Subsystem correlations in Coulomb breakup reactions of ^{6}He

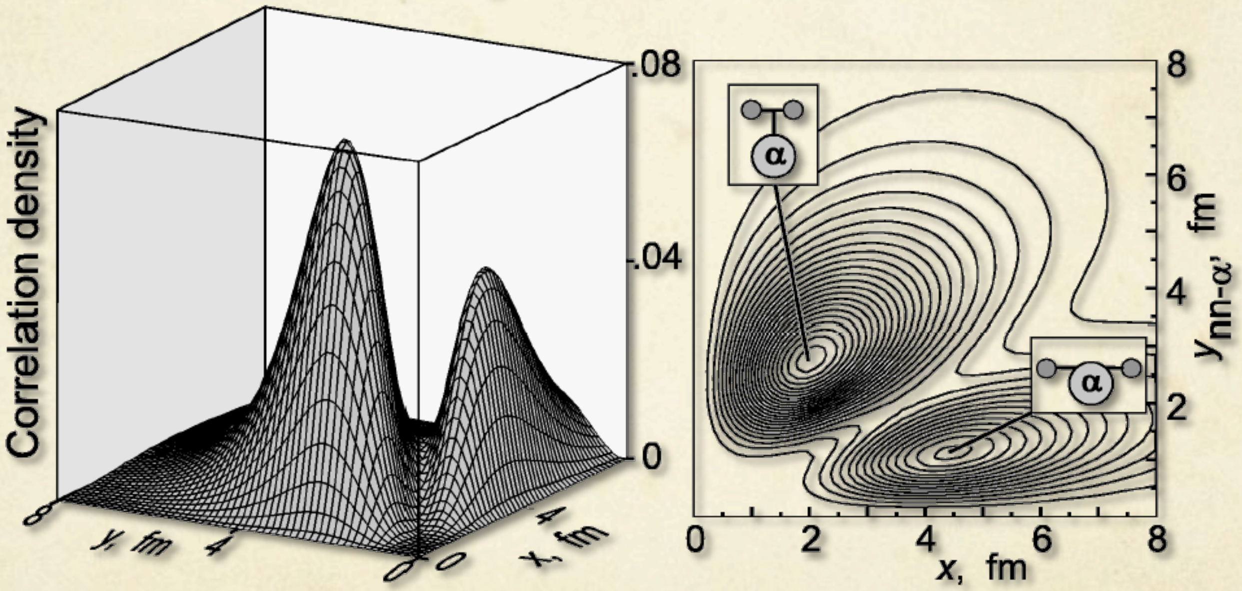
Yuma Kikuchi (Hokkaido University)

Collaborators:
T. Myo, M. Takashina, K. Kato and K. Ikeda

Two-neutron halo nuclei

- **Exotic neutron pair – di-neutron**
  - Spatially-correlated neutron pair was suggested over twenty years ago.

Yu.Ts. Oganessian, *et al.* PRL82(1999), 4996



Coulomb breakup reactions

- **To probe the di-neutron correlations experimentally**
  - Some experiments were performed to investigate the Coulomb breakup reactions of halo nuclei.
    - For ^{6}He
      - GSI and MSU data are available.

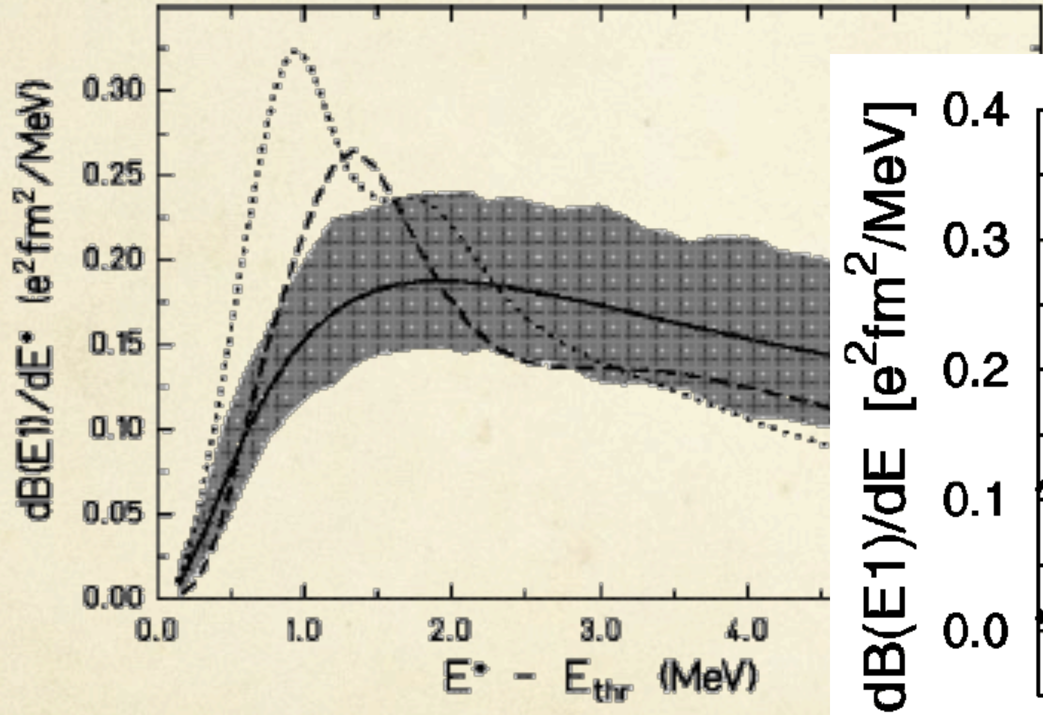
        T. Aumann *et al.*, PRC**59**(1999), 1252.
        J. Wang *et al.*, PRC**65**(2002), 034306.
    - For ^{11}Li
      - MSU, RIKEN and GSI data are available.

        K. Ieki *et al.*, PRL**70**(1993), 730.
        S. Shimoura *et al.*, PLB**348**(1995), 29.
        M. Zinser *et al.*, NPA**619**(1997), 151.
        T. Nakamura *et al.*, PRL**96**(2006), 252502.

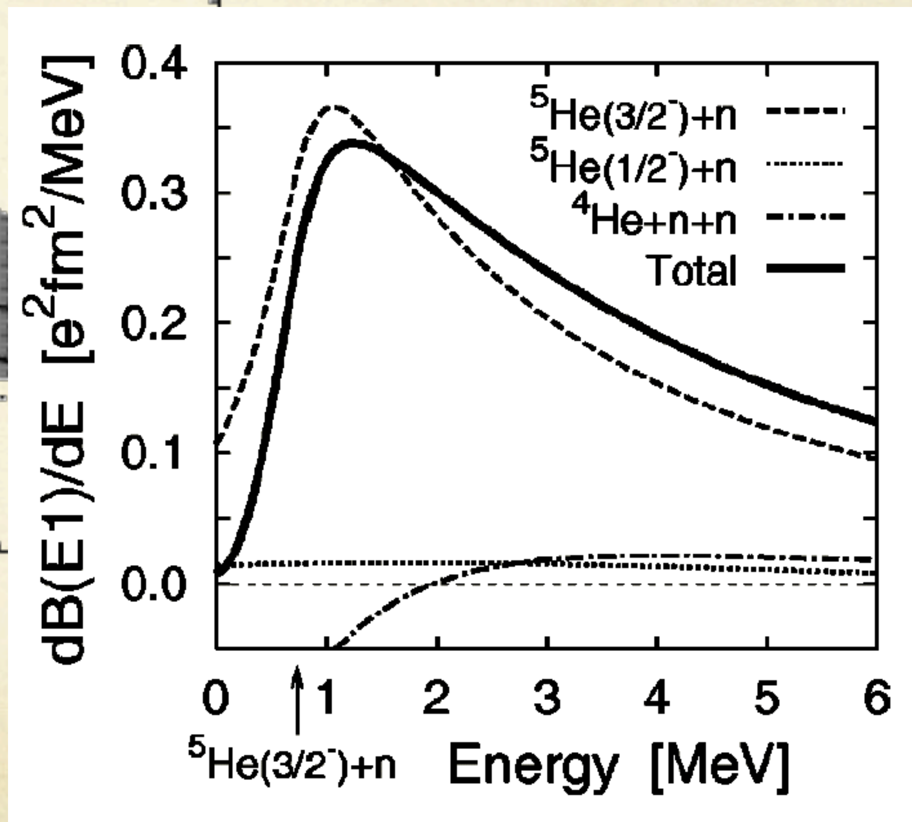
Coulomb breakup reactions

- **Observed data in Coulomb breakups**
  - The low-lying peak is observed in the Coulomb breakups.

T. Aumann *et al.*, PRC**59**(1999), 1252.



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



Di-neutron as n-n subsystem correlation

- **Di-neutron as the correlation of the n-n subsystems**
  - It is essential to analyze the observables as a function of energy of the n-n subsystem.
  - Recently, some data were reanalyzed with respect to the subsystem correlations.
    - For ^{6}He
      - Subsystem energy distributions of the breakup cross section

        L.V. Chulkov *et al.*, NPA**759**(2005), 23.
        S.N. Ershov *et al.*, PRC**74**(2006), 014603.
    - For ^{11}Li
      - Dalitz plot of E1 transition strength

        T. Nakamura, DREB07 oral presentation and etc.

Motivation

- **To extract the di-neutron from the observables**
  - We estimate the E1 strength distribution with respect to the energies of the subsystems and investigate which subsystem correlation is important in the Coulomb breakups.
  - To do:
    - We need the description of the three-body scattering state, which is capable of investigating the subsystem correlations.

Our approach

- **Approach based on the Lippmann-Schwinger Eq.**

$$|\Psi^{(+)}(\mathbf{k},\mathbf{K})\rangle = |\mathbf{k},\mathbf{K}\rangle + \lim_{\varepsilon\to 0}\frac{1}{E-\hat{H}+i\varepsilon}\hat{V}|\mathbf{k},\mathbf{K}\rangle$$

  - We start with the formal solutions of LS Eq.
  - The formal solution is expressed by an asymptotic solution, which is an eigenstate of momenta of decaying particles.

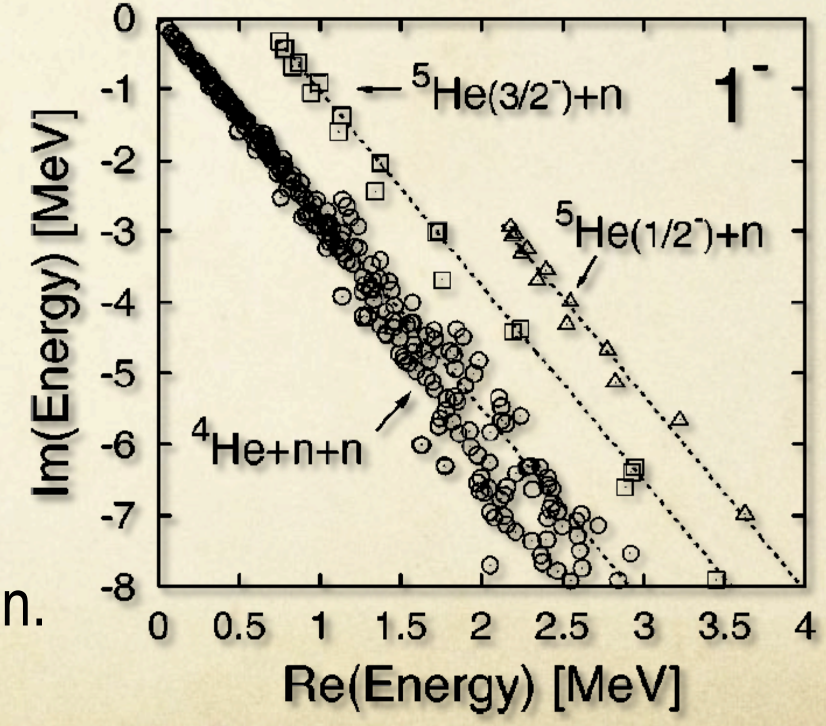
Our approach

- **Complex-scaled Green's function**

A.T. Kruppa *et al.*, PRC75(2007), 044602.

$$\mathcal{G}^\theta(E;\boldsymbol{\xi},\boldsymbol{\xi}') = \left\langle \boldsymbol{\xi} \left| \frac{1}{E-\hat{H}^\theta} \right| \boldsymbol{\xi}' \right\rangle = \sum\!\!\!\!\!\!\int_i \frac{\chi_i^\theta(\boldsymbol{\xi})\tilde{\chi}_i^\theta(\boldsymbol{\xi}')}{E-E_i^\theta}$$

  - Eigenstates in CSM have complex energy, and their imaginary parts shows the boundary conditions of each states.
  - Using such eigenstates, we can include the boundary conditions in the Green's function.



Our approach

- **Complex-scaled solutions of LS Eq. (CSLS)**

$$|\Psi^{(+)}(\mathbf{k},\mathbf{K})\rangle = |\mathbf{k},\mathbf{K}\rangle + \sum\!\!\!\!\!\!\int_i U^{-1}(\theta)|\chi_i^\theta\rangle \frac{1}{E - E_i^\theta} \langle\tilde{\chi}_i^\theta|U(\theta)\hat{V}|\mathbf{k},\mathbf{K}\rangle$$

  - The advantages in CSLS
    - We can easily apply CSLS to the complicated systems.
    - We can decompose the observables into the contribution of the direct breakups and the one of the sequential decays.

Our approach

- **Complex-scaled solutions of LS Eq. (CSLS)**

$$|\Psi^{(+)}(\mathbf{k},\mathbf{K})\rangle = |\mathbf{k},\mathbf{K}\rangle + \sum\!\!\!\!\!\!\int_i U^{-1}(\theta)|\chi_i^\theta\rangle \frac{1}{E - E_i^\theta} \langle\tilde{\chi}_i^\theta|U(\theta)\hat{V}|\mathbf{k},\mathbf{K}\rangle$$

  - The advantages in CSLS
    - We can easily apply CSLS to the complicated systems.
      - The Green's function can be found by solving with the L^2 basis functions.
      - OCM, Coupled-channel method and other theoretical models can be applied in solving the eigenstates.

A.T. Kruppa *et al.*, PRC**75**(2007), 044602.

Our approach

- **Complex-scaled solutions of LS Eq. (CSLS)**

$$|\Psi^{(+)}(\mathbf{k},\mathbf{K})\rangle = |\mathbf{k},\mathbf{K}\rangle + \sum\!\!\!\!\!\!\int_i U^{-1}(\theta)|\chi_i^\theta\rangle \frac{1}{E-E_i^\theta}\langle\tilde{\chi}_i^\theta|U(\theta)\hat{V}|\mathbf{k},\mathbf{K}\rangle$$

  - The advantages in CSLS
    - We can easily apply CSLS to the complicated systems.
    - We can decompose the observables into the contribution of the direct breakups and the one of the sequential decays.

Our approach

- **Complex-scaled solutions of LS Eq. (CSLS)**

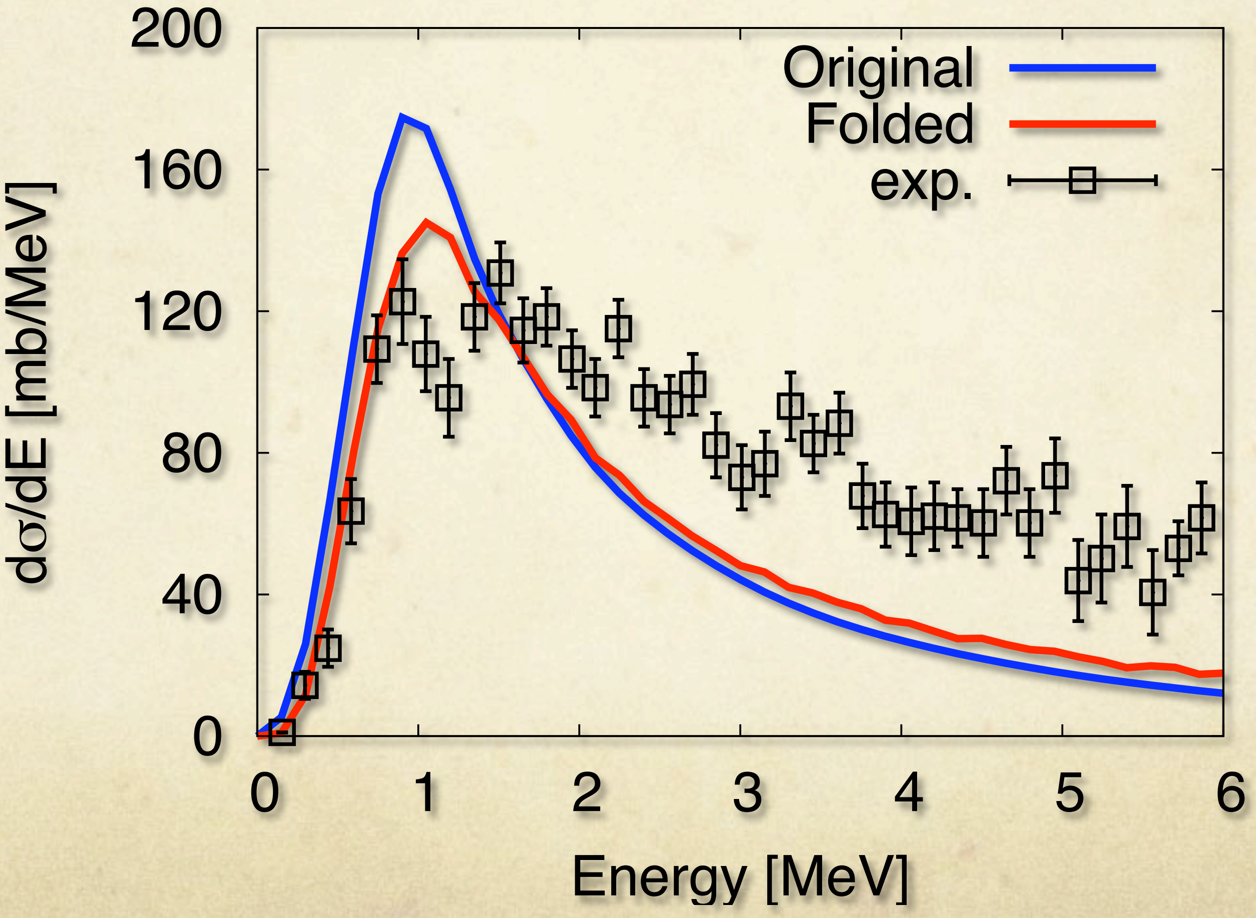
$$|\Psi^{(+)}(\mathbf{k},\mathbf{K})\rangle = \underline{|\mathbf{k},\mathbf{K}\rangle} + \sum\!\!\!\!\!\!\int_i \underline{U^{-1}(\theta)|\chi_i^\theta\rangle \frac{1}{E-E_i^\theta}\langle\tilde{\chi}_i^\theta|U(\theta)\hat{V}|\mathbf{k},\mathbf{K}\rangle}$$

Direct breakups into non-resonant cont. Sequential decays via χ^θ_i

- The advantages in CSLS
  - We can decompose the observables into the contribution of the direct breakups and the one of the sequential decays.
    - We can easily switch on and off the decaying channels by including and excluding the eigenstates belonging to the selected decay modes.

Coulomb breakup cross section in CSLS

- **The obtained cross section for ^{6}He breakups**
  - Our result well reproduces the observed trend in the Coulomb breakup cross section.



Subsystem correlations in ^{6}He

- **Two-dimensional energy distributions of E1 strength**

$$\frac{dB(E1)}{d\varepsilon_1 d\varepsilon_2} = \iint d\mathbf{k}d\mathbf{K}\frac{dB(E1)}{d\mathbf{k}d\mathbf{K}}\delta\left(\varepsilon_1 - \frac{\hbar^2 k^2}{2\mu}\right)\delta\left(\varepsilon_2 - \frac{\hbar^2 K^2}{2M}\right)$$

  - Momentum distributions

$$\frac{dB(E1)}{d\mathbf{k}d\mathbf{K}} = \frac{1}{2J_{\mathrm{g.s.}}+1}\left|\langle\Psi^{(+)}(\mathbf{k},\mathbf{K})||\hat{O}(E1)||\Phi_{\mathrm{g.s.}}\rangle\right|^2$$

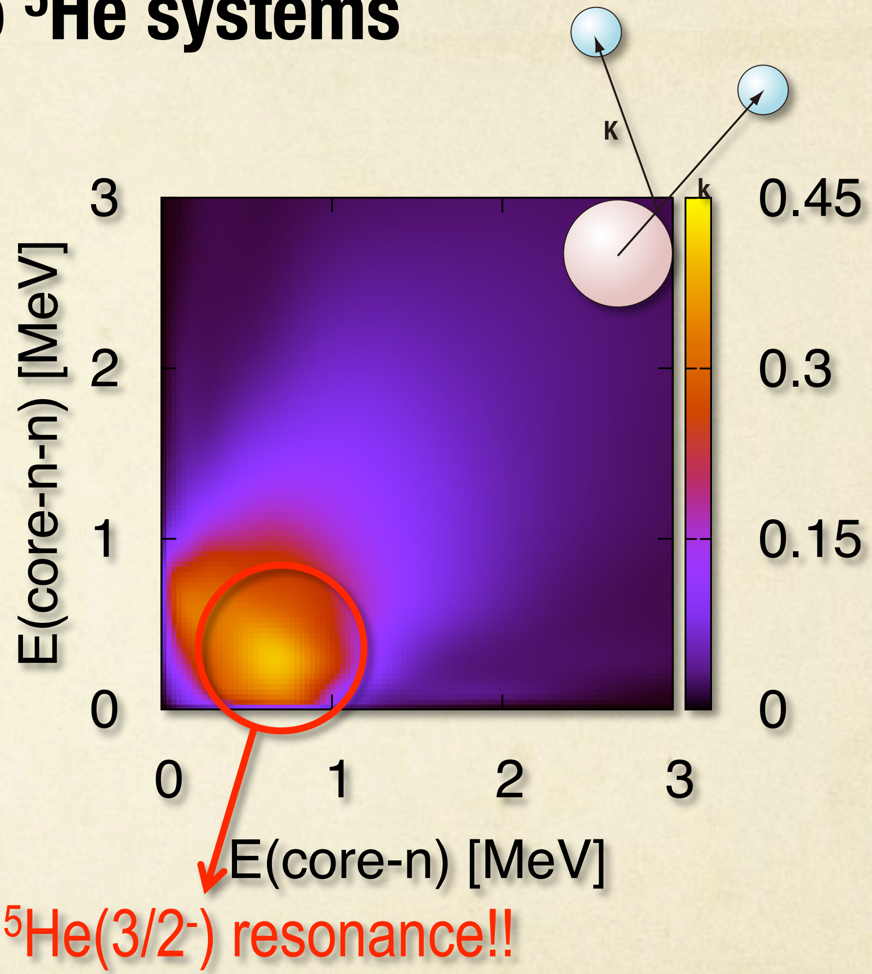
  - Matrix elements

$$\langle\Phi_{\mathrm{g.s.}}|\hat{O}^\dagger(E1)|\mathbf{k},\mathbf{K}\rangle + \sum_i\!\!\!\!\!\!\int \langle\Phi_{\mathrm{g.s.}}|\hat{O}^\dagger(E1)U^{-1}(\theta)|\chi_i^\theta\rangle\frac{1}{E-E_i^\theta}\langle\tilde{\chi}_i^\theta|U(\theta)\hat{V}|\mathbf{k},\mathbf{K}\rangle$$

Correlations of ^{5}He subsystem

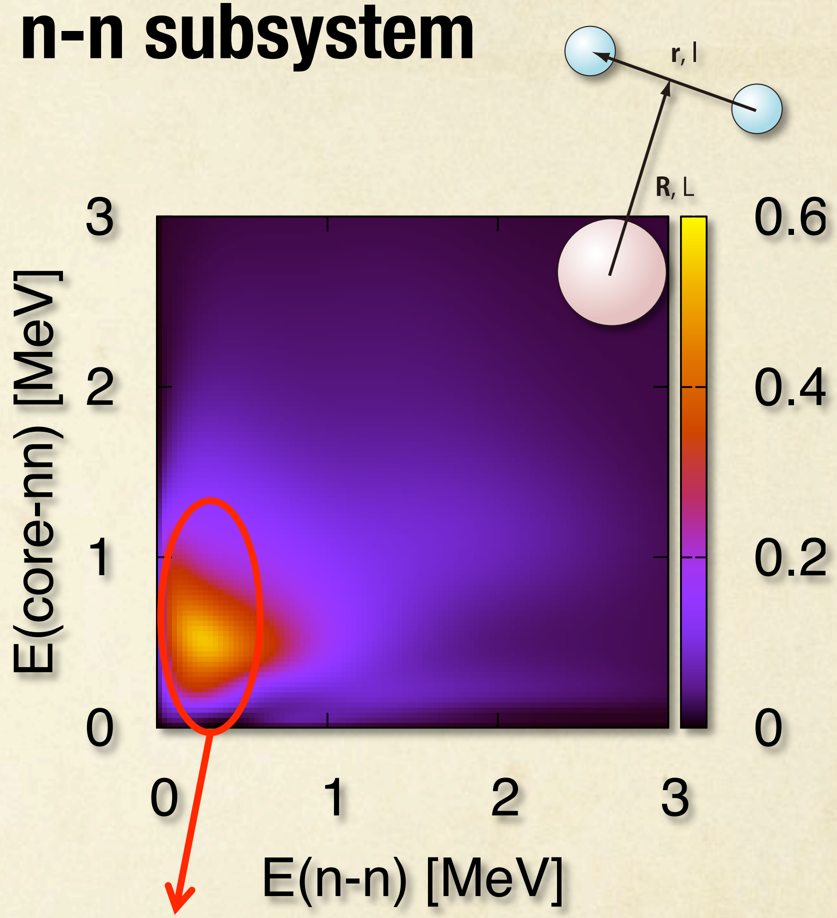
- **E1 strength with respect to ^{5}He systems**
  - The distribution show the clear peak at 0.7 MeV of ^{5}He subsystem energy.

    ➔ ^{5}He(3/2$^-$) is important!!
  - This is a consistent result with our previous work.



Correlation of n-n subsystem

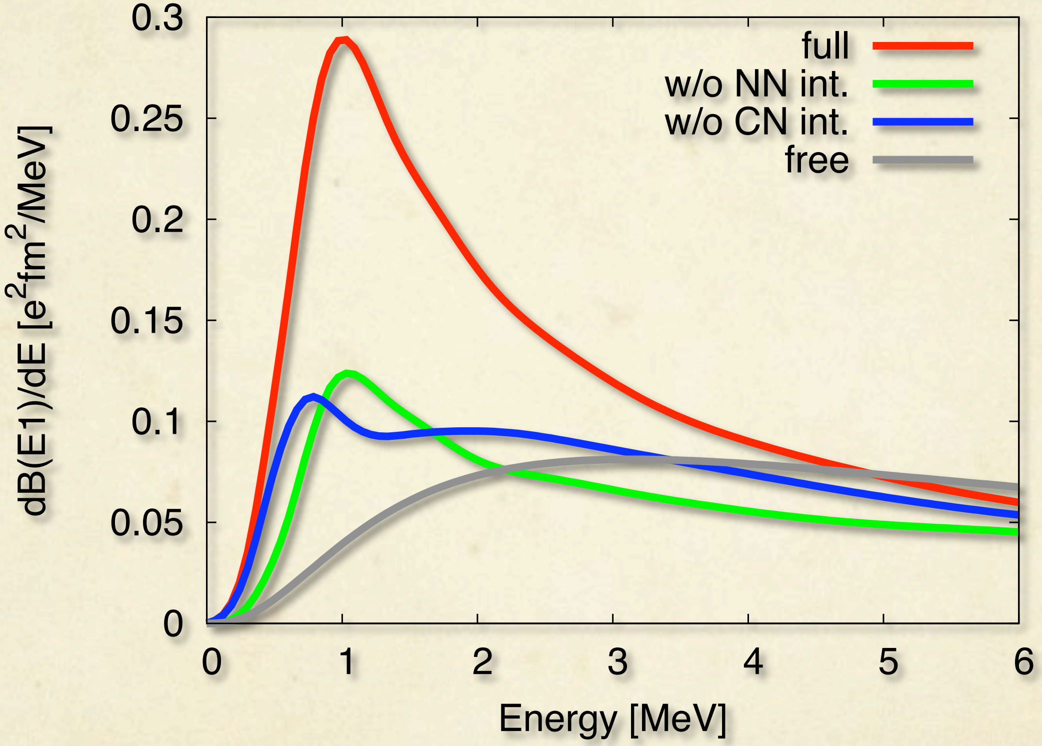
- **E1 strength with respect to n-n subsystem**
  - Strength is concentrated on the axis of E_{nn}=0.
  - This result indicates the contribution of the virtual state of n-n system is important in the Coulomb breakups of ^{6}He.



Strength is concentrated on E_{nn} ~ 0 MeV.

Which subsystem is important?

- **E1 transition w/ and w/o the sequential decays**
  - We switch off the sequential process via ^{5}He+n or/and α+2n.



- Contributions of both the ^{5}He and 2n subsystems are important in the Coulomb breakup.

Summary

- **We investigate the subsystems correlations by calculating the 2D distributions of the E1 strength.**
  - We calculate the 2D distribution of the E1 strength using CSLS.
  - The two-neutron correlation in the Coulomb breakups is found as the virtual state of the n-n subsystem.
  - The correlations not only of the ^{5}He, but also of the n-n subsystems are important to reproduce the observed low-lying peak in the observed cross section.