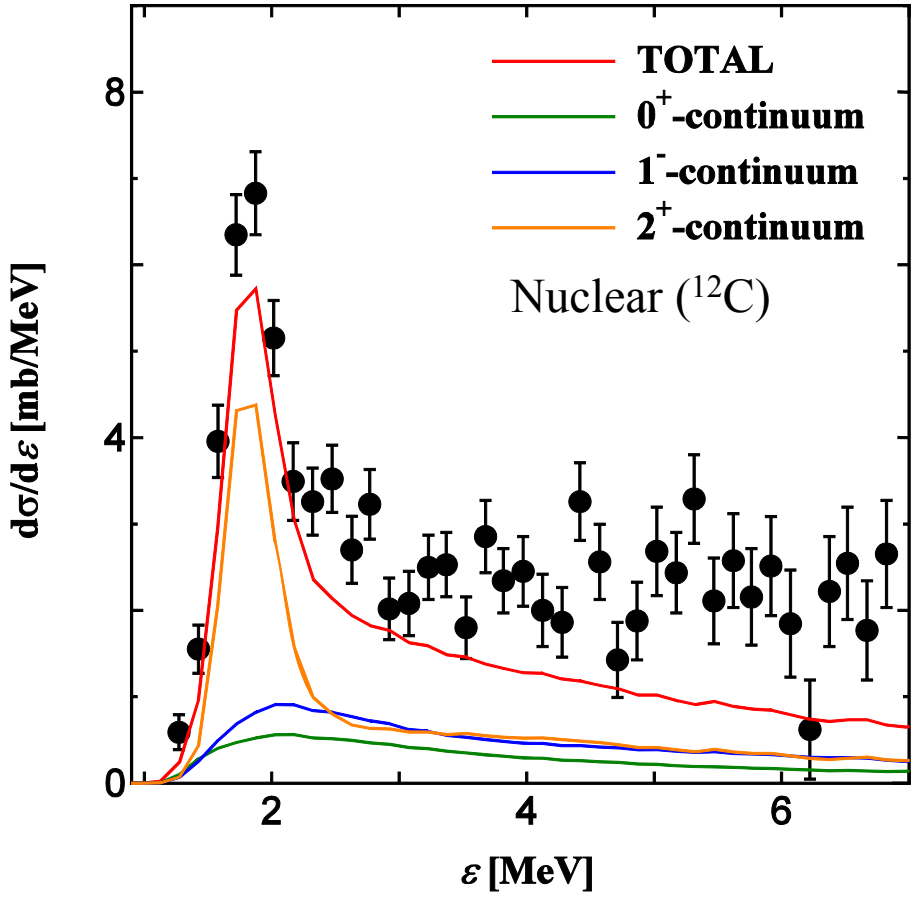
Optical potential (density independent)
→ Cluster (single) folding model

^{6}He+^{12}C, ^{208}Pb @ 240 MeV/nucl.

$$V_{\gamma\gamma'}(\vec{R}) = \int \rho^{\mathrm{P}}_{\gamma\gamma'}(\vec{r}_{\mathrm{P}})(V_{\alpha}(\vec{r}_{\alpha},\vec{R}) + V_{n}(\vec{r}_{n},\vec{R}) + V_{n}(\vec{r}_{n},\vec{R}))d\vec{r}_{\mathrm{P}}$$

Folded with Melbourne g-matrix (Minomo)





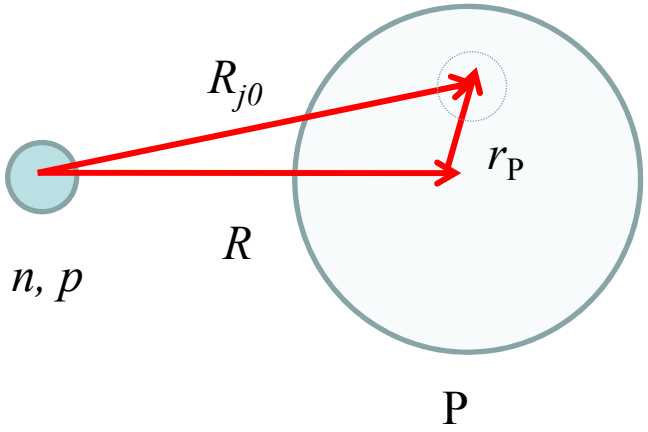
Exp. data from PRC59, 1252 (1999), T. Aumann *et al.* σ_{-2n}, σ_{-n}

- Comparing cluster (single) folding with Double folding
- Validity of double folding model with effective int.
- Validity of coupled-channel calculation with effective int.
- Form of effective interaction (density dependent term)
- Choice of density in density dependent term

MCC with Single Folding Model

Coupling potential

$$V_{\gamma'\gamma}(R) = \int dr_{\rm P}\rho_{\gamma'\gamma}(r_{\rm P})v_{j0}(R_{j0};\rho,E)$$



Transition density of ^{6}Li

$$\rho_{\gamma'\gamma}(r_{\rm P}) = \langle\phi_{\gamma'}|\sum_{k=1}^{A_P}\delta(r_{\rm P}-r_k)|\phi_\gamma\rangle$$

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

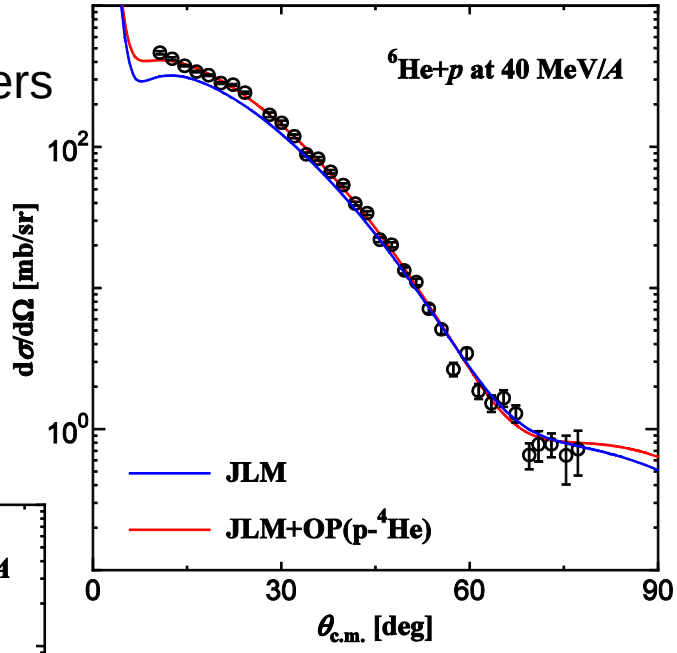
$$v_{j0}(R_{j0};\rho,E) = \lambda_v V(\rho,E)\exp\left(-R_{j0}/t_R^2\right) + i\lambda_w W(\rho,E)\exp\left(-R_{j0}/t_I^2\right)$$

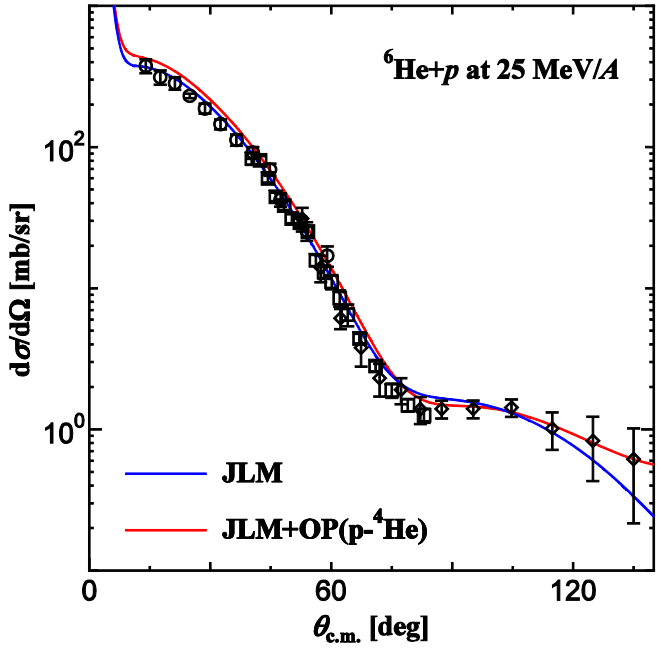
In generally, $t_R = t_I$=1.2, λv = 1.0 and λw = 0.8 (single channel calculation)

^{6}He + p scattering @ 25, 40 70 MeV/nuclon

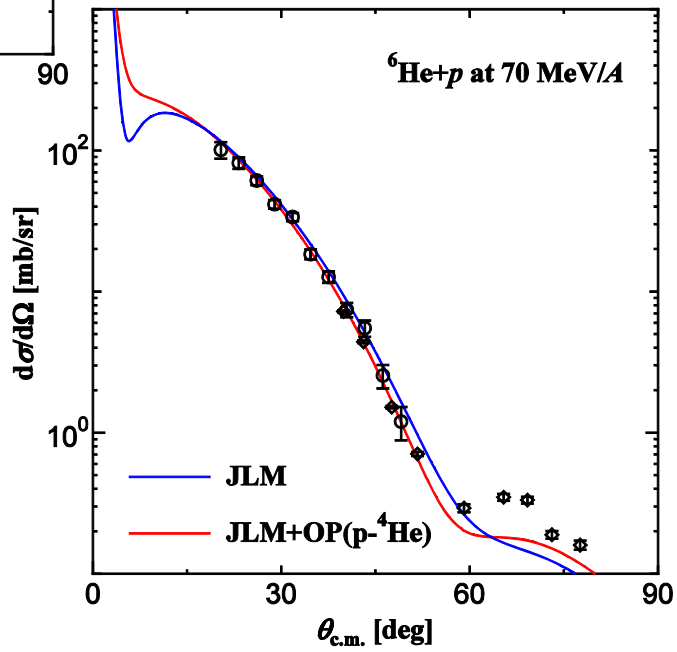
Elastic Cross Section

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





$\lambda_w = 0.5$



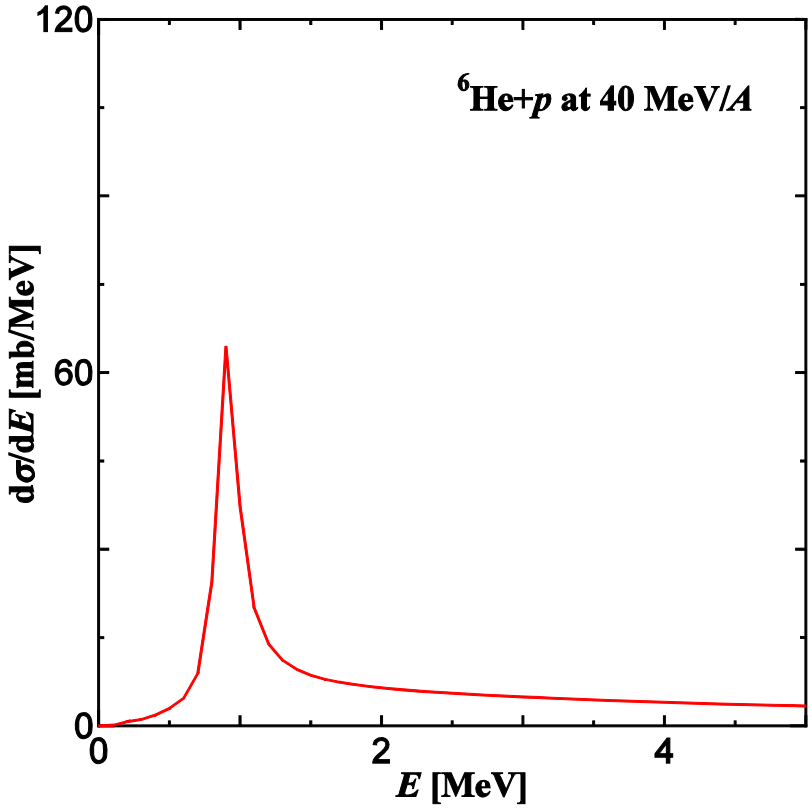
Inelastic Cross Section to 2^+

Energy spectral of ^{6}He

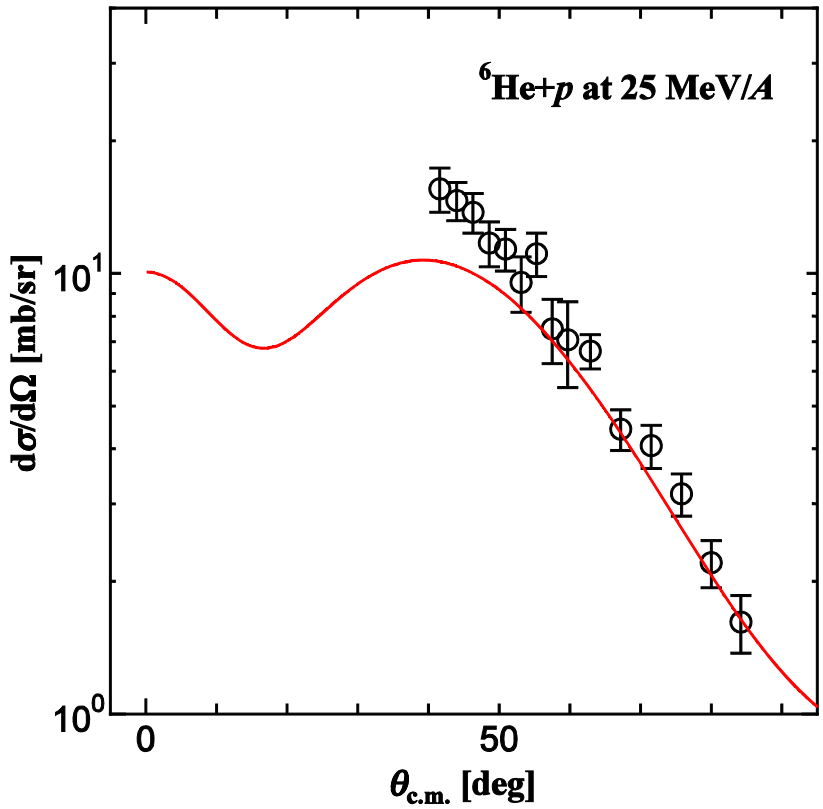
2^+ resonance

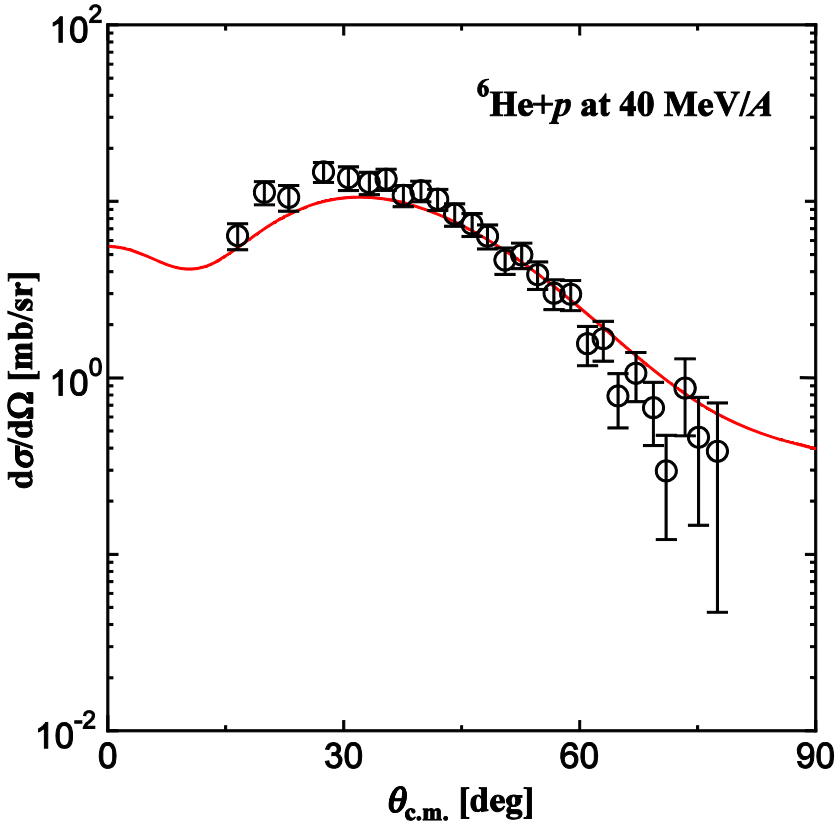
n + n + ^{4}He threshold

0^+ ground state



Inelastic Cross Section

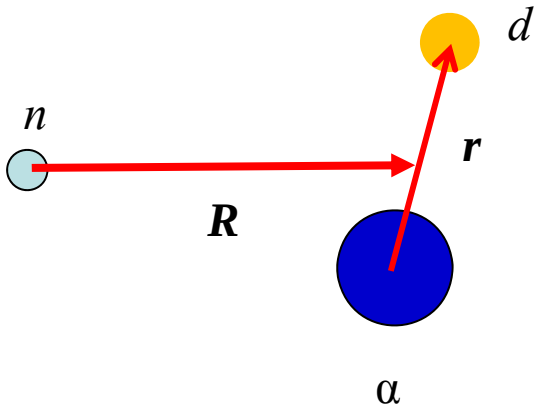




Integrated up to 2.0 MeV

$n + {}^{6}\mathrm{Li}$ scattering @ 10 - 20 MeV

n + ^{6}Li three-body scattering

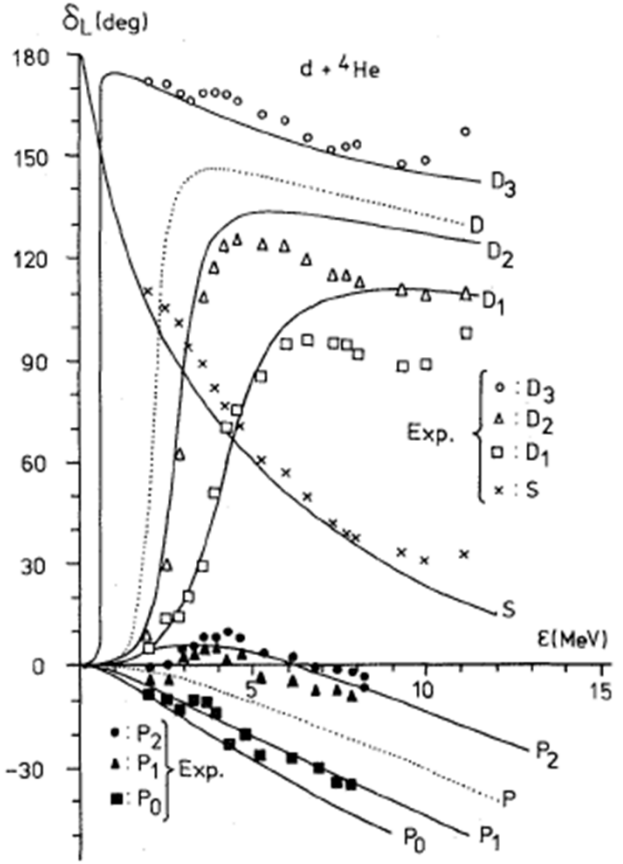


Total Hamiltonian (microscopic model)

$$H = T_R + \sum_{j=1}^{6} v_{j0}(R_{j0}) + h_{d\alpha}$$

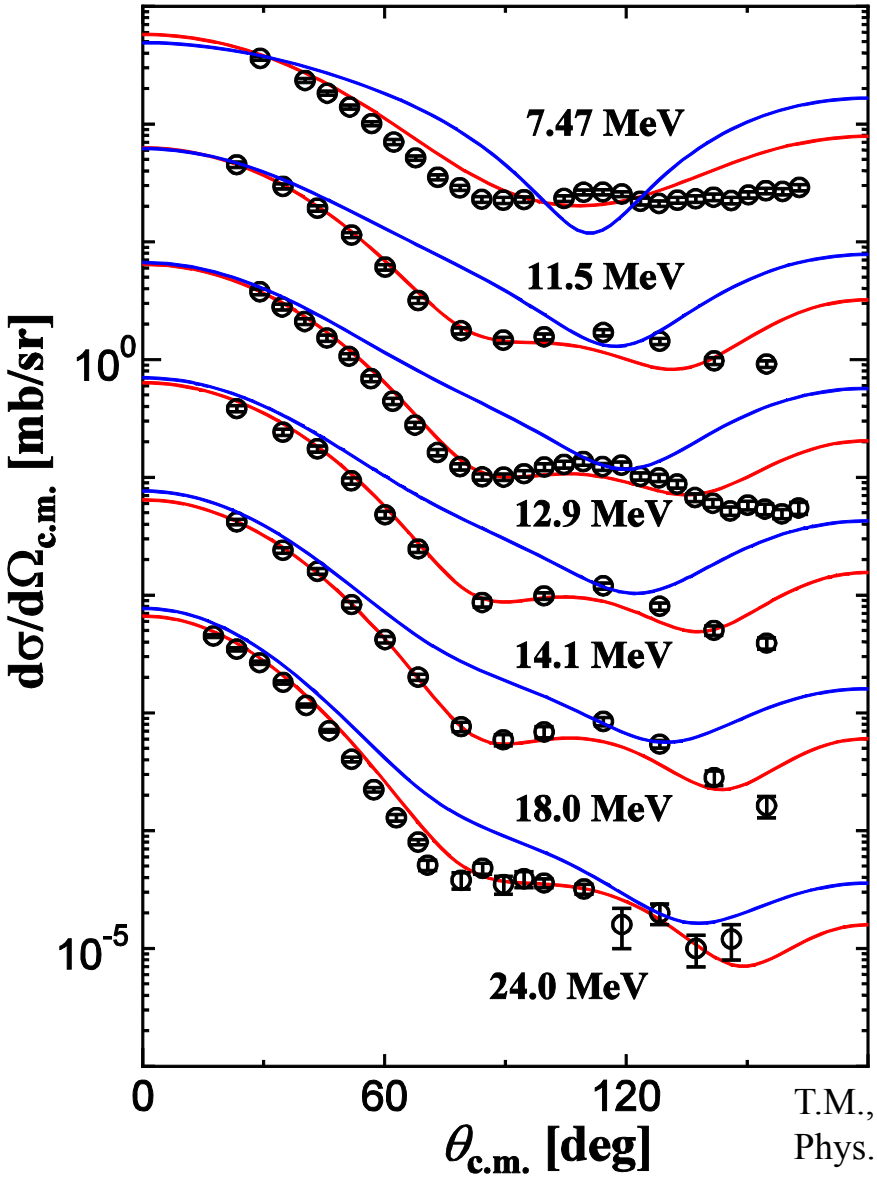
Internal Hamiltonian of ^{6}Li

$$h_{d\alpha} = T_r + V_{d\alpha}(r)$$



Prog. Theor. Phys. Suppl. No.89 (1986) pp. 136-211, Y. Sakurai et al.

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



Blue:
Single channel calc.
(without BU effects)

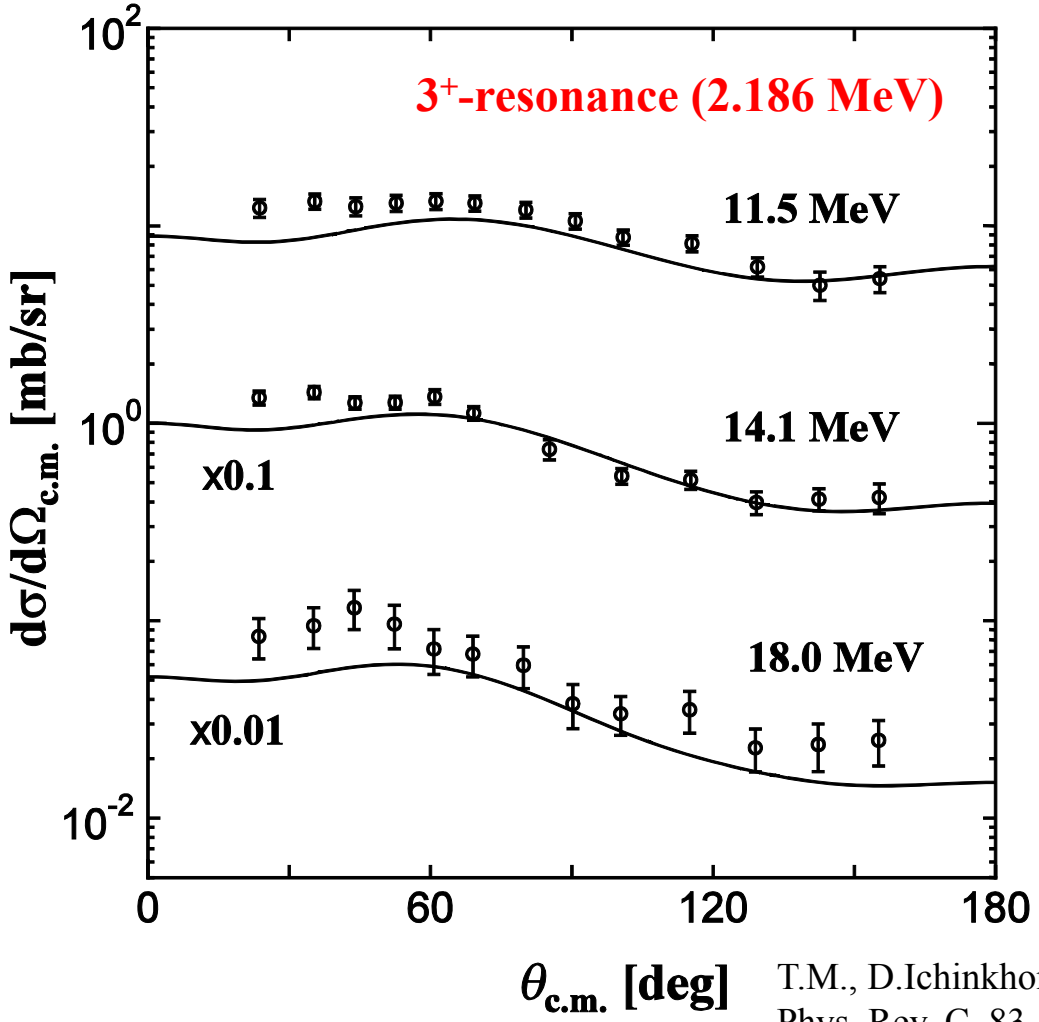
Red: Full CC

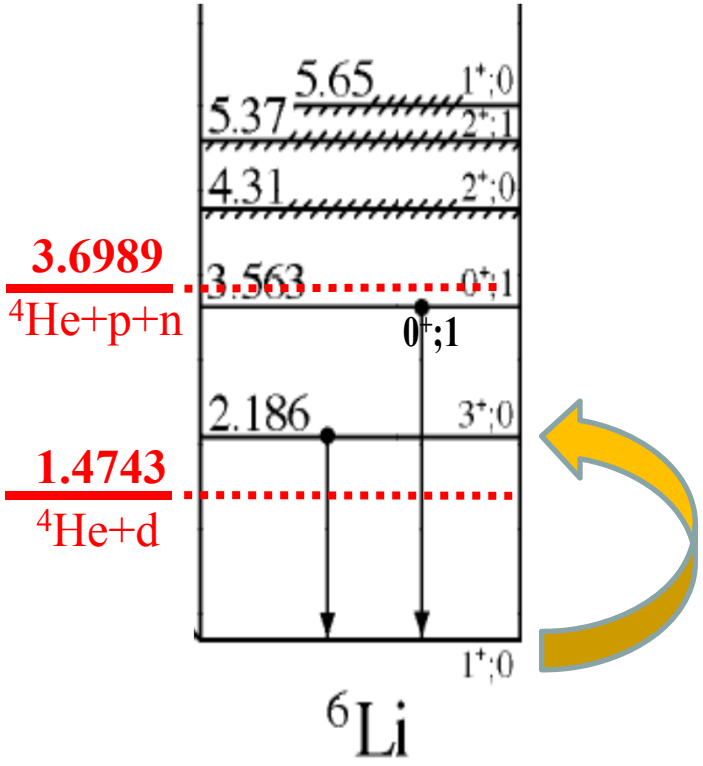
- The optimized λ_w is 0.1.

- Breakup effect is significant

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

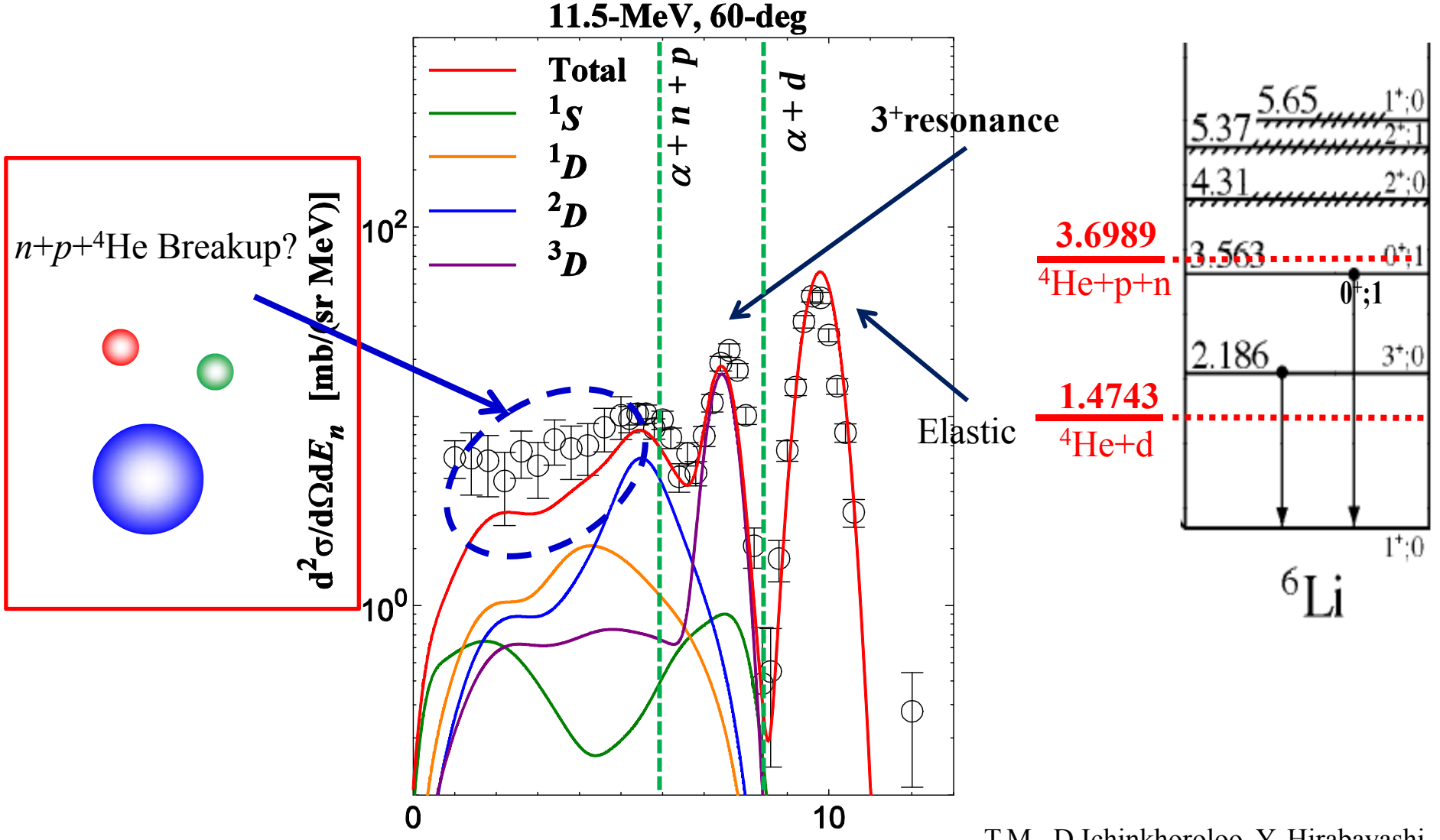
Inelastic cross section





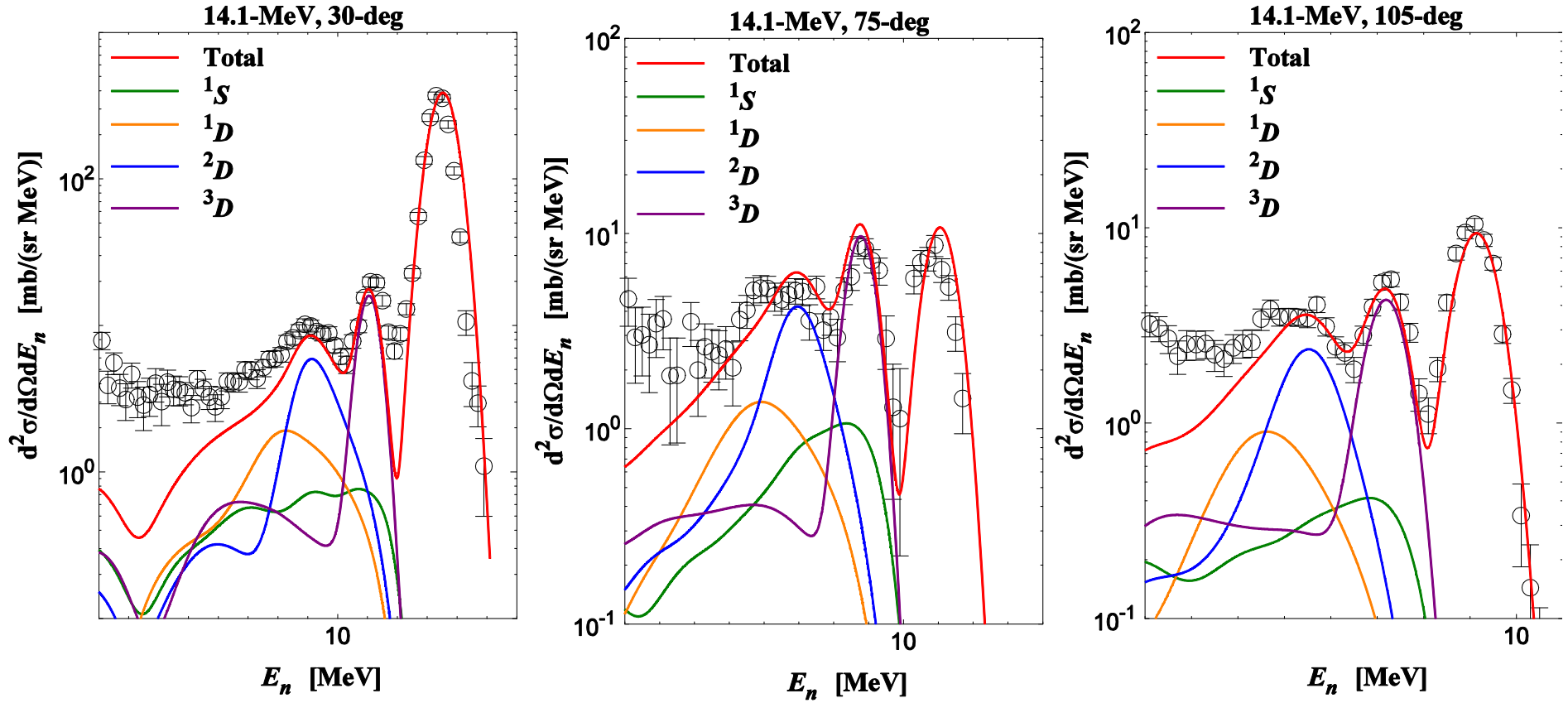
T.M., D.Ichinkhoroloo, Y. Hirabayashi, K. Kato, and S. Chiba, Phys. Rev. C. 83. 064611 (2011)

Neutron spectrum of ^{6}Li(n, n')$d\alpha$



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

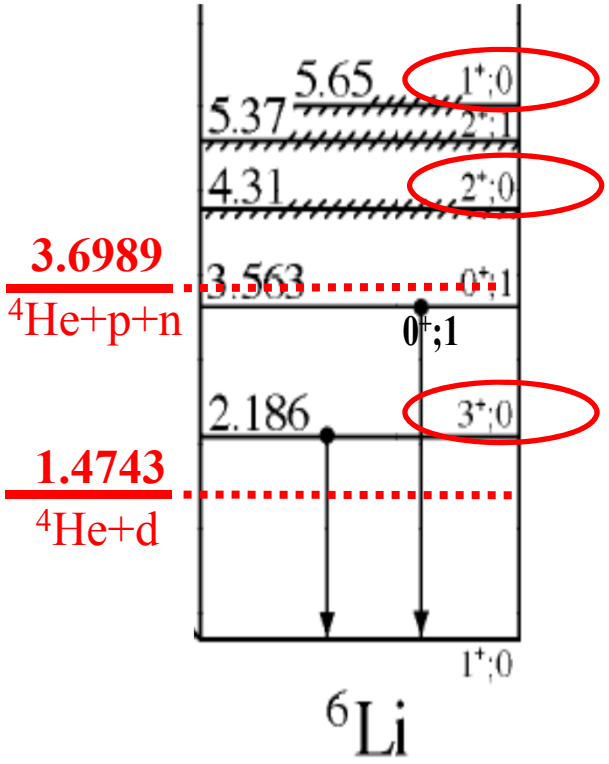
Neutron spectra of ^{6}Li(n, n') 14.1 MeV

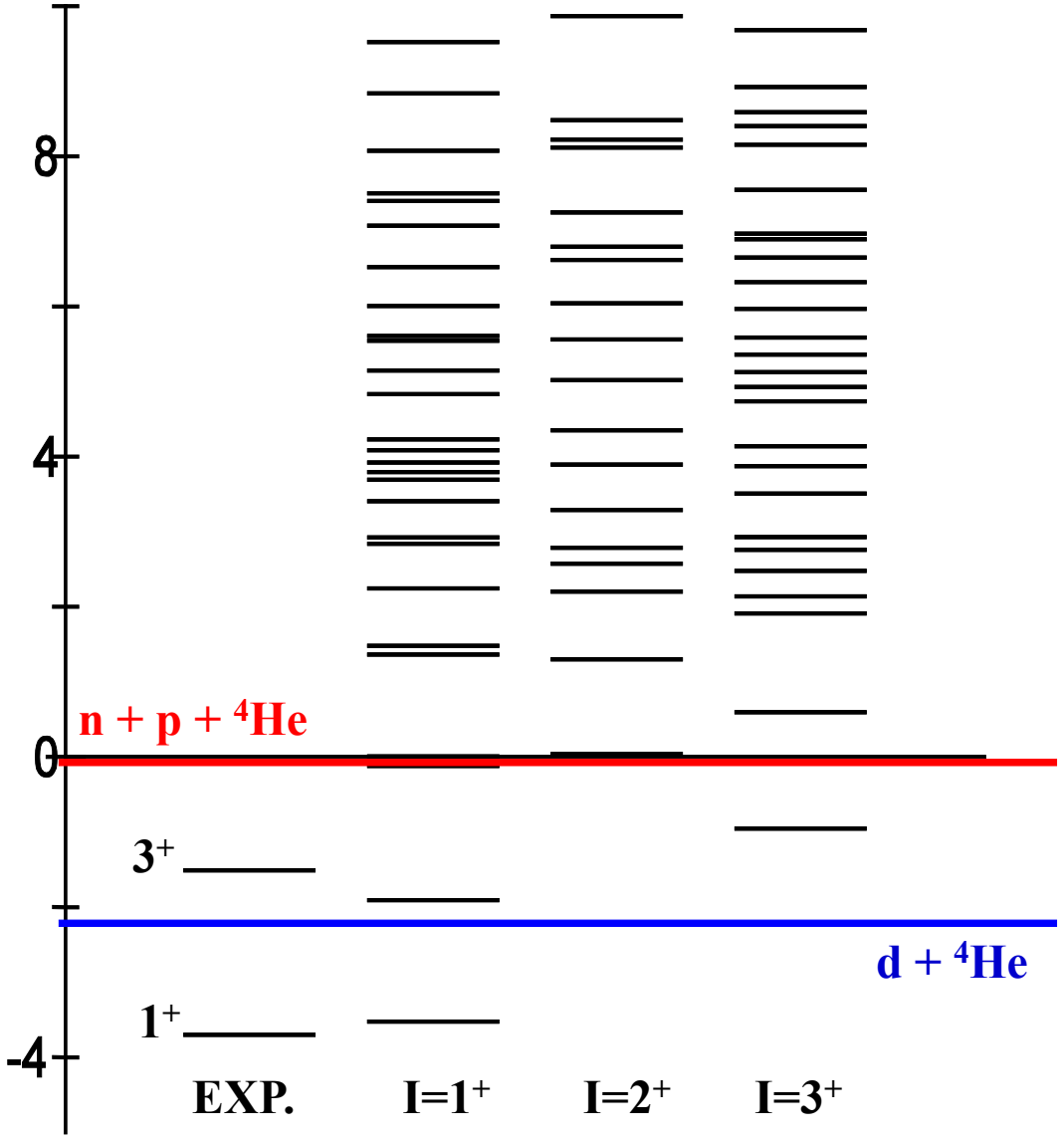


T.M., D.Ichinkhoroloo, Y. Hirabayashi, K. Kato, and S. Chiba, Phys. Rev. C. 83. 064611 (2011)

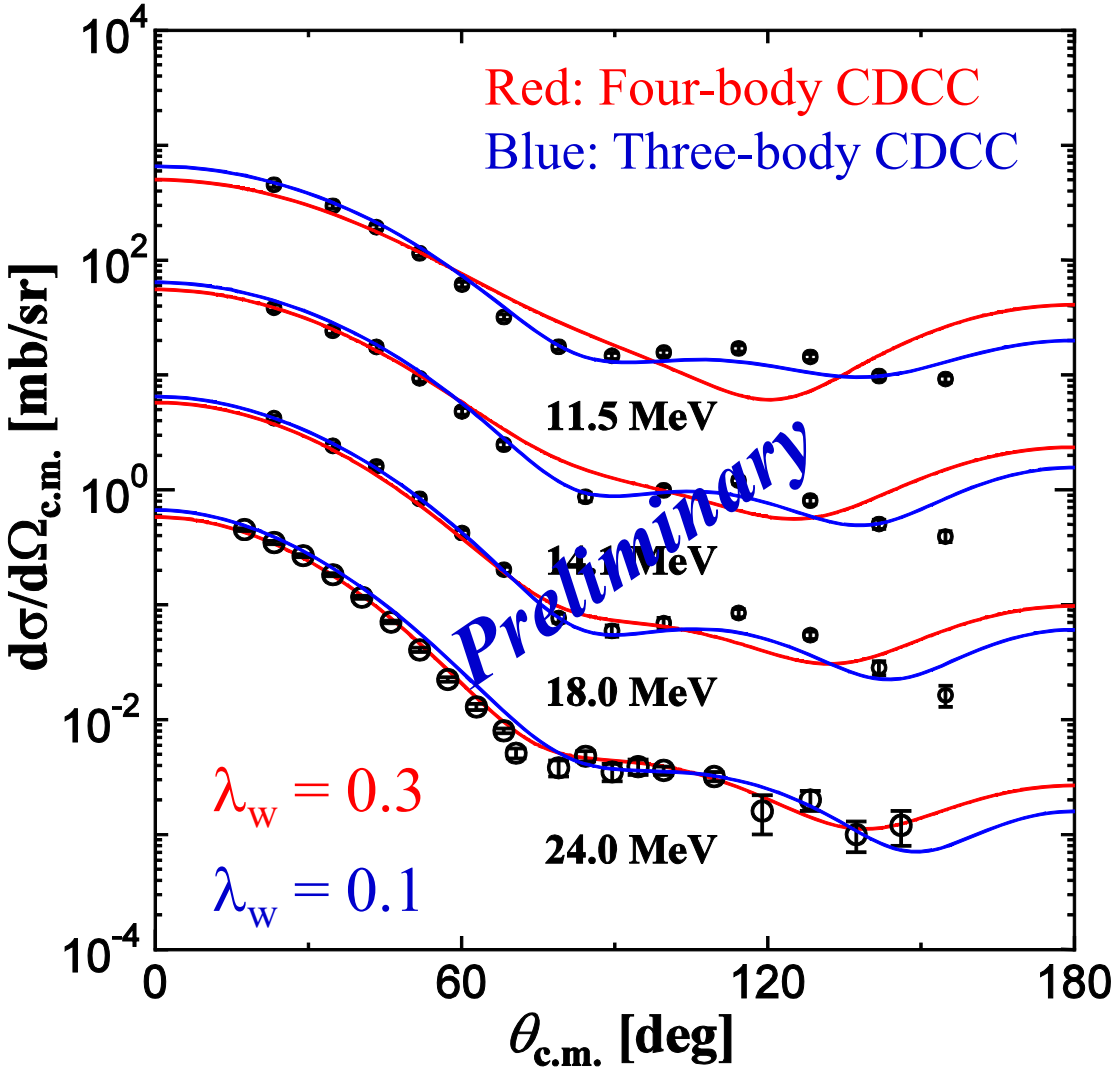
^{6}Li: $n + p + \alpha$ three-body model

^{6}He (T=1) → ^{6}Li (T=0)





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



→ **Neutron spectrum**

Summary

□ 様々な軽い原子核、不安定核に対して微視的チャネル結合計算を行った。

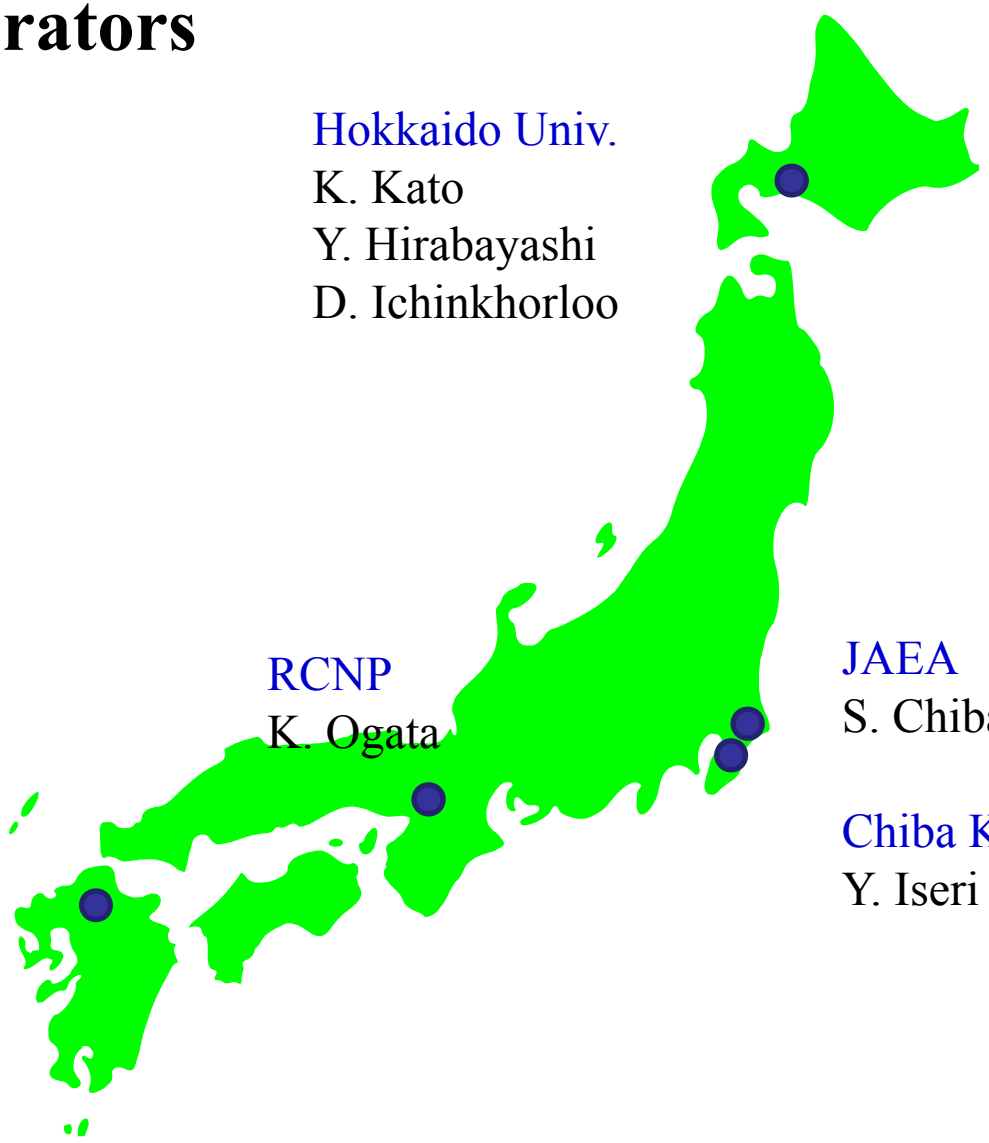
□ 有効相互作用に関しては虚数部に関してはパラメータ。

□ 弾性、非弾性散乱、分解断面積に関して実験値を再現…一つのパラメータで合わせることが可能。

✓ チャネル結合計算に有効相互作用をそのまま用いて大丈夫なのでしょうか？

✓ 2重畳込み模型に関して有効相互作用を用いるのは大丈夫なんでしょうか？

Collaborators



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Thank you