Study on the dineutron in the 2_1^+ resonance of ^{6}He

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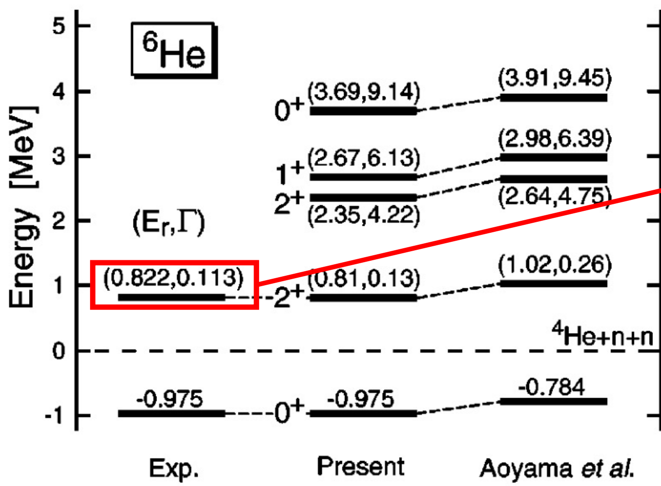
Collaborator : Takuma Matsumoto

Phys. Rev. C **105**, L041601 (2022)

Resonance of ^{6}He

Recently, by the development of experiments, resonant states of nuclei near the neutron dripline have been intensively pursued.

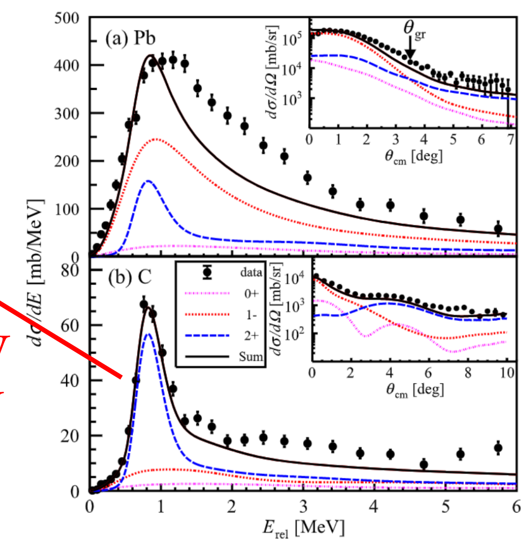
- Resonance in ^{6}He
  - 2_1^+ appears as a sharp peak in the breakup cross section.



T. Myo, et al., PRC **63**, 054313 (2001)

2_1^+

$\varepsilon_r = 0.822$ MeV
$\Gamma = 0.113$ MeV



Y. L. Sun, et al., PLB **814**, 136072 (2021)

- The existence of the dineutron in the 2_1^+ state is discussed.

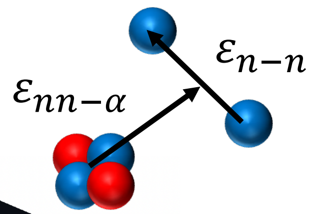
Y. Kikuchi, et al., PRC **88**, 021602(R) (2013)
A. Saito, et al., in preparation (2022)

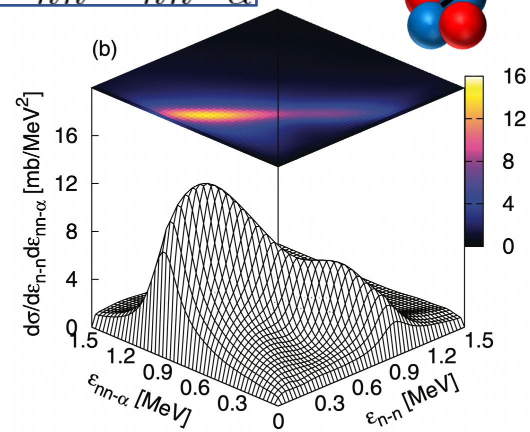
Dineutron in resonance

- Double Differential Breakup Cross Section (DDBUX)

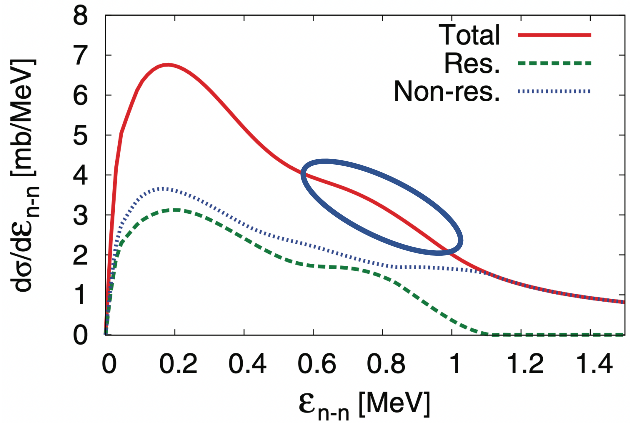
$^6He + {}^{12}C$ @ 240 MeV/A   Y. Kikuchi, et al., PRC **88**, 021602(R) (2013)

$$\frac{d^2\sigma}{d\varepsilon_{nn}d\varepsilon_{nn-\alpha}}$$





$$\frac{d\sigma}{d\varepsilon_{n\text{-}n}} = \int \frac{d\sigma}{d\varepsilon_{n\text{-}n}d\varepsilon_{nn\text{-}\alpha}}d\varepsilon_{nn\text{-}\alpha}$$



- Total (0^+, 1^-, 2^+) : A peak around ε_{n-n} = 0.7 MeV.

Dineutron in resonance

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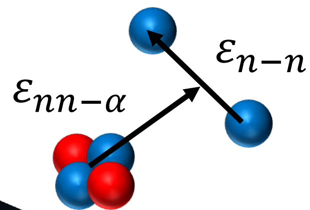
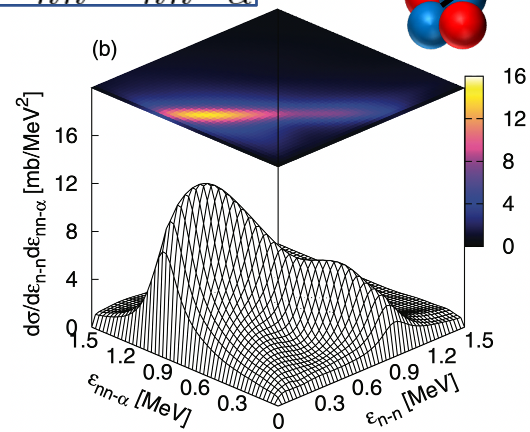
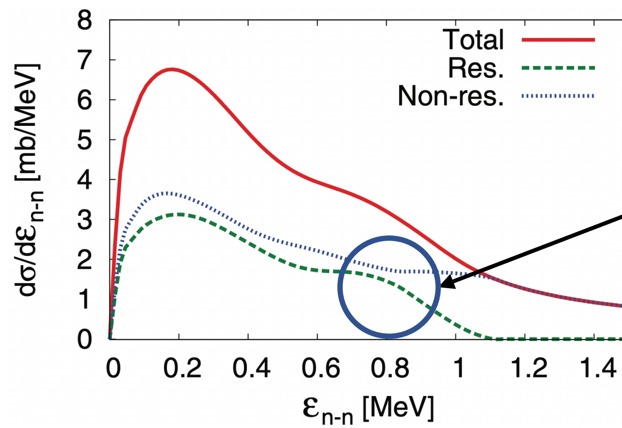
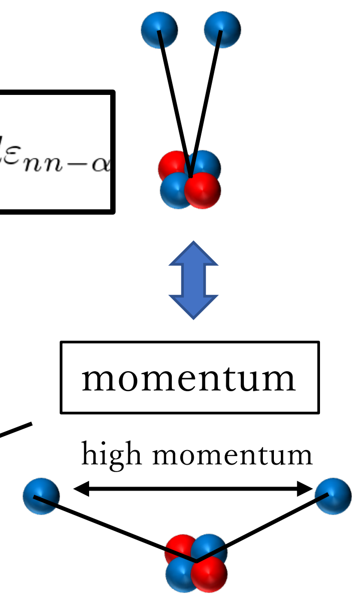




$$\frac{d\sigma}{d\varepsilon_{nn}} = \int_{0.98-0.27/2-\varepsilon_{nn}}^{0.98+0.27/2-\varepsilon_{nn}} \frac{d^2\sigma}{d\varepsilon_{nn}d\varepsilon_{nn-\alpha}} d\varepsilon_{nn-\alpha}$$



spatial

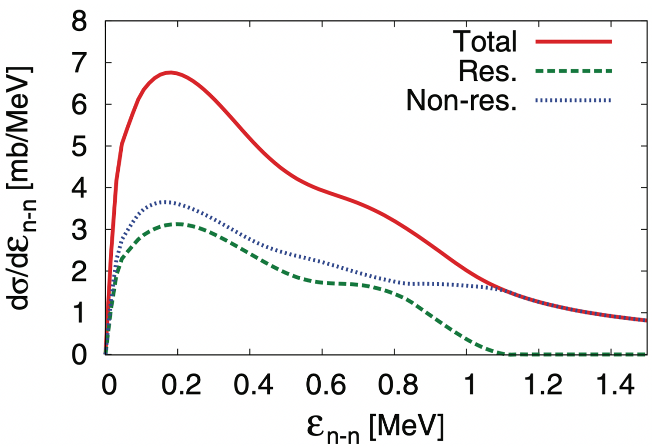


- Total (0^+, 1^-, 2^+) : A peak around $\varepsilon_{n-n} = 0.7$ MeV.
- Res. : The cross section gated within the resonant energy of 2_1^+
  Shoulder peak around $\varepsilon_{n-n} = 0.7$ MeV → Dineutron in 2_1^+?

Motivation

- The shoulder peak comes from the 2_1^+ state?
  - Although the cross section gated within the resonant energy, it cannot completely exclude the nonresonant contributions from the cross section.

- The shoulder peak comes from the dineutron?
  - The previous study only shows the existence of the peak.
  - The dineutron consists of two neutrons with $S = 0$. What is the relationship between spin and peak?



Y. Kikuchi, + PRC **88**, 021602(R) (2013)

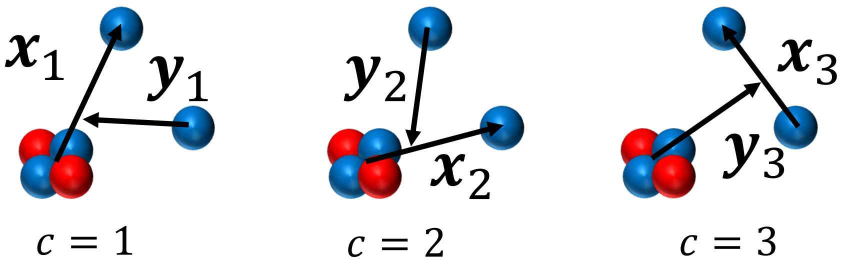
Purpose

We extract the resonant contribution from DDBUX and analyze the decay modes in more detail.

Complex Scaling Method (CSM)

CSM successfully describes resonances in the Few-body system.

- Complex scaling transformation : $U(\theta)\boldsymbol{x}U^{-1}(\theta) = \boldsymbol{x}e^{i\theta}$
- Gaussian Expansion Method



$$\Phi_{Im}(\boldsymbol{x},\boldsymbol{y}) = \sum_{c=1}^{3}\sum_{i,j,l,\lambda}\phi_{i,l}(x_c)\varphi_{j,\lambda}(y_c)\left[\left[Y_l(\hat{\boldsymbol{x}}_c)\otimes Y_\lambda(\hat{\boldsymbol{y}}_c)\right]_\Lambda \otimes \left[\eta_{1/2}\otimes\eta_{1/2}\right]_S\right]_{Im}$$

$$\phi_{i,l}(x_c) = x_c^l e^{-(x_c/x_i)^2} \qquad \varphi_{j,\lambda}(y_c) = y_c^\lambda e^{-(y_c/y_j)^2}$$

→ General eigenvalue problem for complex symmetric matrices

$$\left[\begin{pmatrix} h^\theta_{i'j',ij} \end{pmatrix} - \varepsilon^\theta \begin{pmatrix} N_{i'j',ij} \end{pmatrix}\right]\begin{pmatrix} C^\theta_{ij} \end{pmatrix} = 0$$

$$h^\theta_{i'j',ij} = \langle\tilde{\phi}_{i'}\tilde{\varphi}_{j'}|h^\theta|\phi_i\varphi_j\rangle$$

$$N_{i'j',ij} = \langle\tilde{\phi}_{i'}\tilde{\varphi}_{j'}|\phi_i\varphi_j\rangle$$

Complex Scaling Method (CSM)

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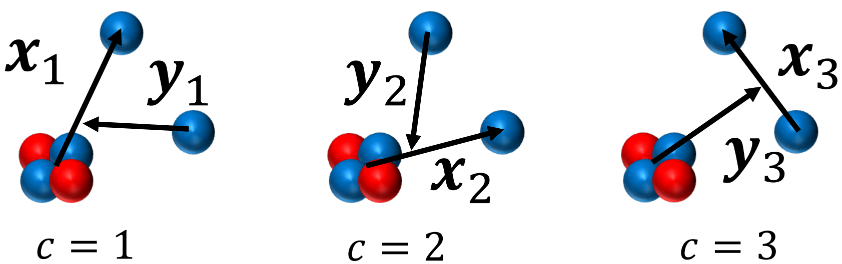

$$\Phi_{Im}(\boldsymbol{x},\boldsymbol{y}) = \sum_{c=1}^{3}\sum_{i,j,l,\lambda} \phi_{i,l}(x_c)\varphi_{j,\lambda}(y_c)\left[\left[Y_l(\hat{\boldsymbol{x}}_c)\otimes Y_\lambda(\hat{\boldsymbol{y}}_c)\right]_\Lambda \otimes \left[\eta_{1/2}\otimes\eta_{1/2}\right]_S\right]_{Im}$$

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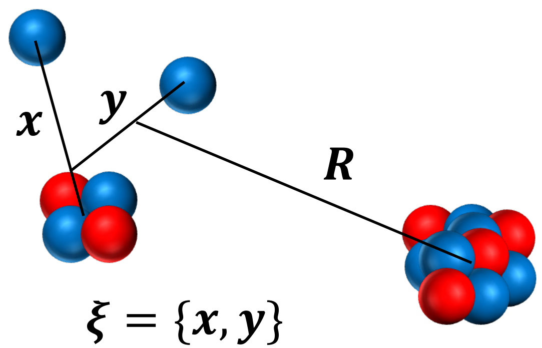
→ General eigenvalue problem for complex symmetric matrices

	ε_r [MeV]	Γ [MeV]
Result	0.823	0.121

Continuum-Discretized Coupled Channels method (CDCC)

- ^{6}He (= α+n+n) + Target → 4-body breakup reaction
- CDCC can describe 4-body breakup reaction precisely.



Schrödinger equation

$$\left[K_R + \sum_{i=nT,nT,\alpha T} U_i + V_C + h_{^6\mathrm{He}} - E\right]\Psi(\boldsymbol{\xi},\boldsymbol{R}) = 0$$

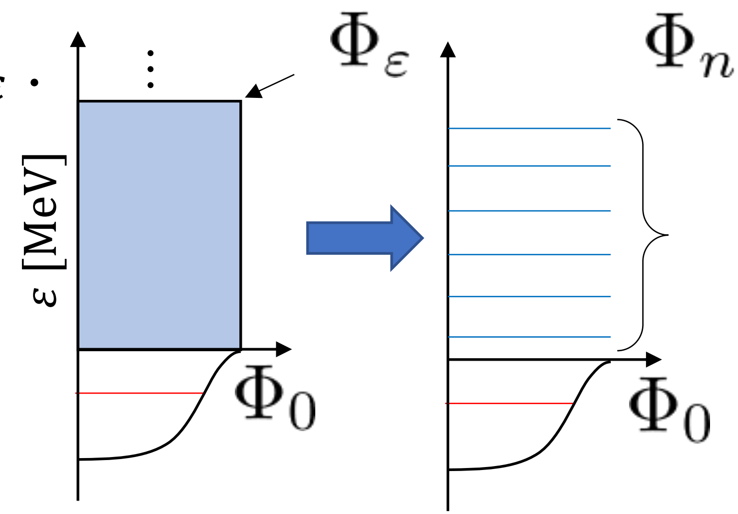
$$(h_{^6\mathrm{He}} - \varepsilon)\Phi_\varepsilon(\boldsymbol{\xi}) = 0 \qquad \Phi_\varepsilon(\boldsymbol{\xi})\text{: eigenstates of } {}^6\mathrm{He}$$

Ψ is expanded by eigenstates of ^{6}He, Φ_ε .

$$\Psi(\boldsymbol{\xi},\boldsymbol{R}) = \Phi_0(\boldsymbol{\xi})\chi_0(\boldsymbol{R}) + \int d\varepsilon\,\Phi_\varepsilon(\boldsymbol{\xi})\chi_\varepsilon(\boldsymbol{R})$$

bound discretized-continuum

$$\Psi(\boldsymbol{\xi},\boldsymbol{R}) \simeq \Phi_0(\boldsymbol{\xi})\chi_0(\boldsymbol{R}) + \sum_{n}^{n_{\max}} \Phi_n(\boldsymbol{\xi})\chi_n(\boldsymbol{R})$$



Smoothing factor for CDCC

- The cross section obtained by CDCC is discretized with respect to energy.

- Continuous T-matrix

$$T_\varepsilon \simeq \sum_n \langle \Phi_\varepsilon^{(-)} | \Phi_n \rangle \, T_n^{\mathrm{CDCC}}$$

smoothing factor

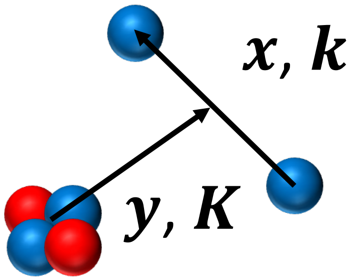
wavefunction of ^{6}He
$\Phi_\varepsilon^{(-)}$: exact state
Φ_n : discretized state

- Complex Scaled solutions of Lippmann-Schwinger eq. (CSLS)

Y. Kikuchi, et al., Phys. Rev. C **88** (2013), 021602(R)

$$\langle \Phi_\varepsilon^{(-)} | = \langle \phi_\varepsilon | + \langle \phi_\varepsilon | V \frac{1}{\varepsilon - h + i\eta}$$

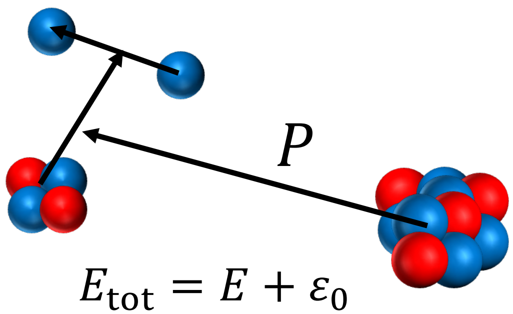
$$\frac{1}{\varepsilon - h + i\eta} = U^{-1}(\theta) \sum_\nu |\Phi_\nu^\theta\rangle \frac{1}{\varepsilon - \varepsilon_\nu^\theta} \langle \tilde{\Phi}_\nu^\theta | U(\theta)$$



$$\langle \Phi_{\mathrm{CSLS}}^{(-)} | = \langle \phi_\varepsilon | + \sum_\nu \langle \phi_\varepsilon | V U^{-1}(\theta) | \Phi_\nu^\theta \rangle \frac{1}{\varepsilon - \varepsilon_\nu^\theta} \langle \tilde{\Phi}_\nu^\theta | U(\theta)$$

plane wave : $\phi_\varepsilon = e^{i\boldsymbol{k}\cdot\boldsymbol{r}} e^{i\boldsymbol{K}\cdot\boldsymbol{R}}$

Double Differential Breakup Cross section (DDBUX)



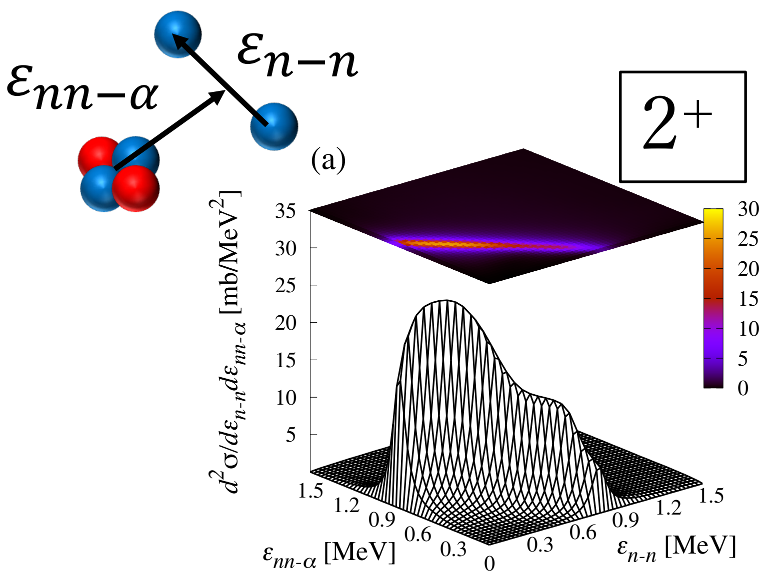
- Continuous T-matrix with CSLS

$$T(\boldsymbol{k}, \boldsymbol{K}) = \sum_n \langle \Phi^{(-)}_{\mathrm{CSLS}} | \Phi_n \rangle \, T^{\mathrm{CDCC}}_n$$

- DDBUX

$$\frac{d^2\sigma}{d\varepsilon_{n\text{-}n} d\varepsilon_{nn\text{-}\alpha}} = \sum_{nn'} T_n T^\dagger_{n'} \int d\boldsymbol{k} d\boldsymbol{K} d\boldsymbol{P} \, \langle \Phi^{(-)}_{\mathrm{CSLS}} | \Phi_n \rangle \langle \Phi_{n'} | \Phi^{(-)}_{\mathrm{CSLS}} \rangle$$

$$\times \, \delta\left(E_{\mathrm{tot}} - \frac{\hbar^2 \boldsymbol{P}^2}{2\mu} - \varepsilon_{n\text{-}n} - \varepsilon_{nn\text{-}\alpha} \right) \delta\left(\varepsilon_{n\text{-}n} - \frac{\hbar^2 \boldsymbol{k}^2}{2\mu_{n\text{-}n}} \right) \delta\left(\varepsilon_{nn\text{-}\alpha} - \frac{\hbar^2 \boldsymbol{K}^2}{2\mu_{nn\text{-}\alpha}} \right)$$



^{6}He + ^{12}C @ 240 MeV /A

- A peak structure at $\varepsilon_{n-n} + \varepsilon_{nn-\alpha} \sim 0.8$ MeV.
- Both of resonant and nonresonant contributions are included.

Cross section for resonant state

- Rewrite T-matrix

$$U^{-1}(\theta)U(\theta) = 1$$

Extended Complete Relation

$$\sum_{\nu} |\Phi_{\nu}^{\theta}\rangle \langle\tilde{\Phi}_{\nu}^{\theta}| \simeq 1$$

$$T_{\varepsilon} = \sum_{n} \langle\Phi_{\rm CSLS}^{(-)}|\Phi_{n}\rangle\, T_{n}^{\rm CDCC}$$

$$= \sum_{n} \langle\Phi_{\rm CSLS}^{(-)}| \sum_{\nu} U^{-1}(\theta)\, |\Phi_{\nu}^{\theta}\rangle \langle\tilde{\Phi}_{\nu}^{\theta}|\, U(\theta)\, |\Phi_{n}\rangle\, T_{n}^{\rm CDCC}$$

$$= \sum_{\nu} \langle\Phi_{\rm CSLS}^{(-)}|U^{-1}(\theta)|\Phi_{\nu}^{\theta}\rangle\, \tilde{T}_{\nu}^{\theta} \quad \left(\tilde{T}_{\nu}^{\theta} = \sum_{n} \langle\tilde{\Phi}_{\nu}^{\theta}|U(\theta)|\Phi_{n}\rangle\, T_{n}^{\rm CDCC}\right)$$

- DDBUX with the rewritten T-matrix

$$\frac{d^2\sigma}{d\varepsilon_{n\text{-}n}\, d\varepsilon_{nn\text{-}\alpha}} = \sum_{\nu\nu'} \tilde{T}_{\nu}^{\theta} \tilde{T}_{\nu'}^{\theta\dagger} \int d\boldsymbol{k}\, d\boldsymbol{K}\, d\boldsymbol{P}\, \langle\Phi_{\rm CSLS}^{(-)}|U^{-1}(\theta)|\Phi_{\nu}^{\theta}\rangle \langle\tilde{\Phi}_{\nu'}^{-\theta}|U^{-1}(\theta)|\Phi_{\rm CSLS}^{(-)}\rangle$$

$$\times\, \delta\left(E_{\rm tot} - \frac{\hbar^2 \boldsymbol{P}^2}{2\mu} - \varepsilon_{n\text{-}n} - \varepsilon_{nn\text{-}\alpha}\right) \delta\left(\varepsilon_{n\text{-}n} - \frac{\hbar^2 \boldsymbol{k}^2}{2\mu_{n\text{-}n}}\right) \delta\left(\varepsilon_{nn\text{-}\alpha} - \frac{\hbar^2 \boldsymbol{K}^2}{2\mu_{nn\text{-}\alpha}}\right)$$

Cross section for resonant state

- Rewrite T-matrix

$$T_\varepsilon = \sum_n \langle \Phi^{(-)}_{\rm CSLS} | \Phi_n \rangle T^{\rm CDCC}_n$$

$$= \sum_n \langle \Phi^{(-)}_{\rm CSLS} | \sum_\nu U^{-1}(\theta) | \Phi^\theta_\nu \rangle \langle \tilde{\Phi}^\theta_\nu | U(\theta) | \Phi_n \rangle T^{\rm CDCC}_n$$

$$= \sum_\nu \langle \Phi^{(-)}_{\rm CSLS} | U^{-1}(\theta) | \Phi^\theta_\nu \rangle \tilde{T}^\theta_\nu \quad \left(\tilde{T}^\theta_\nu = \sum_n \langle \tilde{\Phi}^\theta_\nu | U(\theta) | \Phi_n \rangle T^{\rm CDCC}_n \right)$$

$$U^{-1}(\theta) U(\theta) = 1$$

Extended Complete Relation

$$\sum_\nu |\Phi^\theta_\nu\rangle \langle \tilde{\Phi}^\theta_\nu | \simeq 1$$

- $\nu = \nu' = \text{Res.}$

  → We define this term as a cross section for the resonance.

$$\frac{d^2\sigma_{\rm Res.}}{d\varepsilon_{n\text{-}n} d\varepsilon_{nn\text{-}\alpha}} \equiv |\tilde{T}^\theta_{\rm Res.}|^2 \int d\boldsymbol{k} d\boldsymbol{K} d\boldsymbol{P} | \langle \Phi^{(-)}_{\rm CSLS} | U^{-1}(\theta) | \Phi^\theta_{\rm Res.} \rangle |^2$$

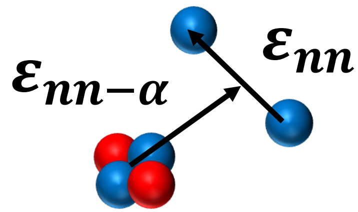
$$\times \delta\left(E_{\rm tot} - \frac{\hbar^2 \boldsymbol{P}^2}{2\mu} - \varepsilon_{n\text{-}n} - \varepsilon_{nn\text{-}\alpha} \right) \delta\left(\varepsilon_{n\text{-}n} - \frac{\hbar^2 \boldsymbol{k}^2}{2\mu_{n\text{-}n}} \right) \delta\left(\varepsilon_{nn\text{-}\alpha} - \frac{\hbar^2 \boldsymbol{K}^2}{2\mu_{nn\text{-}\alpha}} \right)$$

  - The shape of the cross section is reflected by $\left| \left\langle \Phi^{(-)}_{\rm CSLS} \middle| U^{-1}(\theta) \middle| \Phi^\theta_{\rm Res.} \right\rangle \right|^2$.

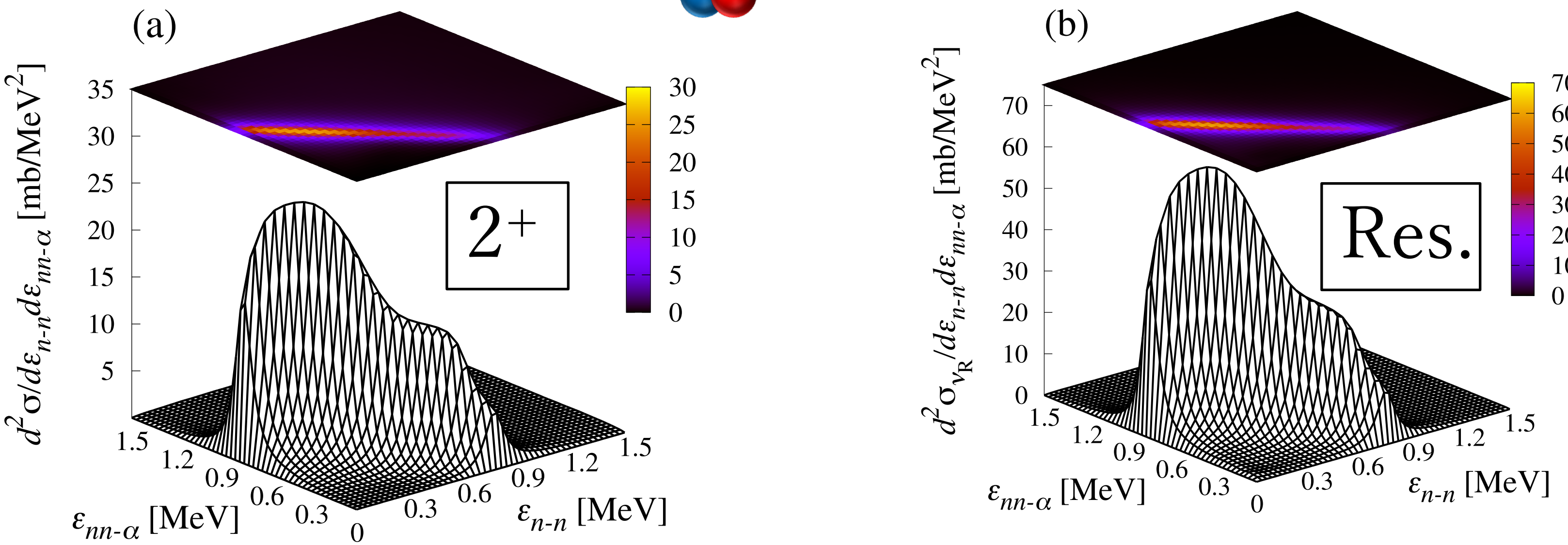
Double differential breakup cross section

^{6}He + ^{12}C @ 240 MeV /A

$$\frac{d^2\sigma}{d\varepsilon_{nn}d\varepsilon_{nn-\alpha}}$$



$$\frac{d^2\sigma_{\mathrm{Res.}}}{d\varepsilon_{nn}d\varepsilon_{nn-\alpha}}$$



- DDBUX for the resonance has a peak structure at the same position as DDBUX for $I^\pi = 2^+$ state.

Double differential breakup cross section

^{6}He + ^{12}C @ 240 MeV /A

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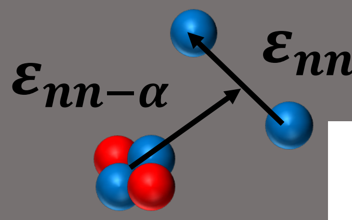
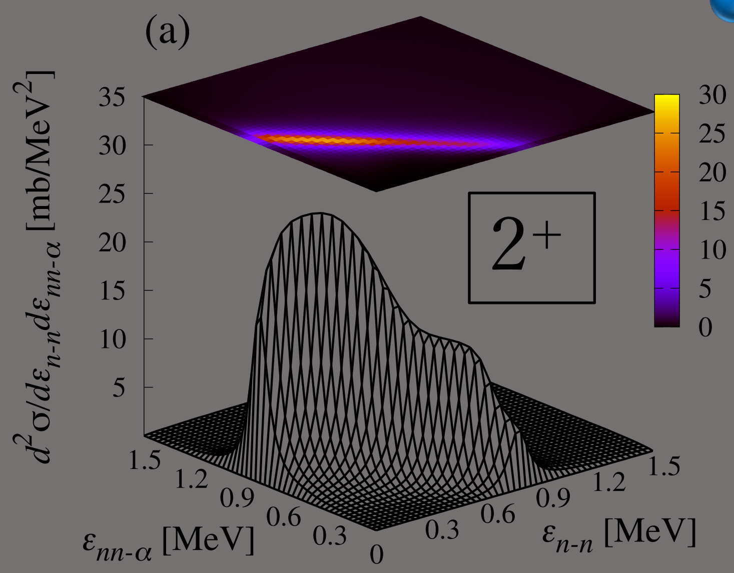
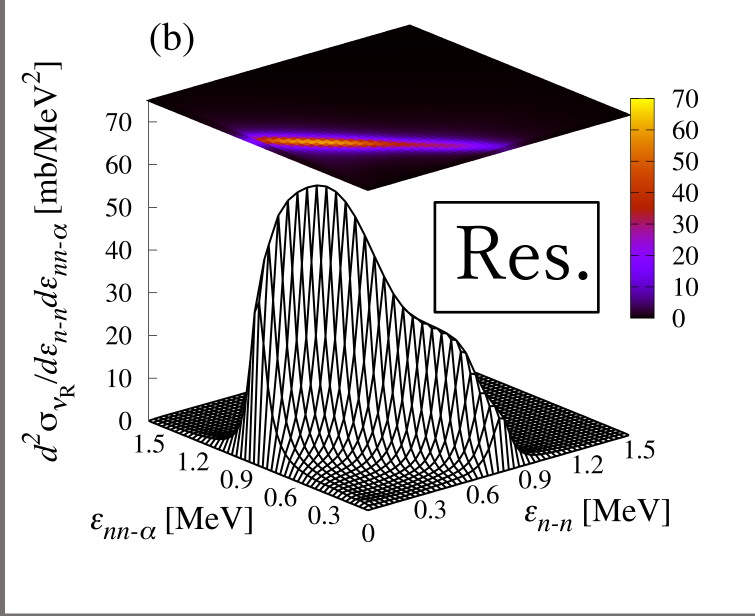


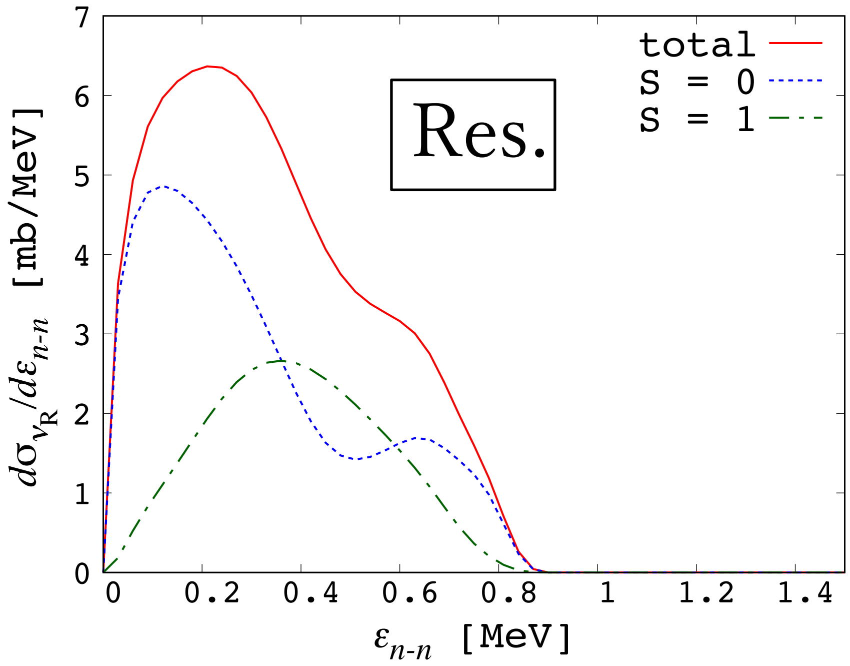
$$\frac{d^2\sigma_{\mathrm{Res.}}}{d\varepsilon_{nn}d\varepsilon_{nn-\alpha}}$$





- DDBUX for the resonance has a peak structure at the same position as DDBUX for $I^{\pi} = 2^{+}$ state.

Contribution from 2_1^+



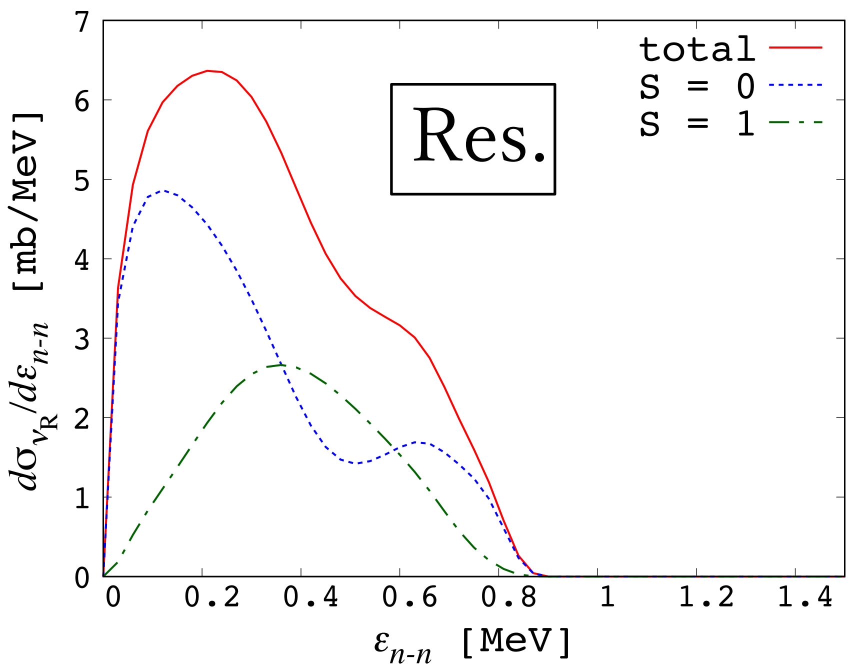
DDBUX is integrated over $\varepsilon_{nn-\alpha}$ in the region D.

$$\frac{d\sigma_{\text{Res.}}}{d\varepsilon_{n-n}} = \int_D \frac{d^2\sigma_{\text{Res.}}}{d\varepsilon_{n-n}\, d\varepsilon_{nn-\alpha}}\, d\varepsilon_{nn-\alpha}$$

$$\left(D : \varepsilon_r - \frac{\Gamma}{2} \le \varepsilon_{n-n} + \varepsilon_{nn-\alpha} \le \varepsilon_r + \frac{\Gamma}{2}\right)$$

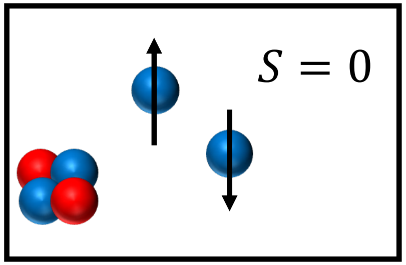
- Solid line： shoulder peak around $\varepsilon_{n-n} = 0.7$ MeV

Contribution from 2_1^+

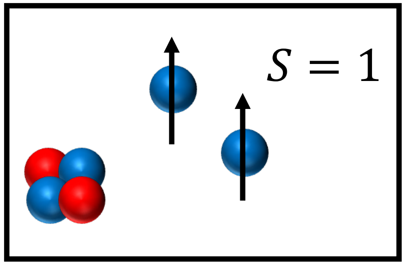


Separate the cross section into the $S = 0$ and 1 contribution.

$$\frac{d\sigma_{\mathrm{Res.}}}{d\varepsilon_{n-n}} = \left(\frac{d\sigma_{\mathrm{Res.}}}{d\varepsilon_{n-n}}\right)_{S=0} + \left(\frac{d\sigma_{\mathrm{Res.}}}{d\varepsilon_{n-n}}\right)_{S=1}$$



or



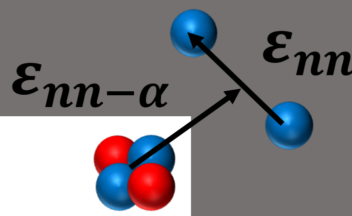
- Solid line : shoulder peak around $\varepsilon_{n-n} = 0.7$ MeV
- Dotted line : $S = 0$ component has a peak at $\varepsilon_{n-n} = 0.7$ MeV.

→ These results indicate existence of the dineutron in the 2_1^+ state.

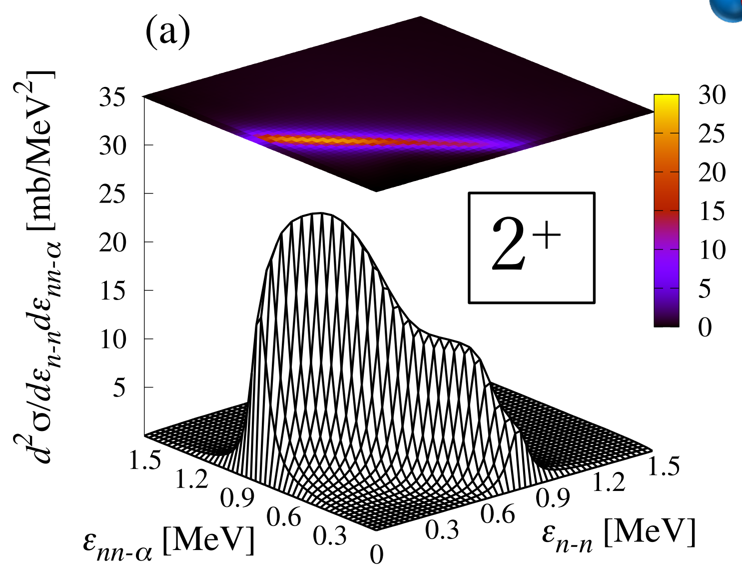
Double differential breakup cross section

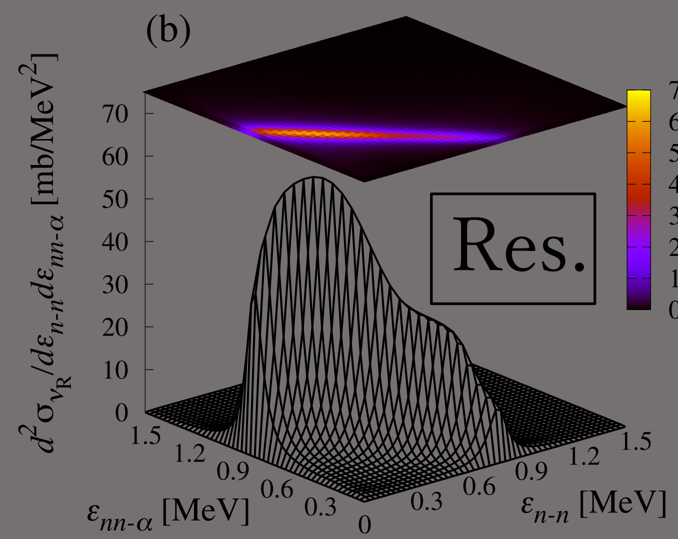
^{6}He + ^{12}C @ 240 MeV /A

$$\frac{d^2\sigma}{d\varepsilon_{nn}d\varepsilon_{nn-\alpha}}$$



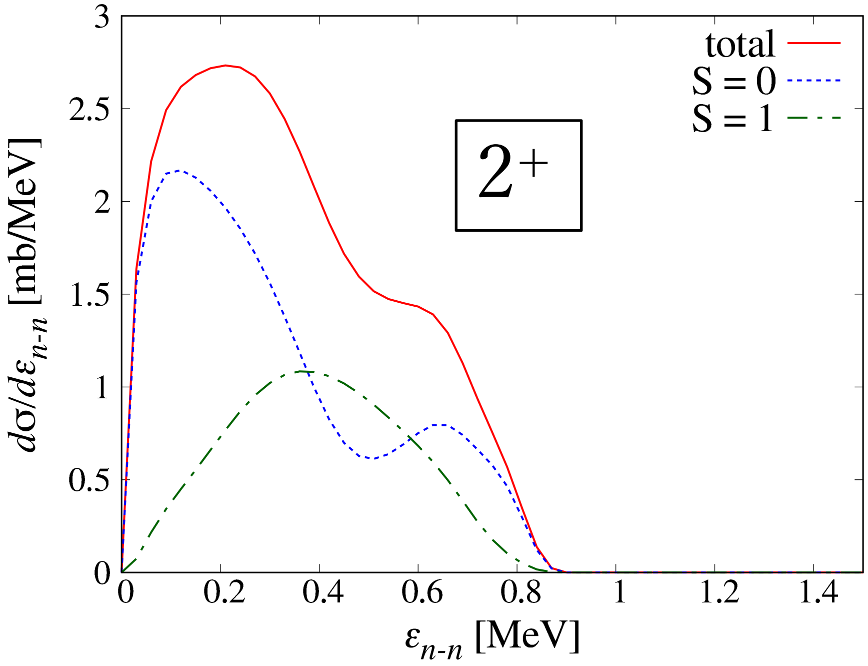
$$\frac{d^2\sigma_{\mathrm{Res.}}}{d\varepsilon_{nn}d\varepsilon_{nn-\alpha}}$$





- DDBUX for the resonance has a peak structure at the same position as DDBUX for $I^{\pi} = 2^{+}$ state.

Measurable cross section



The same definition as one, which discussed in the previous work.

$$\frac{d\sigma}{d\varepsilon_{n-n}} = \int_D \frac{d^2\sigma}{d\varepsilon_{n-n} d\varepsilon_{nn-\alpha}} d\varepsilon_{nn-\alpha}$$

$$\left(D : \varepsilon_r - \frac{\Gamma}{2} \leq \varepsilon_{n-n} + \varepsilon_{nn-\alpha} \leq \varepsilon_r + \frac{\Gamma}{2}\right)$$

- The same shoulder peak as in the case of the resonance.
- $S = 0$ component of the measurable cross section has also the peak at $\varepsilon_{n-n} = 0.7$ MeV.

The behavior of the resonant cross section and measurable cross section is same.
→ The shoulder peak can be expected to come from the dineutron in 2_1^+.

Summary

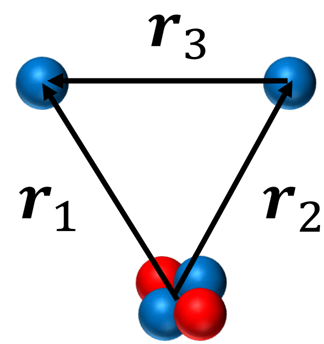
We analyze the breakup reaction for ^{6}He + ^{12}C system, with CDCC and CSLS.

- We define the DDBUX for the resonance.
- From the analysis of the cross sections of the resonant states, it is found that two neutrons with $S = 0$ contribute to the shoulder peak.
- Similar peaks from the S=0 component appears in the measurable cross sections.
- These results strongly support the existence of the dineutron in the 2_1^+ state of ^{6}He.

Back up

Hamiltonian of ^{6}He

$$h = \sum_{i=1}^{3} t_i - T_G + \sum_{i=1}^{2} V_{n\alpha}(r_i) + V_{nn}(r_3) + V_{nn\alpha}(r_1, r_2, r_3) + V_{\text{Pauli}}$$



- $V_{n\alpha}$: KKNN interaction

  H. Kanada et al., Prog. Theor. Phys. **61**, 1327.

- V_{nn} : Minnesota interaction

  D. R. Thompson, et al., Nucl. Phys. A **286**, 53.

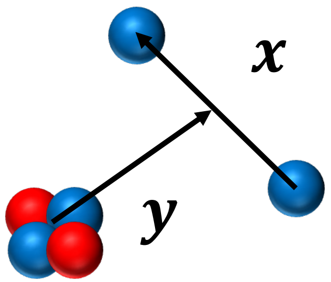
- $V_{nn\alpha}$: Phenomenological 3-body force

  We introduce $V_{nn\alpha}$ to reproduce the binding energy of ground state and the resonant energy and decay width of the 2_1^+ state.

- V_{Pauli} : Orthogonal condition model

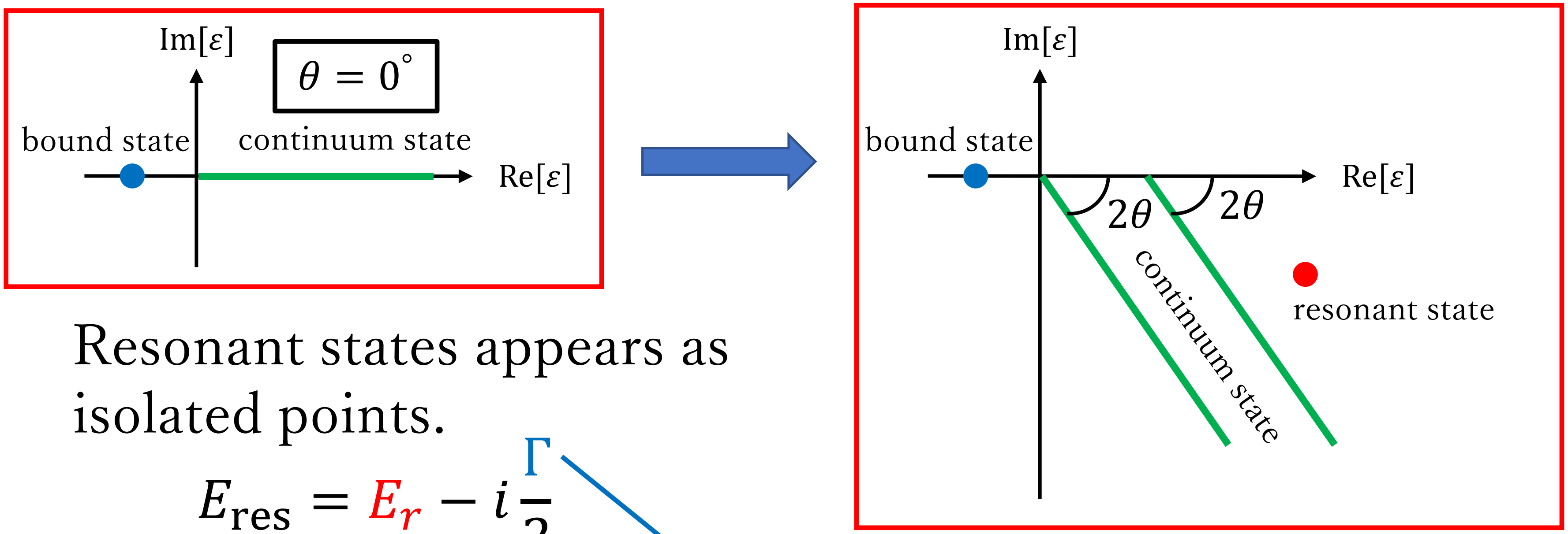
  S. Saito, Prog. Theor. Phys. **41**, 705.

Complex Scaling Method (CSM)



Transform the internal coordinates $\boldsymbol{x}$, $\boldsymbol{y}$ of ^{6}He as follow:

$$U(\theta)\boldsymbol{x}U^{-1}(\theta) = \boldsymbol{x}e^{i\theta}, \quad U(\theta)\boldsymbol{y}U^{-1}(\theta) = \boldsymbol{y}e^{i\theta}$$



Resonant states appears as isolated points.

$$E_{\mathrm{res}} = E_r - i\frac{\Gamma}{2}$$

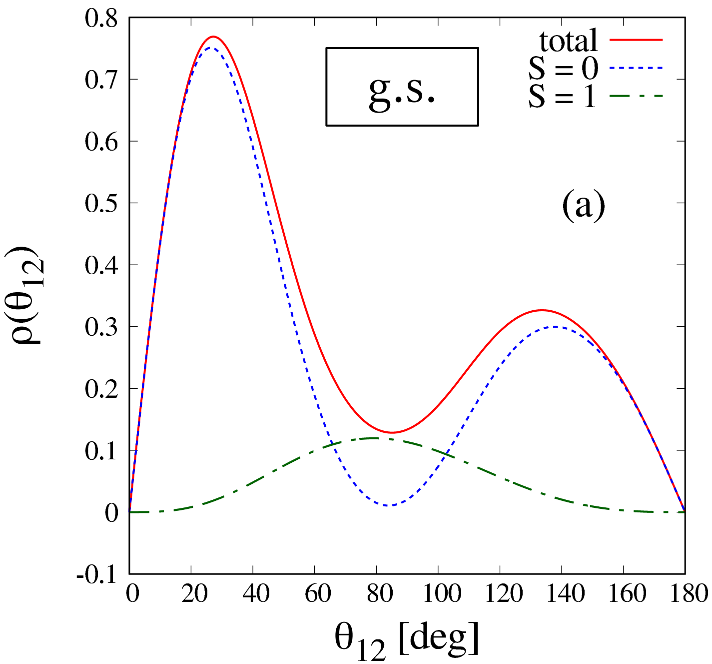
Resonant energy

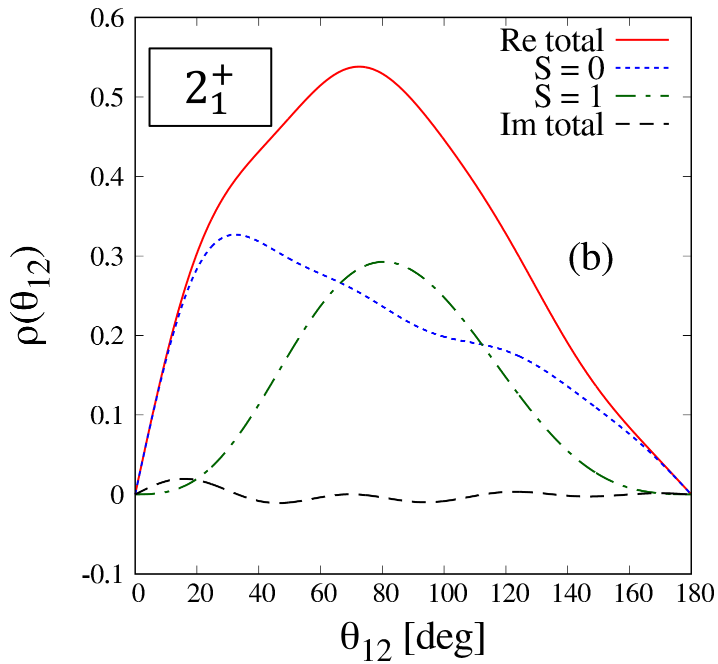
Decay width

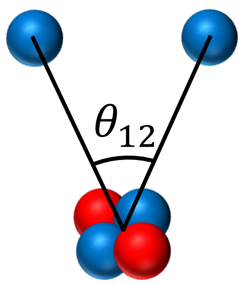
Angular density

$$\rho(\theta_{12}) = \langle \tilde{\Phi}^{\theta}_{\mathrm{Res.}} | \delta(\theta_{12} - \omega) | \Phi^{\theta}_{\mathrm{Res.}} \rangle$$

This density is defined in [A. T. Kruppa, et al., PRC **89**, 014330 (2013)].







- This density does not depend on the scaling angle θ.
- 2^+_1
  - Total : A peak at $\theta_{12} \sim 80^\circ$.
  - $S = 0$: A peak at $\theta_{12} \sim 30^\circ$ $\rightarrow$ dineutron?

Complex scaling transformation

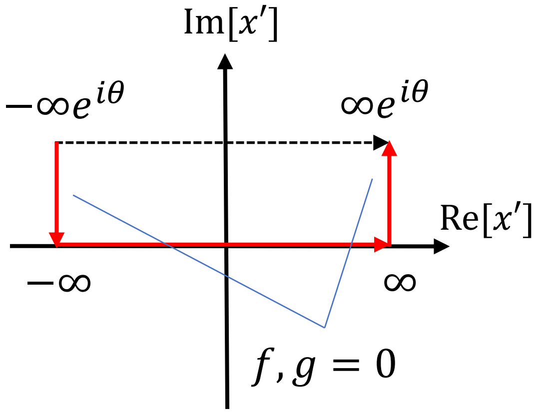
- Property of complex scaling transformation

$$U^{-1}(\theta) = U(-\theta) = [U(\theta)]^*$$

$$\langle g|U(\theta)f\rangle = \langle U^\dagger(\theta)g|f\rangle$$

$$\begin{aligned}\langle g|U(\theta)f\rangle &= \int_{-\infty}^{\infty} dx\, g^*(x) e^{i\frac{\theta}{2}} f\left(xe^{i\theta}\right) \\ &= \int_{-\infty e^{i\theta}}^{\infty e^{i\theta}} dx' e^{-i\frac{\theta}{2}} g^*\left(x' e^{-i\theta}\right) f(x') \qquad \left(x' = xe^{i\theta}\right) \\ &= \int_{-\infty}^{\infty} dx\, e^{-i\frac{\theta}{2}} g^*\left(xe^{-i\theta}\right) f(x) \\ &= \int_{-\infty}^{\infty} dx \left[e^{i\frac{\theta}{2}} g\left(xe^{i\theta}\right)\right]^* f(x) \\ &= \langle U(\theta)g|f\rangle \end{aligned}$$

$\Rightarrow$ $U(\theta) = U^\dagger(\theta)$



- Property of the scaled Hamiltonian

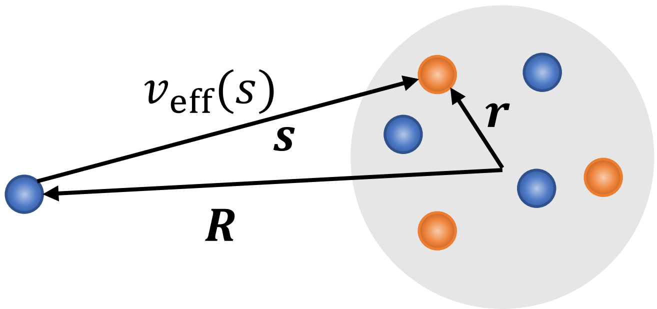
$$h^{\theta\,\dagger} = [U(\theta)hU^{-1}(\theta)]^\dagger = U^{-1}(\theta)hU(\theta) = h^{-\theta}$$

Optical potential

✓ Potential between n and T

Single Folding Model

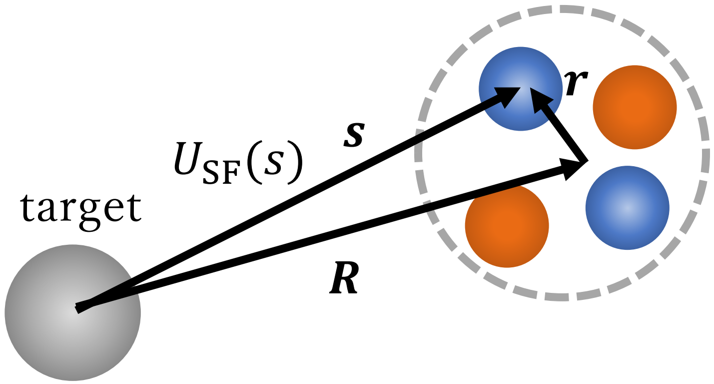
$\rho_{\mathrm{T}}(r)$: target density



$$U_{\mathrm{SF}}(R) = \int \rho^{(^{12}\mathrm{C})}(r) v_{\mathrm{eff}}(s) d\boldsymbol{r}$$

✓ Potential between α and T

Double Single Folding Model



$$U_{\mathrm{DSF}}(R) = \int d\boldsymbol{r} U_{\mathrm{SF}}(s) \rho^{(\alpha)}(\boldsymbol{r})$$

$v_{\mathrm{eff}}(s)$: Melbourne g-matrix

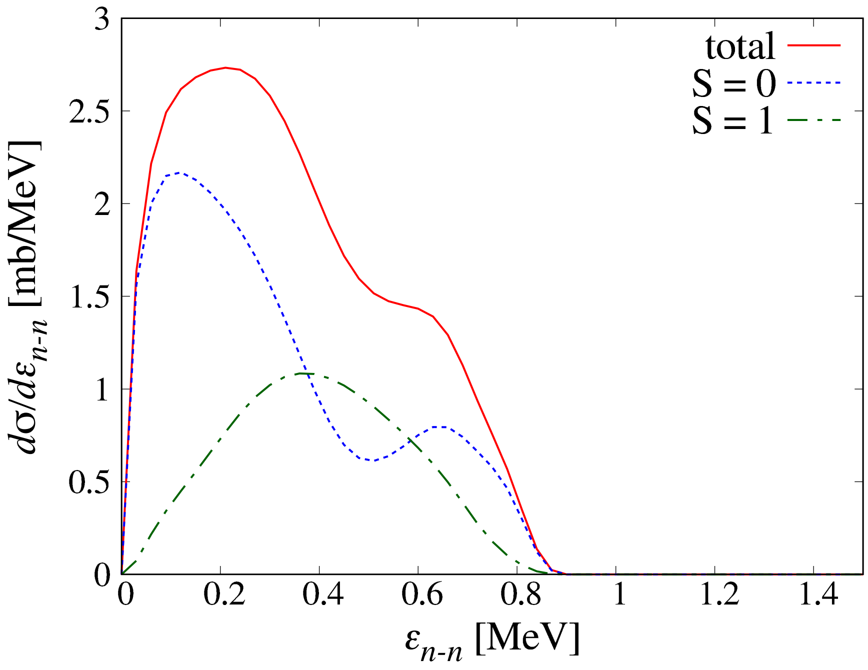
K. Amos, et al., in Advances in Nuclear Physics, **25**, 275 (2000).

NN interaction and the shape of the cross section

$$\frac{d\sigma}{d\varepsilon_{n-n}} = \int_D \frac{d^2\sigma}{d\varepsilon_{n-n} d\varepsilon_{nn-\alpha}} d\varepsilon_{nn-\alpha} \qquad \left(D : \varepsilon_r - \frac{\Gamma}{2} \leq \varepsilon_{n-n} + \varepsilon_{nn-\alpha} \leq \varepsilon_r + \frac{\Gamma}{2}\right)$$

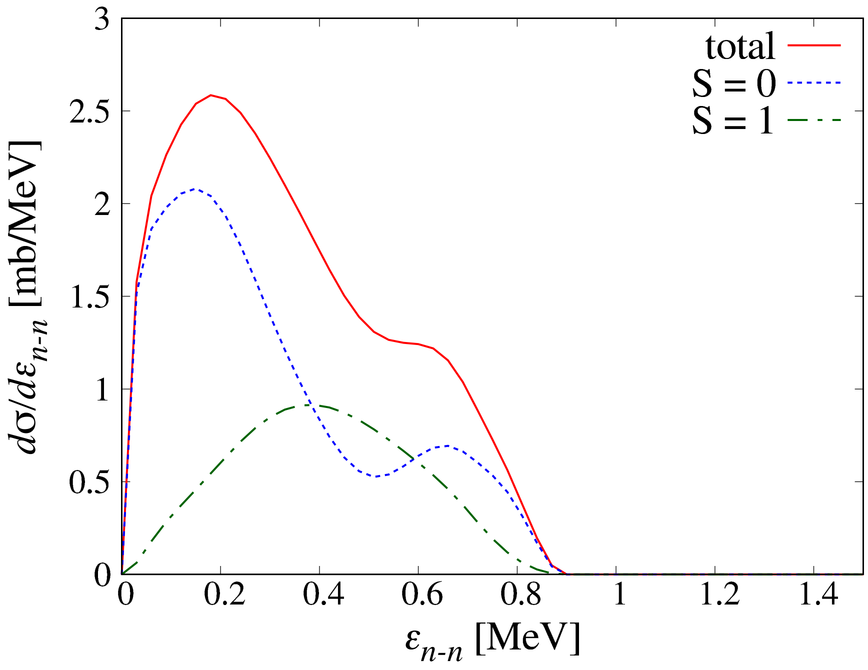
Minnesota interaction

D. R. Thompson, et al., Nucl. Phys. A 286, 53 (1977)



Gogny-Pires-Tourreil interaction

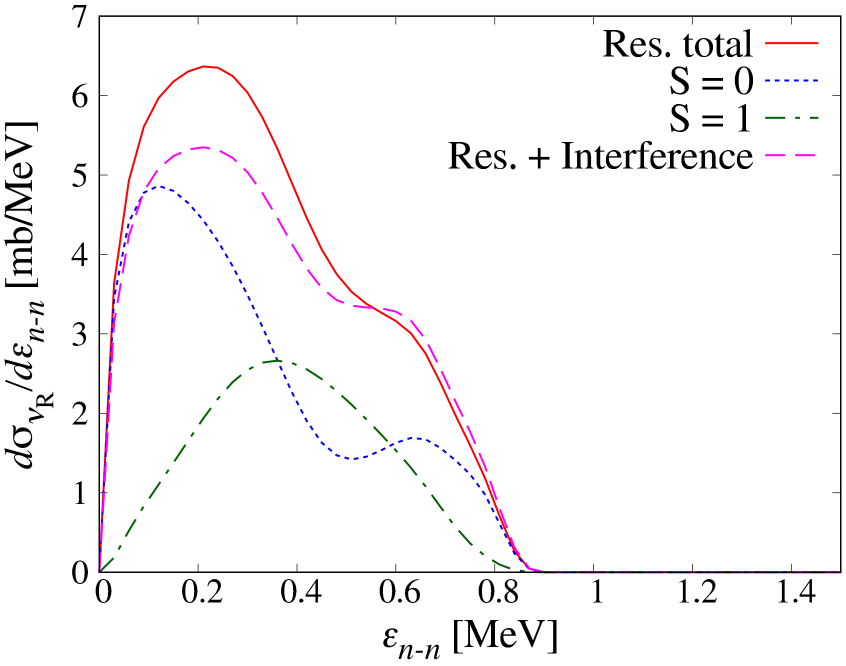
D. Gogny, et al., Phys. Lett. B 32, 591 (1970).



Interference between the resonant and nonresonant states

$$\left(\frac{d\sigma}{d\varepsilon_{n\text{-}n}}\right)_{\text{interference}} \equiv \int_D d\varepsilon_{n\text{-}n} 2\mathrm{Re}\left[\sum_{\nu\in D'} T_\nu^\theta T_{\nu_\mathrm{R}}^\theta \int d\boldsymbol{k} d\boldsymbol{K} d\boldsymbol{P} \langle\Phi_{\mathrm{CSLS}}^{(-)}|U^{-1}(\theta)|\Phi_{\nu_\mathrm{R}}^\theta\rangle\langle\Phi_\nu^{-\theta}|U^{-1}(\theta)|\Phi_{\mathrm{CSLS}}^{(-)}\rangle \delta_{e.c.}\right]$$

$$(D' : \varepsilon_r - \Gamma/2 \le \mathrm{Re}[\varepsilon_\nu^\theta] \le \varepsilon_r + \Gamma/2, \quad \nu \ne \nu_R).$$

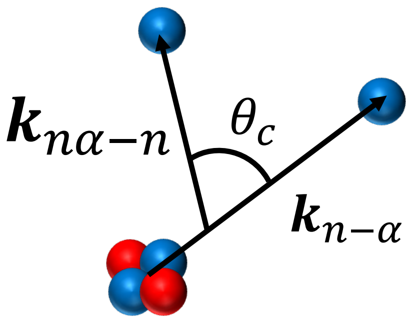


Future work

I will investigate the distribution of the correlation angle θ_c.

- Calculate the triple differential breakup cross section

$$\frac{d^3\sigma}{d\varepsilon_{n\text{-}\alpha}d\varepsilon_{n\alpha\text{-}n}d\theta_c}$$



- Discuss the following cross section

$$\frac{d^2\sigma}{d\varepsilon_{n\text{-}\alpha}d\theta_c} = \int_D d\varepsilon_{n\alpha\text{-}n}\frac{d^3\sigma}{d\varepsilon_{n\text{-}\alpha}d\varepsilon_{n\alpha\text{-}n}d\theta_c}$$

$$(\varepsilon_r - \Gamma/2 \leq \varepsilon_{n\text{-}\alpha} + \varepsilon_{n\alpha\text{-}n} \leq \varepsilon_r + \Gamma/2)$$