Two-neutron correlations in the ground and excited states of ^{6}He

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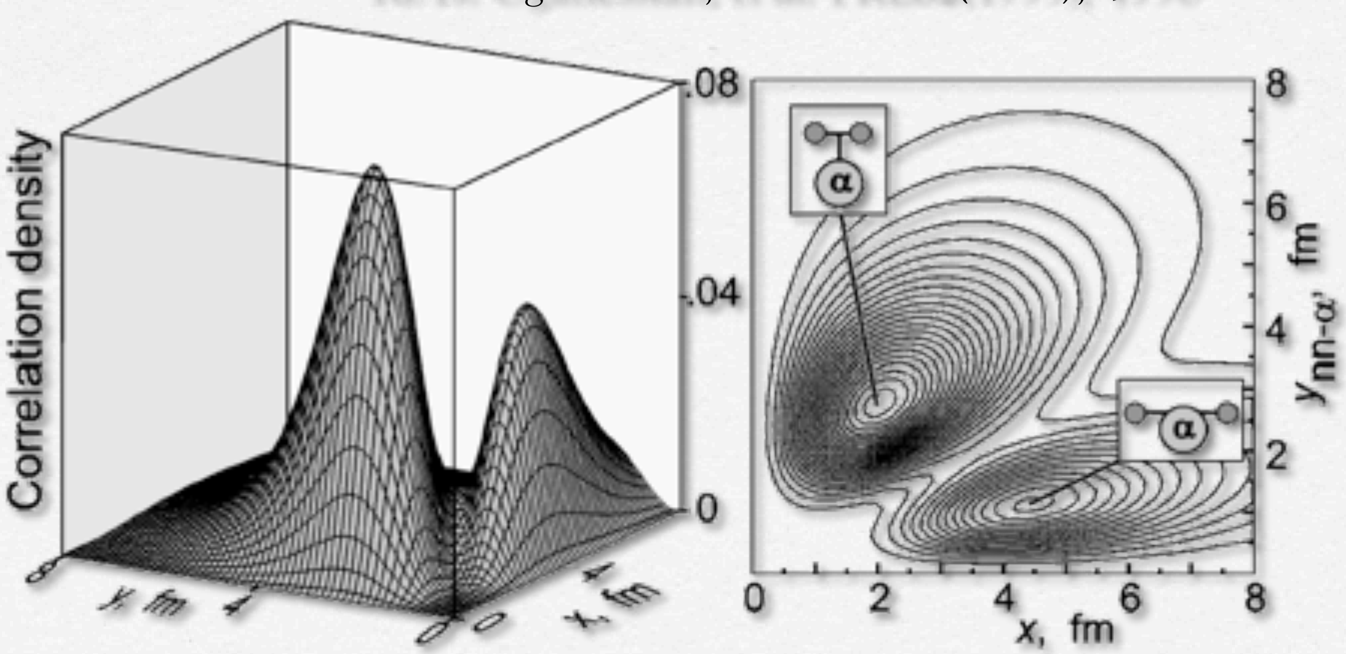
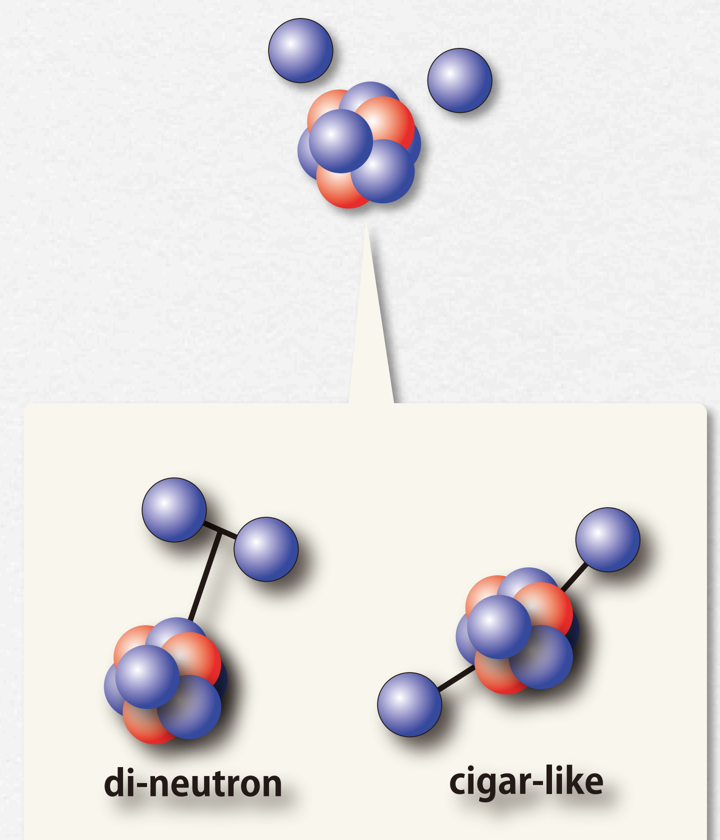
Exotic n-n correlation in two-neutron halo nuclei

- Two-neutron halo nuclei have been studied based on core+n+n three-body model.
  - The results of three-body models show that:
    - A correlation between halo neutrons has an important role in their binding mechanisms.
    - This correlation is characterized as a spatially-correlated n-n pair, the so-called “dineutron.”

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

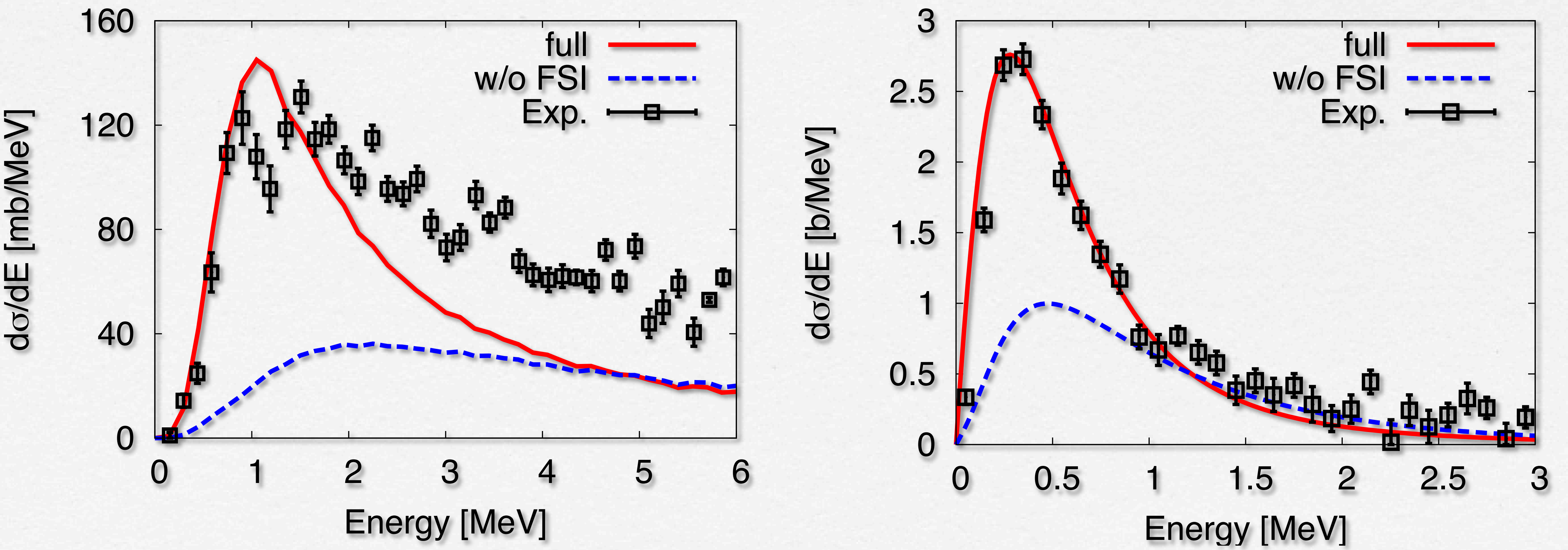




Coulomb breakup reactions as a tool to investigate the dineutron

- Coulomb breakup reactions have been performed to investigate the exotic structure of two-neutron halo nuclei and their electric response.
  - The low-lying enhancements are observed in the cross sections.
  - This enhancement has been expected to be useful to investigate the ground-state structure.
  - The shapes of the cross sections are governed by strong FSIs.
    - It is difficult to extract the information on the ground-state structure from the Coulomb breakup cross sections.

T. Aumann et al., PRC 59, 1252 (1999). T. Nakamura et al., PRL 96, 252502 (2006).



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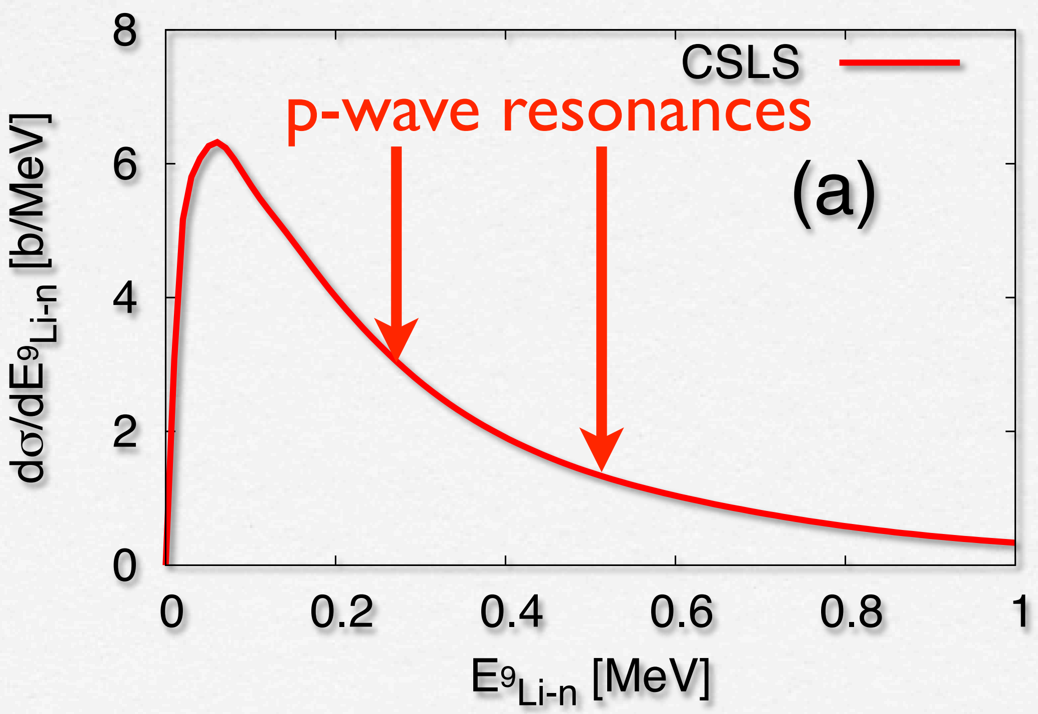
Invariant mass spectra for ^{10}Li subsystem



We cannot identify the p-wave resonance in the spectra, while the ground state has comparable components of p-wave to that of s-wave.

Coulomb breakup reactions as a tool to investigate the dineutron

- The dineutron is also discussed in terms of cluster sum rule of E1 transitions.
  - The cluster rule value of E1 transition is expressed as

$$B(E1) = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^2 + r_2^2 + 2r_1 r_2 \cos\theta \right\rangle$$

    and depends only on the ground-state structure.
    - For ^{11}Li, the opening angle between two halo neutrons is determined as $\theta=48^{+14}_{-18}$ deg. T. Nakamura et al., PRL 96, 252502 (2006).

  - However, in our previous work, we show that the sum rule value is reduced by ~15 % by taking into account the core excitation effect in the case of ^{11}Li. YK et al., PRC 87, 034606 (2013).
    - The careful analysis is required to obtain the quantitative results.

What kinds of reactions is helpful to understand the dineutron?

- To investigate the dineutron more in detail, the other kinds of reactions than the Coulomb breakup reaction is needed.
- We here consider the following two reactions:
  - Nuclear breakup reaction of ^{6}He
    - In the reaction, the excited resonant state, 2^+, is populated.
    - The 2^+ state has a similar single-particle configuration to g.s., and hence, we can learn about the n-n correlation in the excited states.
  - Quasi-free knockout reaction ^{6}He(p,pn)
    - In the quasi-free condition, the knocked-out neutron is free from FSIs.
      ➡ This fact might overcome the problem in the Coulomb breakups.
    - This reaction is one of the possible candidates for the direct measurement of dineutron.

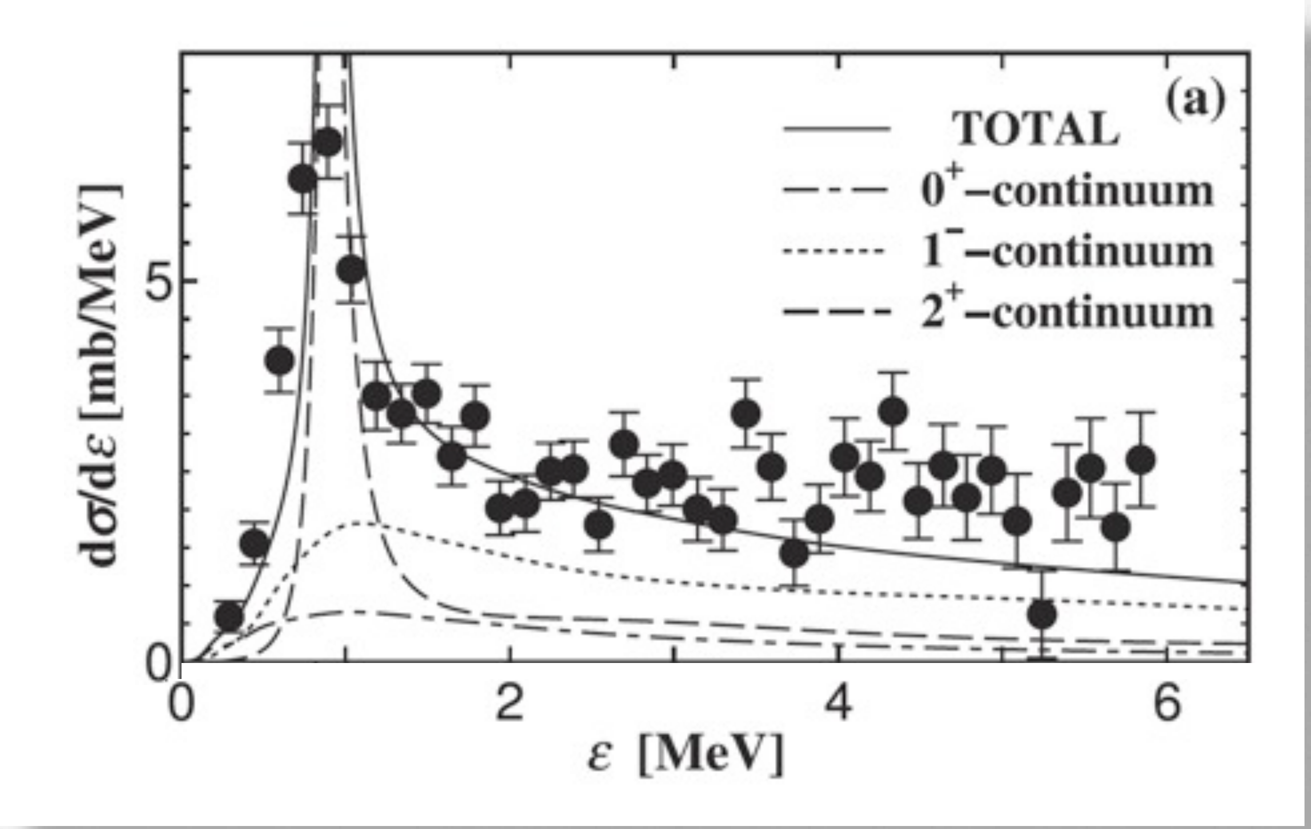
Nuclear breakup reaction of ^{6}He to investigate the dineutron in the excited state 2^{+}_{1}

YK et al., PRC 88, 021602 (2013).

Breakup reaction of ^{6}He by ^{12}C @ 240 MeV/nucleon

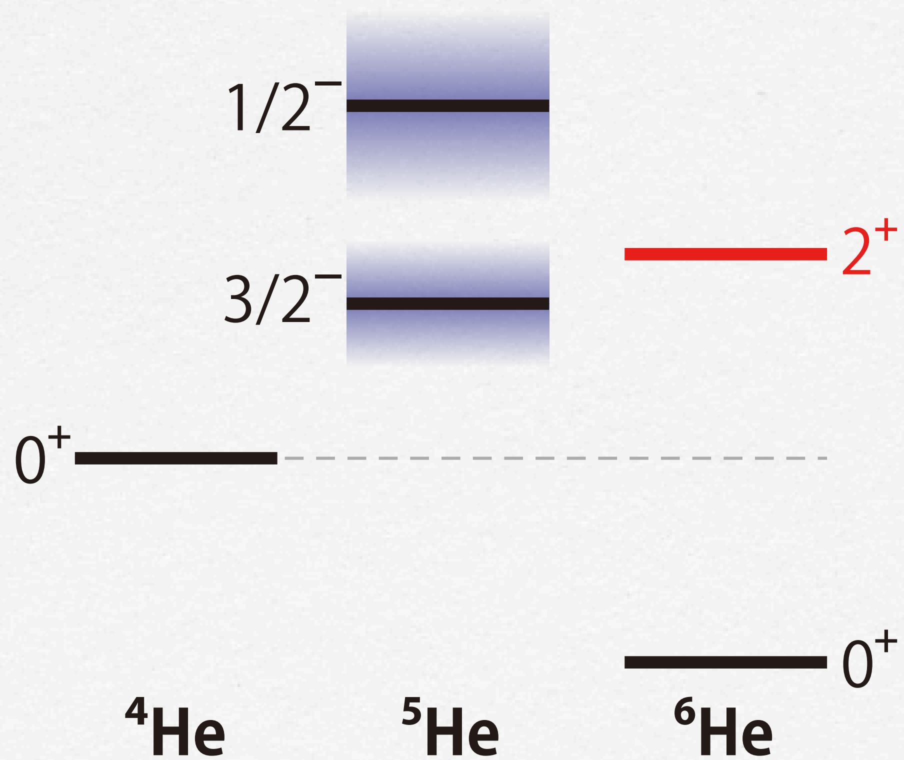
- The cross section of the ^{6}He breakup reactions by ^{12}C shows the peak coming from the 2^+_1 state of ^{6}He, which cannot observed in the Coulomb breakup.
  - We can learn about structure of the excited state of two-neutron halo from this kind of reactions.
    - The 2^+_1 has a similar single-particle configuration to g.s. of $(p_{3/2})^2$.
    - There exists the dineutron correlation in excited resonant states?

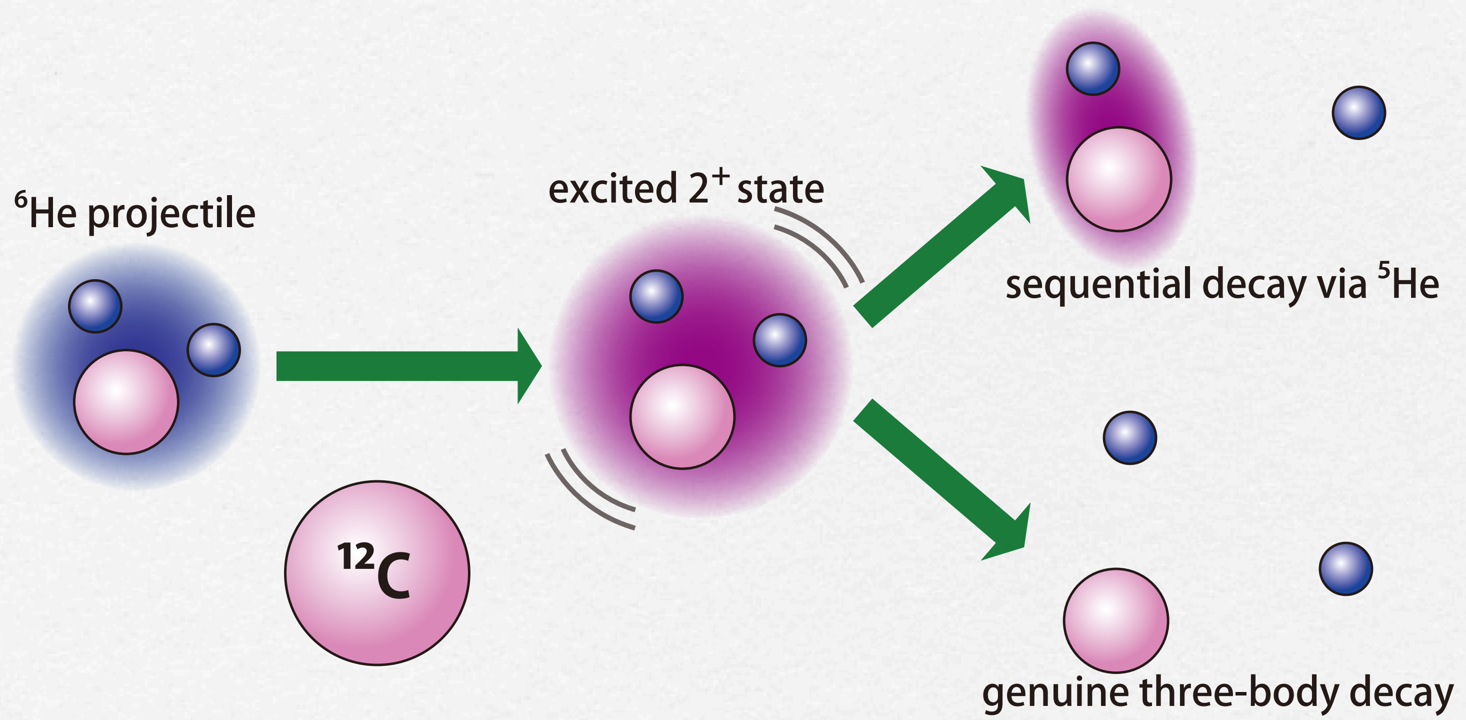
T. Aumann et al., PRC 59, 1252 (1999).



Breakup reaction of ^{6}He by ^{12}C @ 240 MeV/nucleon

- To investigate the structure of 2^+_1 state of ^{6}He, we need to clarify the decay modes of the state.
  - The 2^+_1 state is located above the thresholds of α+n+n and ^{5}He($3/2^-$)+n.
  - Which is dominant decay mode? sequential or genuine three-body decay?





Model: core+n+n three-body model for ^{6}He

- **Hamiltonian**

$$\hat{H} = \sum_{i=1}^{3} t_i - T_{\rm c.m.} + \sum_{i=1}^{2} V_{\alpha N}(\mathbf{r}_i) + V_{NN} + V_{\alpha NN}$$

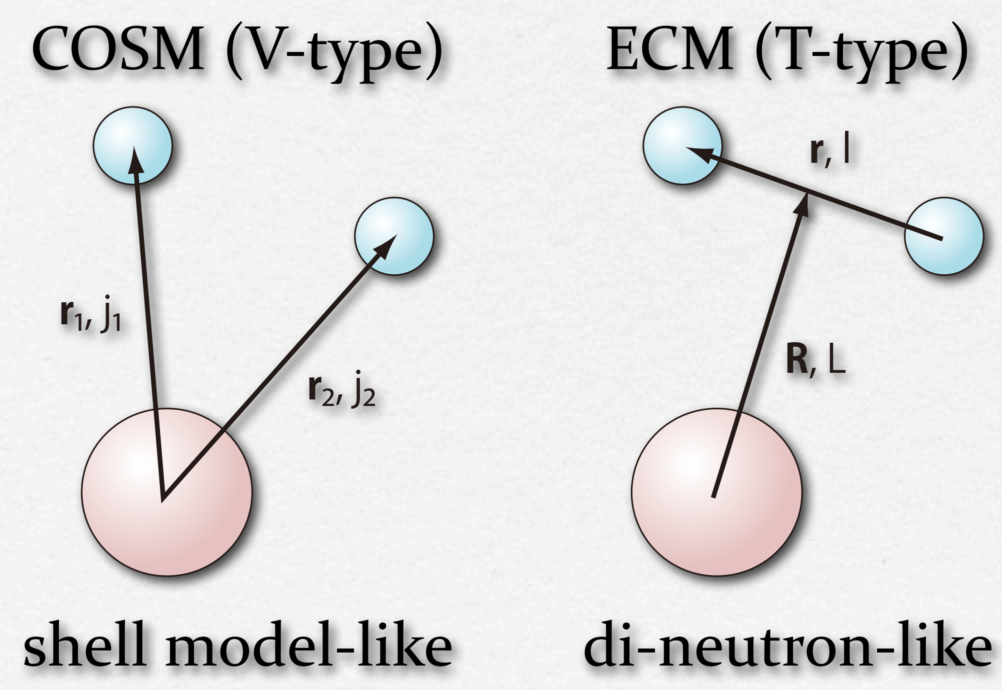
where $V_{\alpha N}$: KKNN potential, V_{NN}: Minnesota force

  - **We introduce the phenomenological three-body potential to reproduce the observed S_{2n}.**

- **Wave functions**

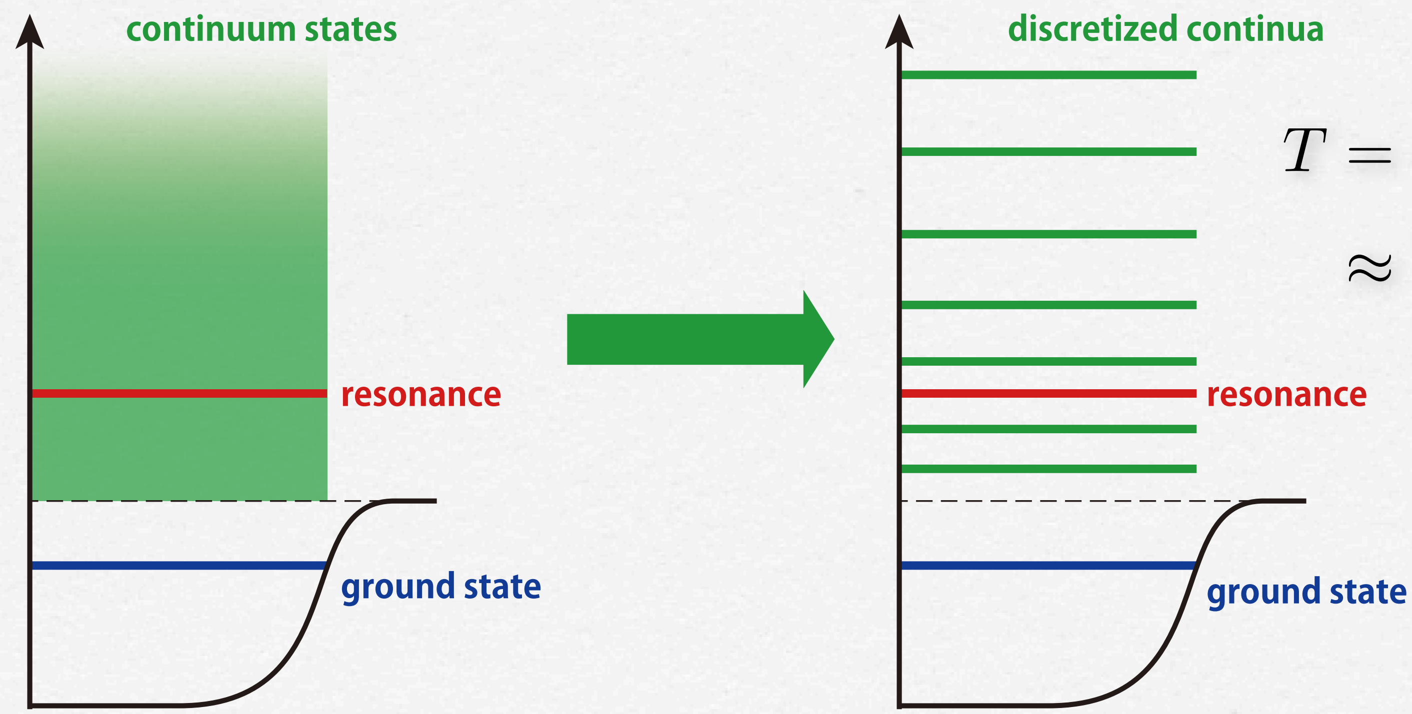
$$\Phi_{\rm gs}(^6{\rm He}) = \Phi_V + \Phi_T$$

  - **We solve the relative motions of the α+n+n three-body system with GEM.**



Model: Continuum-discretized coupled-channel (CDCC) method

- To describe the scattering problem between ^{6}He and ^{12}C, we use CDCC.
  - We take into account the coupling to continuum states by solving the coupled-channel equation between the discretized pseudo states.
  - The pseudo states are calculated within the L^2-basis functions by diagonalizing the Hamiltonian for the ^{6}He projectile.
    - We here consider the 0^+, 1^-, and 2^+ states for pseudo states.

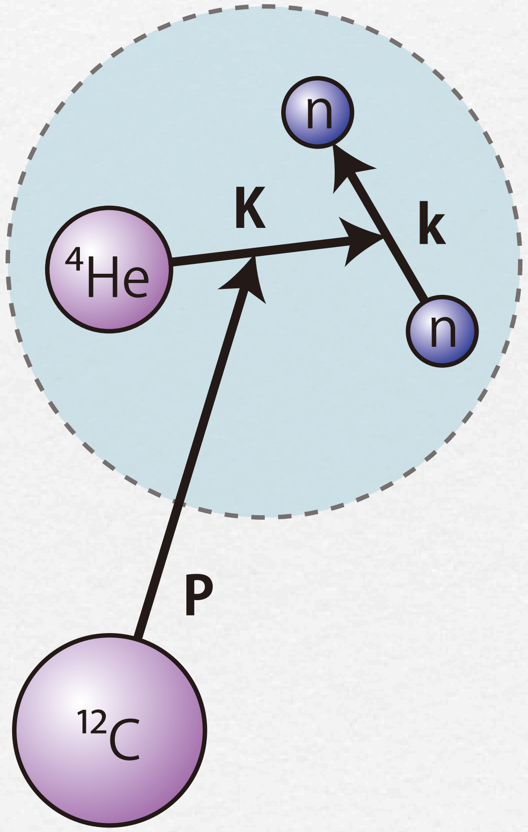


$$T = \langle \psi^{(-)}(\mathbf{k}, \mathbf{K}) \chi^{(-)}(\mathbf{P}) | V | \Psi^{(+)} \rangle$$
$$\approx \sum_n \langle \psi^{(-)}(\mathbf{k}, \mathbf{K}) | \Phi_n \rangle \langle \Phi_n \chi^{(-)}(\mathbf{P}) | V | \Psi^{(+)} \rangle$$

Model: Double-differential breakup cross sections (DDBUX)

- We here calculate the DDBUX as functions of relative energies in the α+n+n three-body system.
  - To obtain DDBUX as functions of continuous energies, we need the smoothing function.

$$\frac{d^2\sigma}{d\varepsilon_1 d\varepsilon_2} = \frac{(2\pi)^4\mu_R}{\hbar^2 P_0}\int d\boldsymbol{k}d\boldsymbol{K}d\boldsymbol{P}|T(\boldsymbol{k},\boldsymbol{K},\boldsymbol{P})|^2$$
$$\times\,\delta\left(E_{\rm tot}-\frac{\hbar^2P^2}{2\mu_R}-\varepsilon_1-\varepsilon_2\right)$$
$$\times\,\delta\left(\varepsilon_1-\frac{\hbar^2k^2}{2\mu_r}\right)\delta\left(\varepsilon_2-\frac{\hbar^2K^2}{2\mu_y}\right)$$

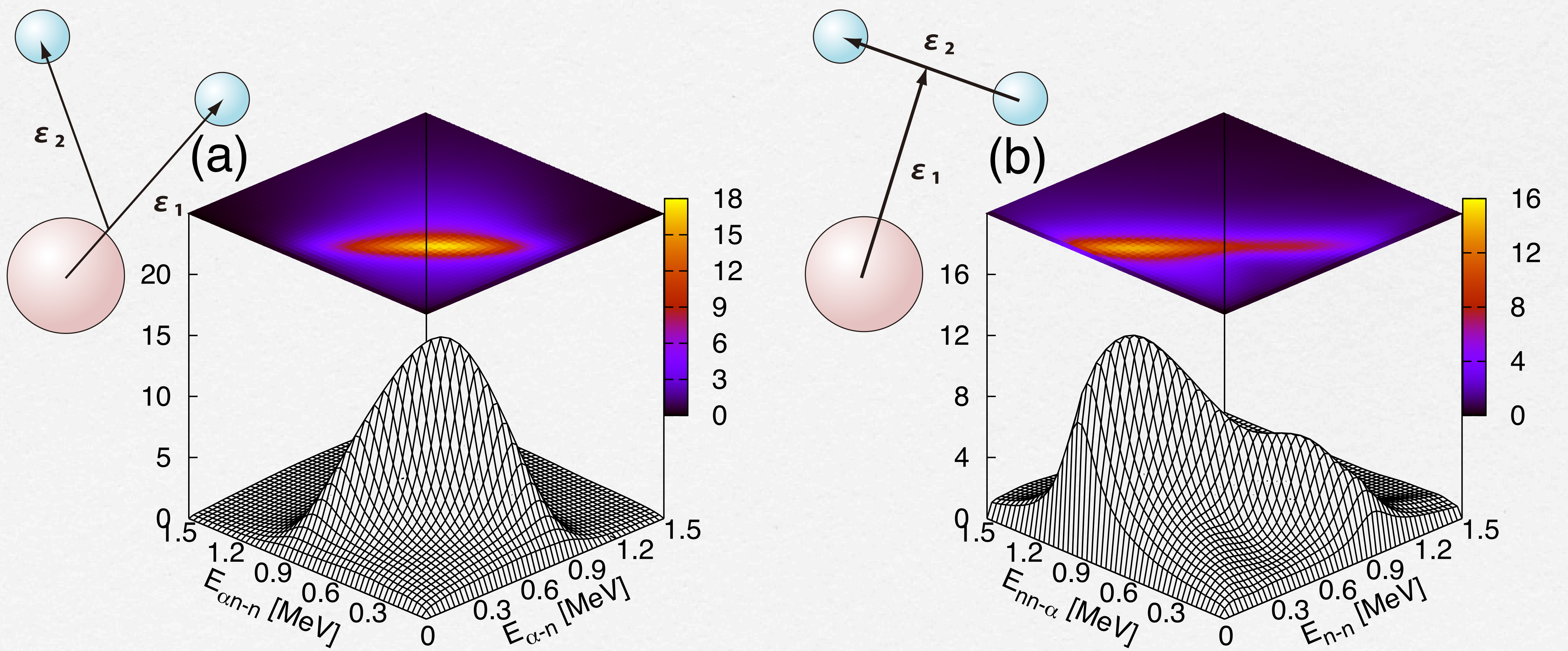


$$T = \langle\psi^{(-)}(\mathbf{k},\mathbf{K})\chi^{(-)}(\mathbf{P})|V|\Psi^{(+)}\rangle$$
$$\approx\sum_n \underbrace{\langle\psi^{(-)}(\mathbf{k},\mathbf{K})|\Phi_n\rangle}_{\text{smoothing func.}}\underbrace{\langle\Phi_n\chi^{(-)}(\mathbf{P})|V|\Psi^{(+)}\rangle}_{\text{CDCC T-matrix}}$$

smoothing func. CDCC T-matrix

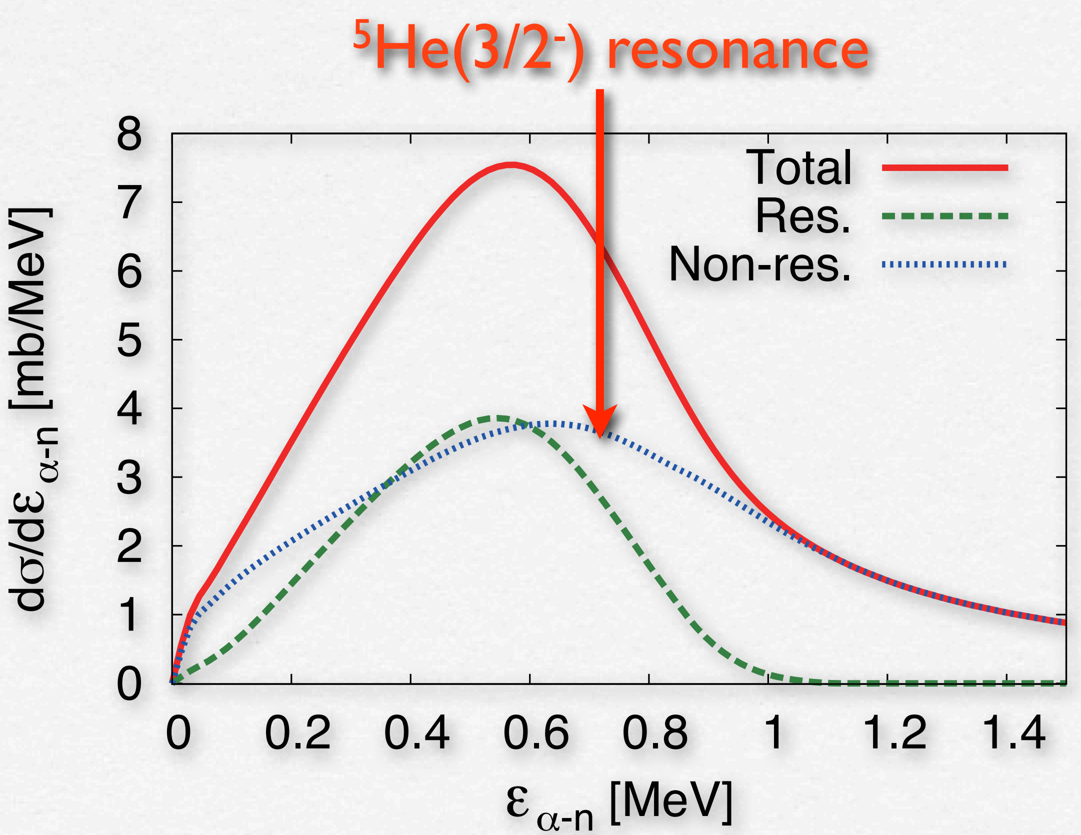
Results: Double-differential breakup cross sections (DDBUX)

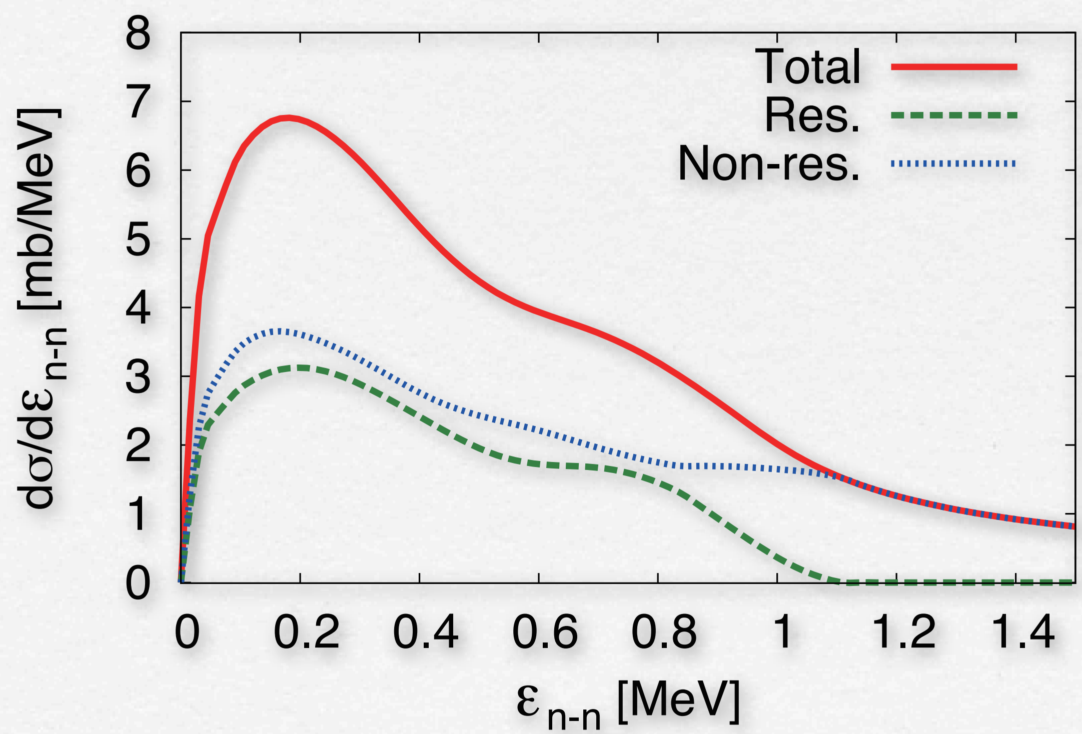
- DDBUX in two types of Jacobi coordinates
  - Both of DDBUX show the ridge structure at total energy of ^{6}He as ~ 1 MeV.
    - ➡ The shapes of DDBUX show the dominance of the excitation to 2^+_1.
  - To investigate the decay mode, we next calculate the invariant mass spectra (IMS) for binary subsystems.



Results: Correlations in binary subsystem & decay modes

- To clarify the decay modes of 2^+_1, we calculate the IMS by gating on the total energy as 0.98±0.135 MeV, which corresponds to the resonance energy and decay width of the 2^+_1 state.
  - From the result of α-n, we find that the sequential decay via ^{5}He resonance is suppressed.
  - The result shows that the decay of 2^+_1 state is a genuine three-body decay.





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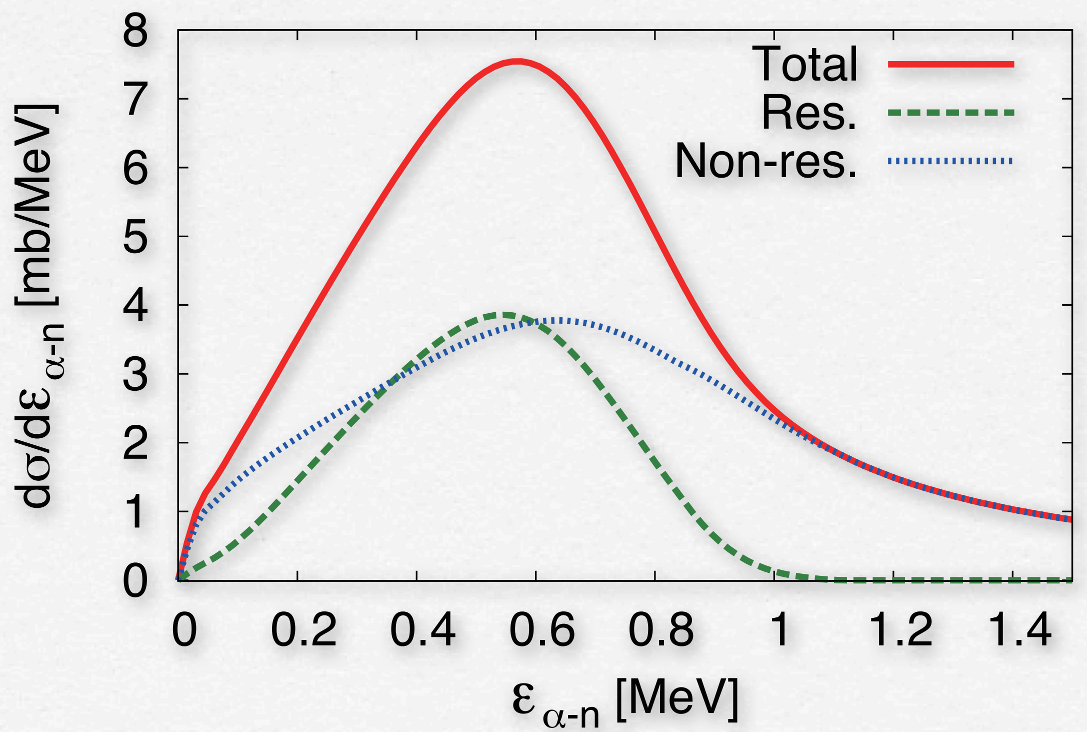
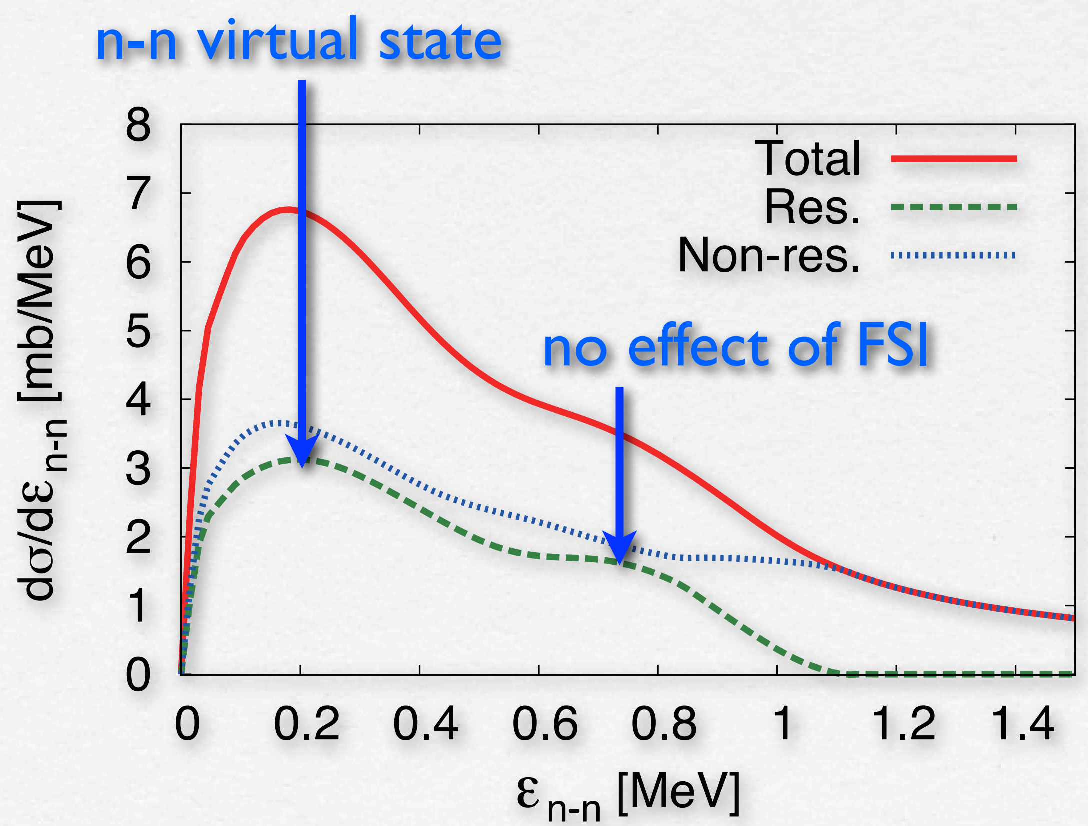
  - The IMS for n-n shows two peaks: The 1st peak comes from the n-n FSI and the 2nd one seems to be free from FSI.
  - The 2nd peak shows the back-to-back emission of two neutrons.
    - ➡ The resonance energy is almost exhausted by the n-n relative motion.





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  - The 2nd peak shows the back-to-back emission of two neutrons.
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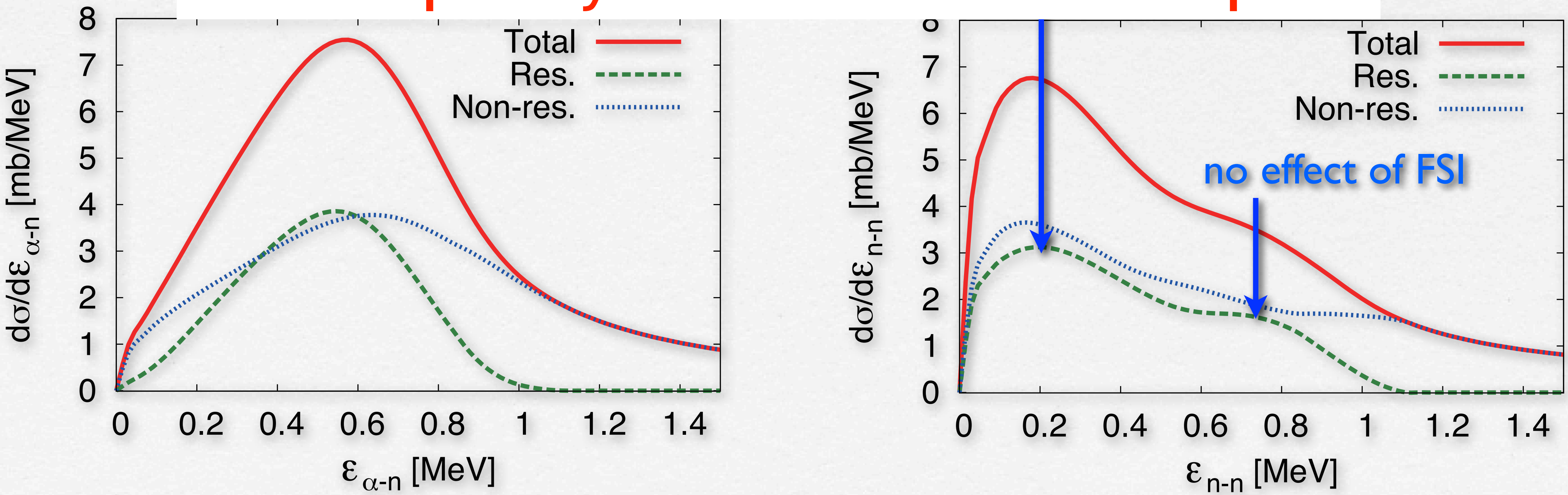
The 2nd peak could be a signature for the spatially-localization of neutron pair.

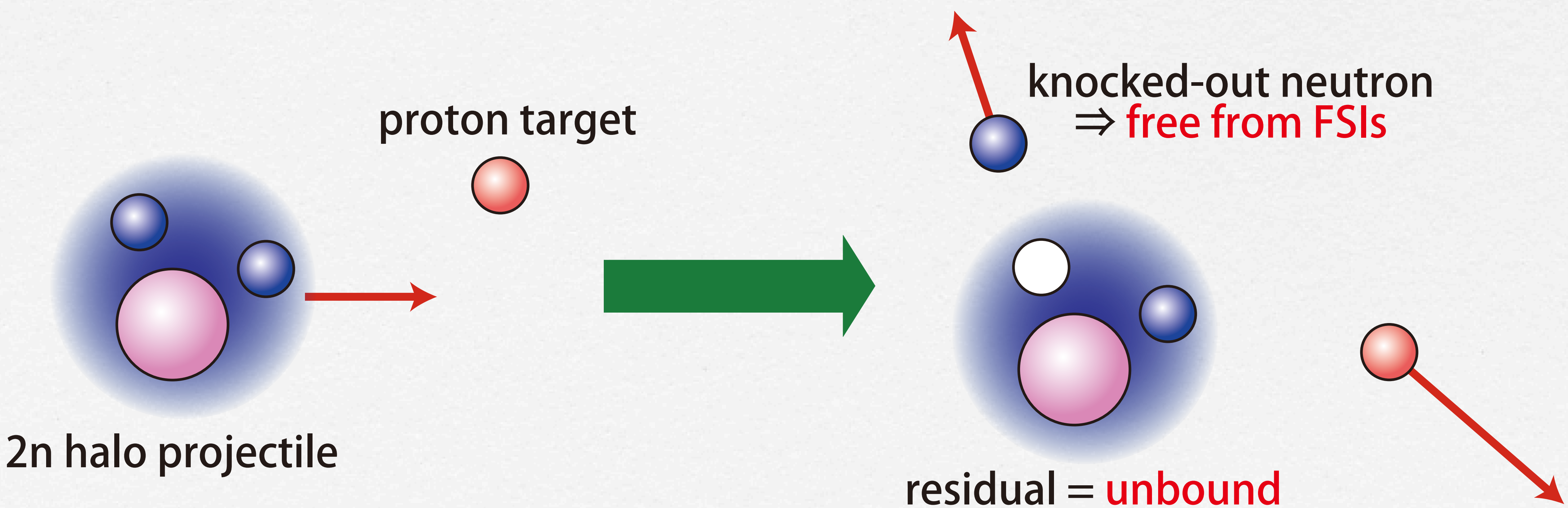


Neutron knockout reaction of ^{6}He to investigate the dineutron in the ground state

Quasi-free knockout reactions for ^{6}He

- The problem in Coulomb breakups is dominance of FSIs.
  - FSIs disturb to extract the information on the g.s. structure from the data.
  - To investigate the ground-state structure more in detail, we need to select the reactions, in which the effects of FSIs are minimized.

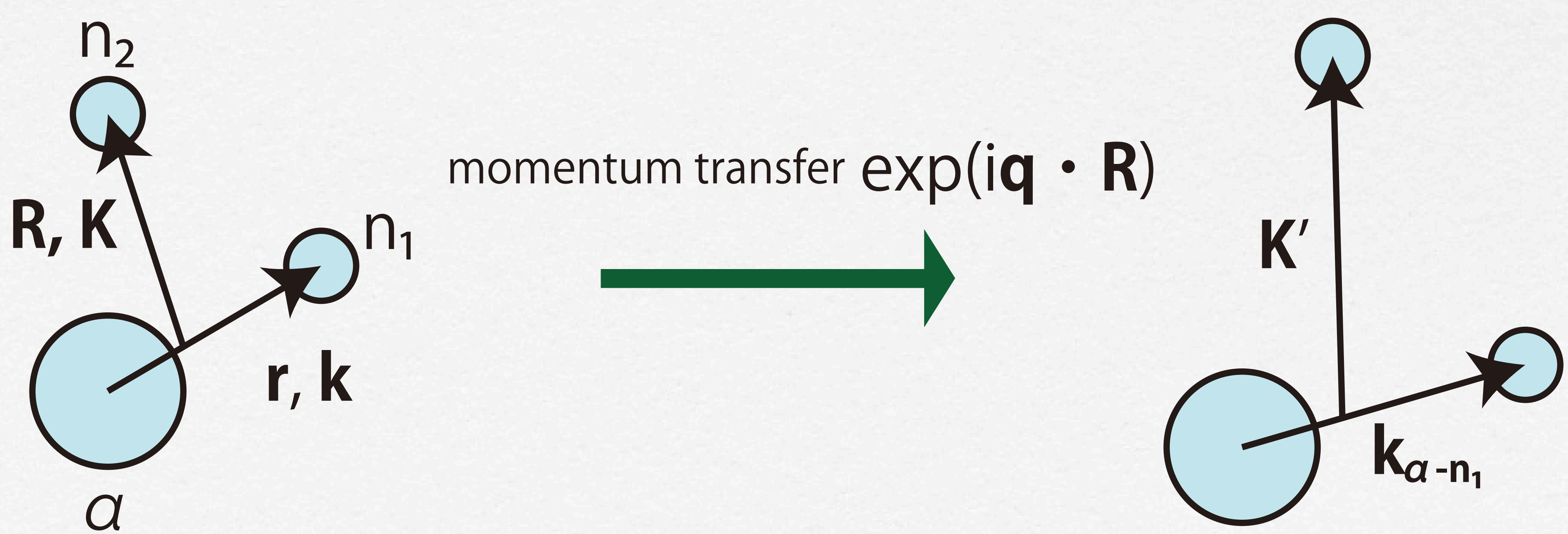
- We here consider the quasi-free neutron knockout reaction ^{6}He(p,pn).
  - In the quasi-free condition, the knocked-out neutron is free from FSIs.
  - However, the residual nucleus ^{5}He is unbound due to Borromean nature.
  - How the process via ^{5}He resonance impact on the knockout reaction?



Model: Knockout reaction using sudden approximation

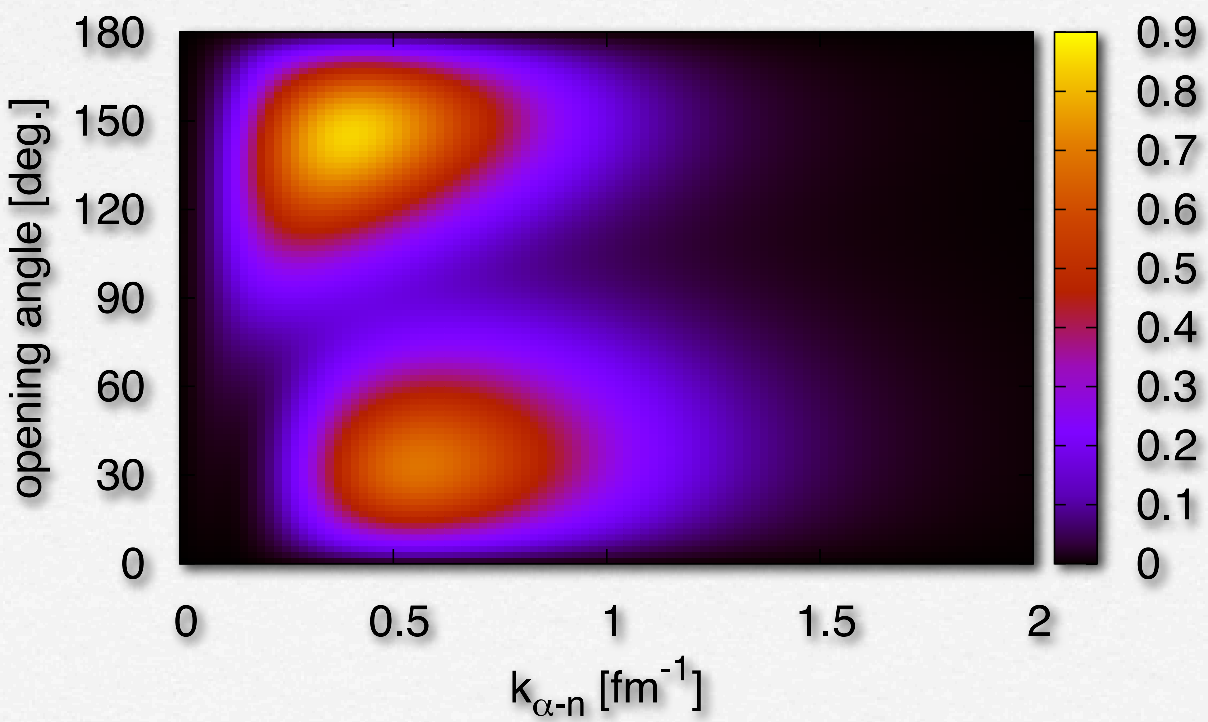
- As first step, we use the simple model in calculating the knockout reaction.
  - We here use the sudden approximation in the present calculation.
    - The (p,pn) part is treated by the simple momentum-transfer operator.
    - The scattering wave of the knocked-out neutron is described by a plane wave.
  - To estimate the effect of the process via ^{5}He resonance on the reaction, the exact scattering states of α+n system for the residual part.
  - The T-matrix for the knockout reaction is given as

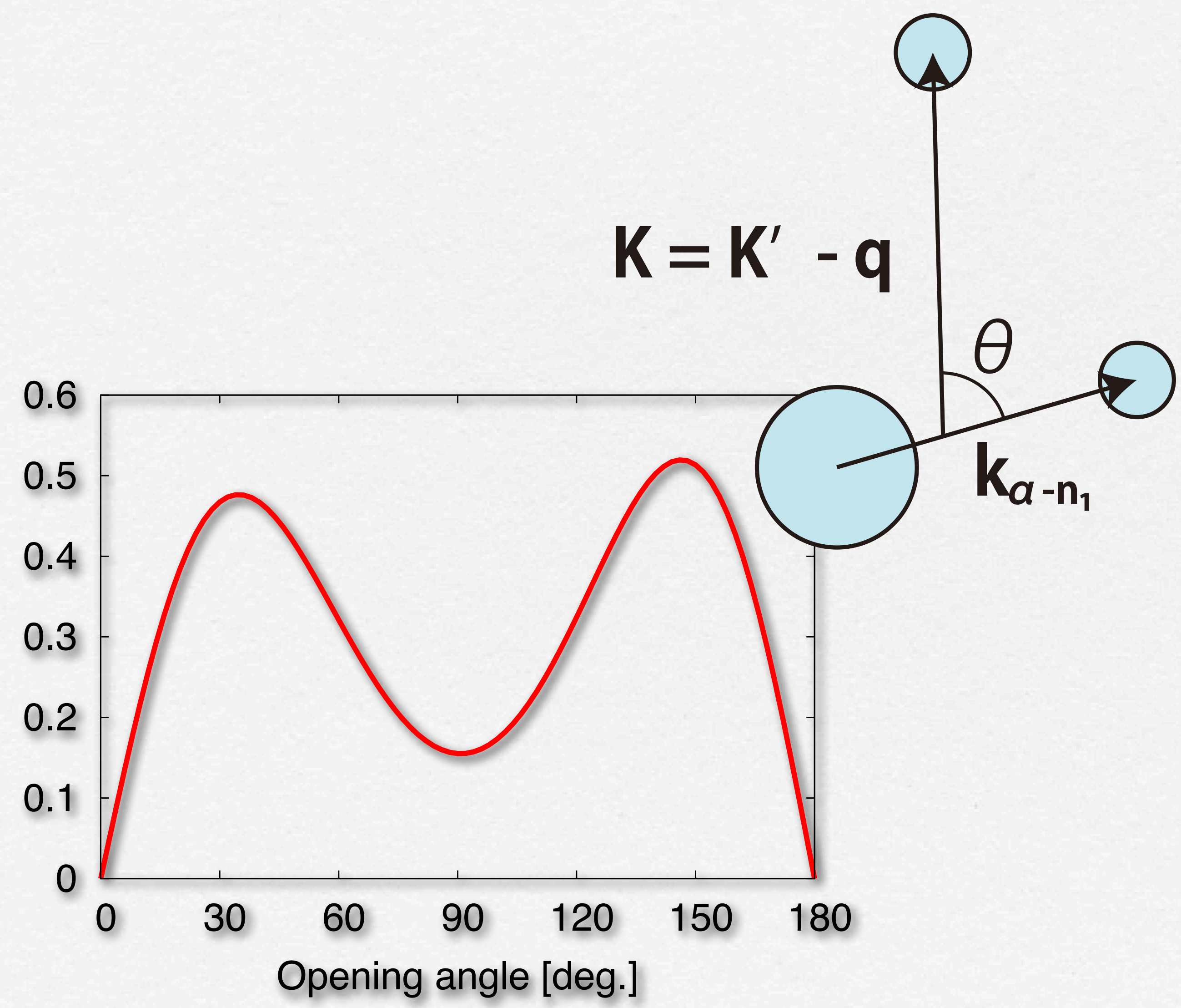
$$\mathcal{T} = \left\langle \Psi_{^5\mathrm{He}}(\mathbf{k}_{\alpha\text{-}n_1}) \otimes e^{i\mathbf{K}'\cdot\mathbf{R}} \middle| e^{i\mathbf{q}\cdot\mathbf{R}} \middle| \Phi_{^6\mathrm{He}} \right\rangle$$



Model: Ground-state momentum distributions

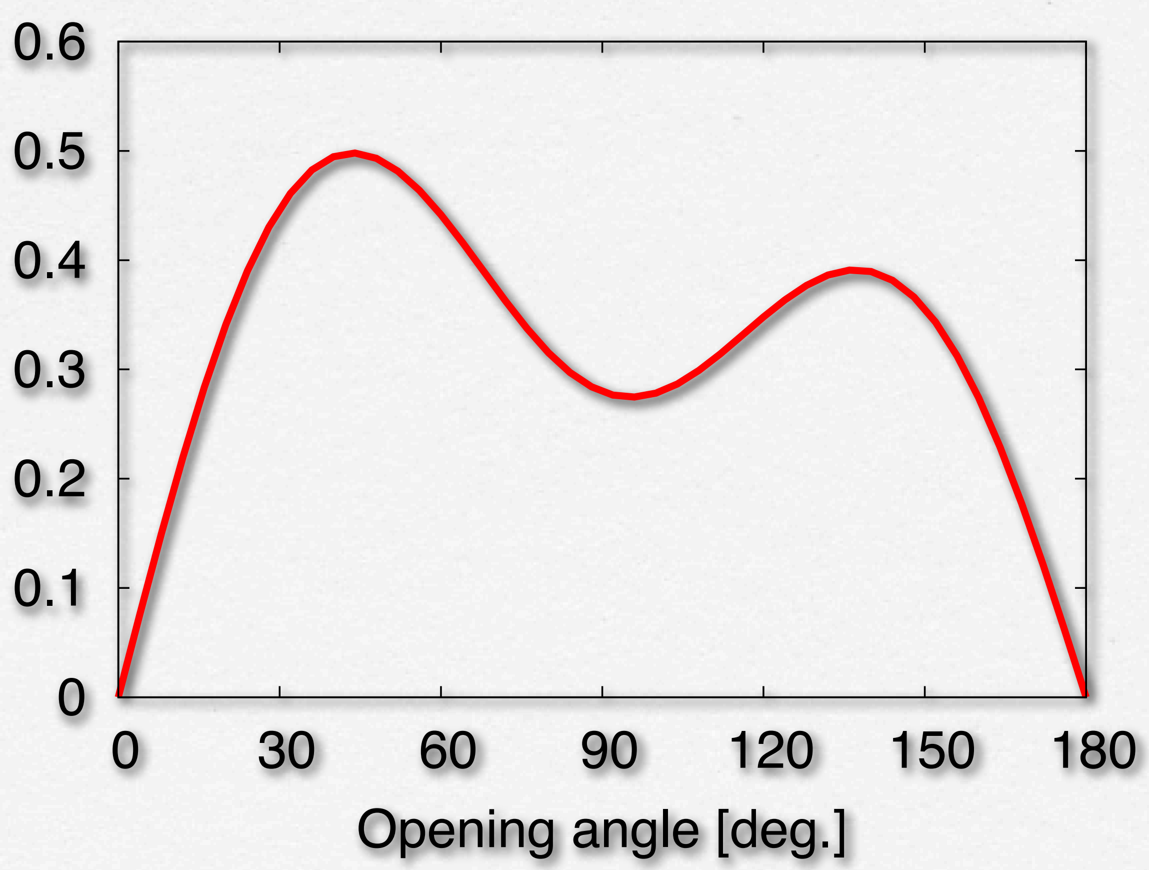
- Momentum distribution and angular correlation in the ground state of ^{6}He
  - In both distributions, the peaks are seen at the region of large angle.
    - These indicate the dineutron in the ground state.

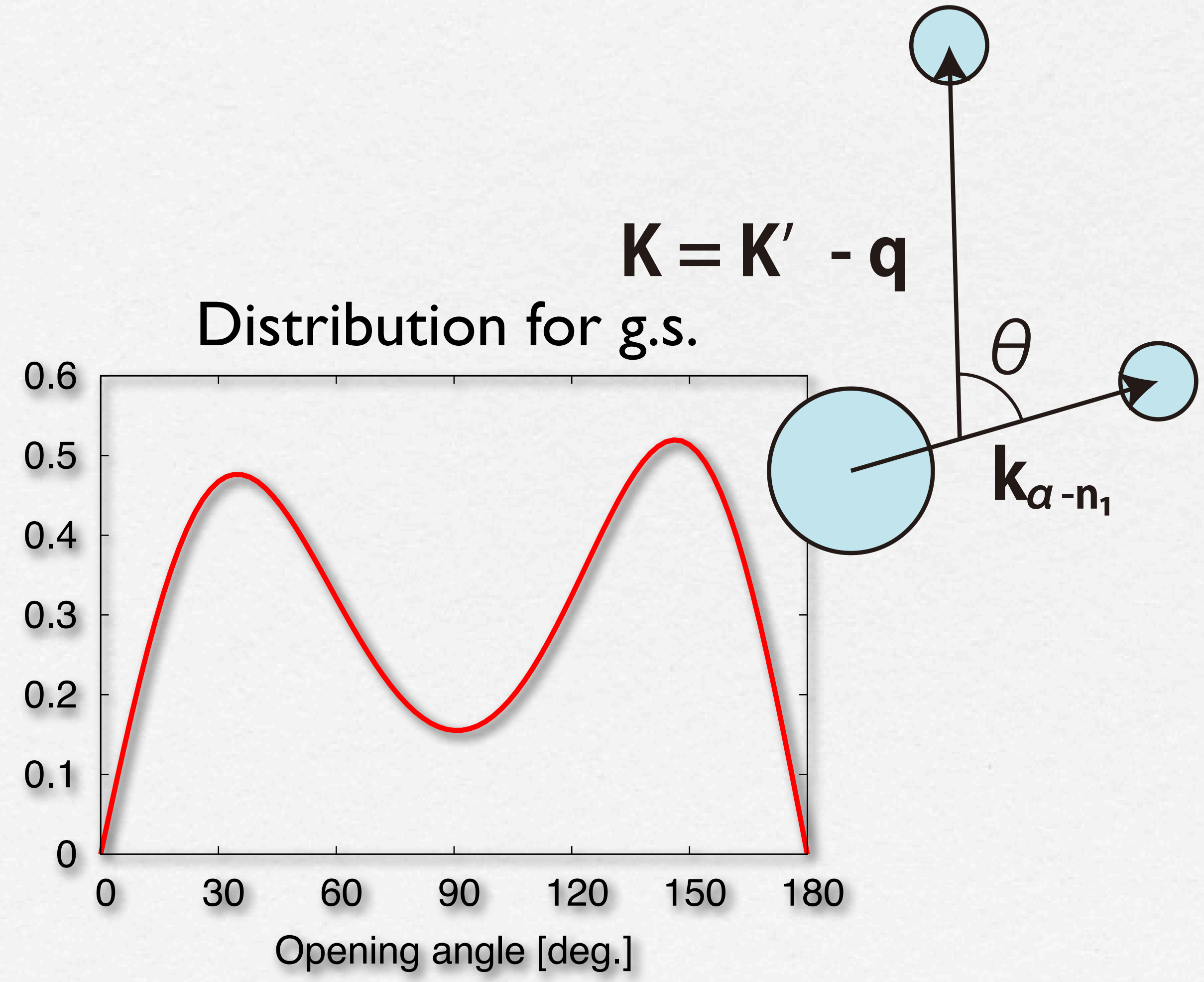




Results: Angular correlations in knockout reactions

- We calculate the angular correlation in the knockout reaction.
  - The calculated distribution shows the two-peaked structure.
  - However, in the result for knockout reaction, the 2nd peak, corresponding to the dineutron, is reduced compared to the ground-state distribution.
  - The process via ^{5}He changes the angular correlation, especially for the dineutron part.

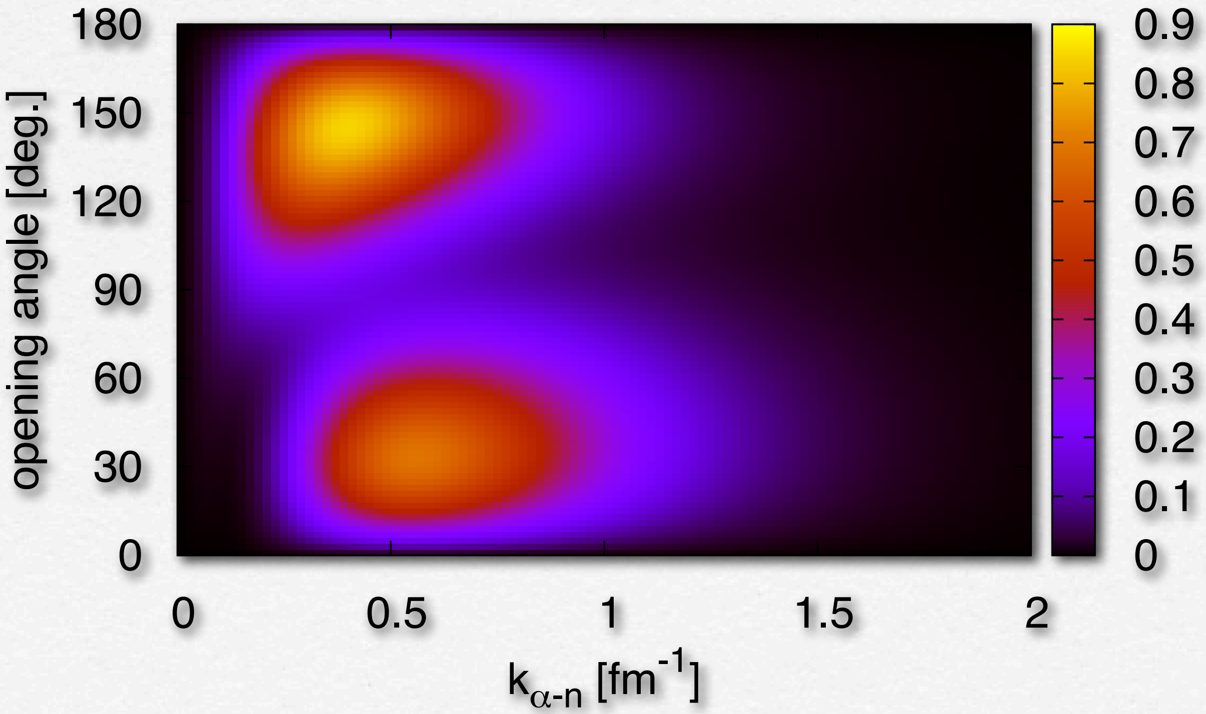




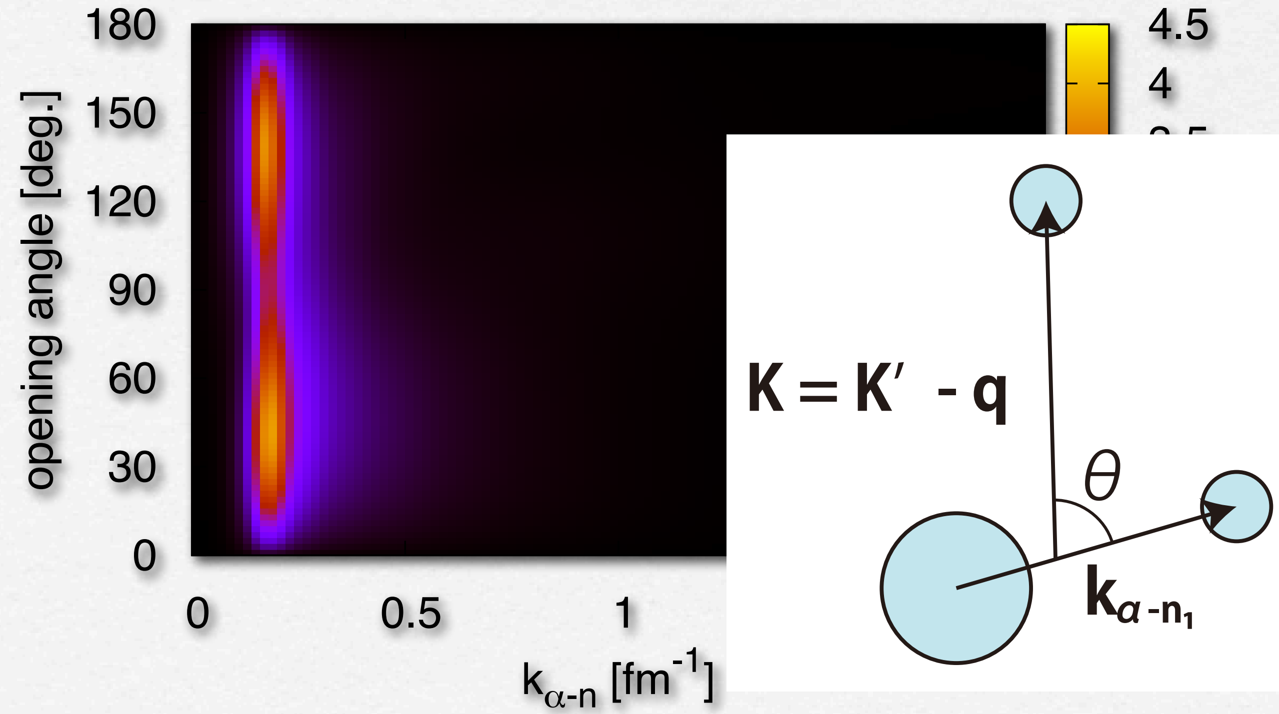
Results: Effects of process via ^{5}He resonances

- What happens by taking into account the process via ^{5}He resonance?
  - Inclusion of the process via ^{5}He resonance, the momentum distributions is concentrated on the momentum region corresponding to ^{5}He(3/2$^-$).
  - The process via ^{5}He resonance drastically changes the angular correlation.
  - Next, to minimize the effect of such as process, we select the off-resonance region in calculating the angular correlations.

2D distribution for g.s.

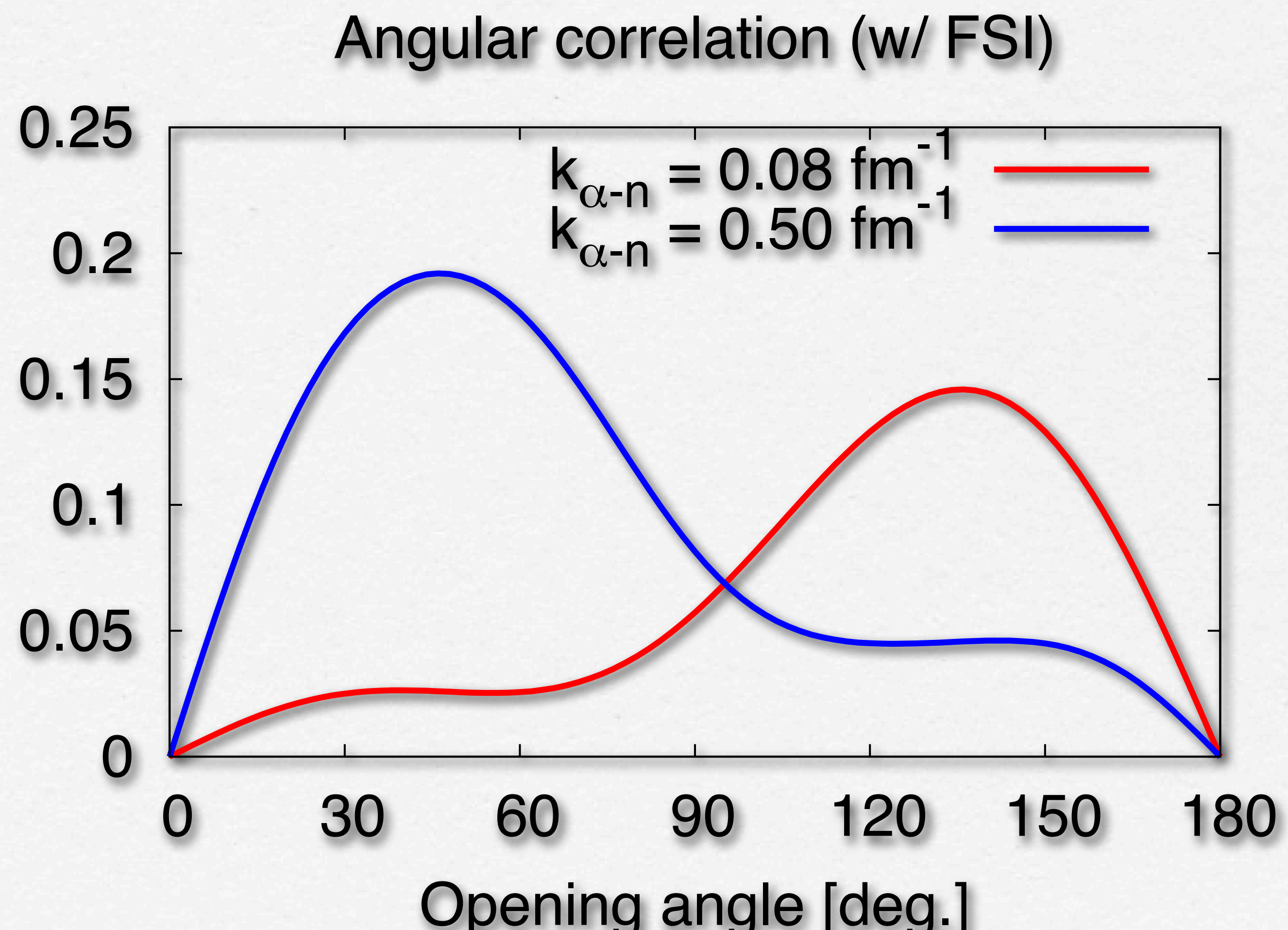


2D distribution for knockout



Results: Angular correlations in off-resonance region

- Lower and higher momentum parts of off-resonance region
  - The lower part, which corresponds to the surface region of ^{6}He, shows the strong enhancement at large angle.
    - ➡ This indicates the dineutron configuration in the ground state of ^{6}He.
  - The higher part, on the other hand, shows the signature of cigar-like one.



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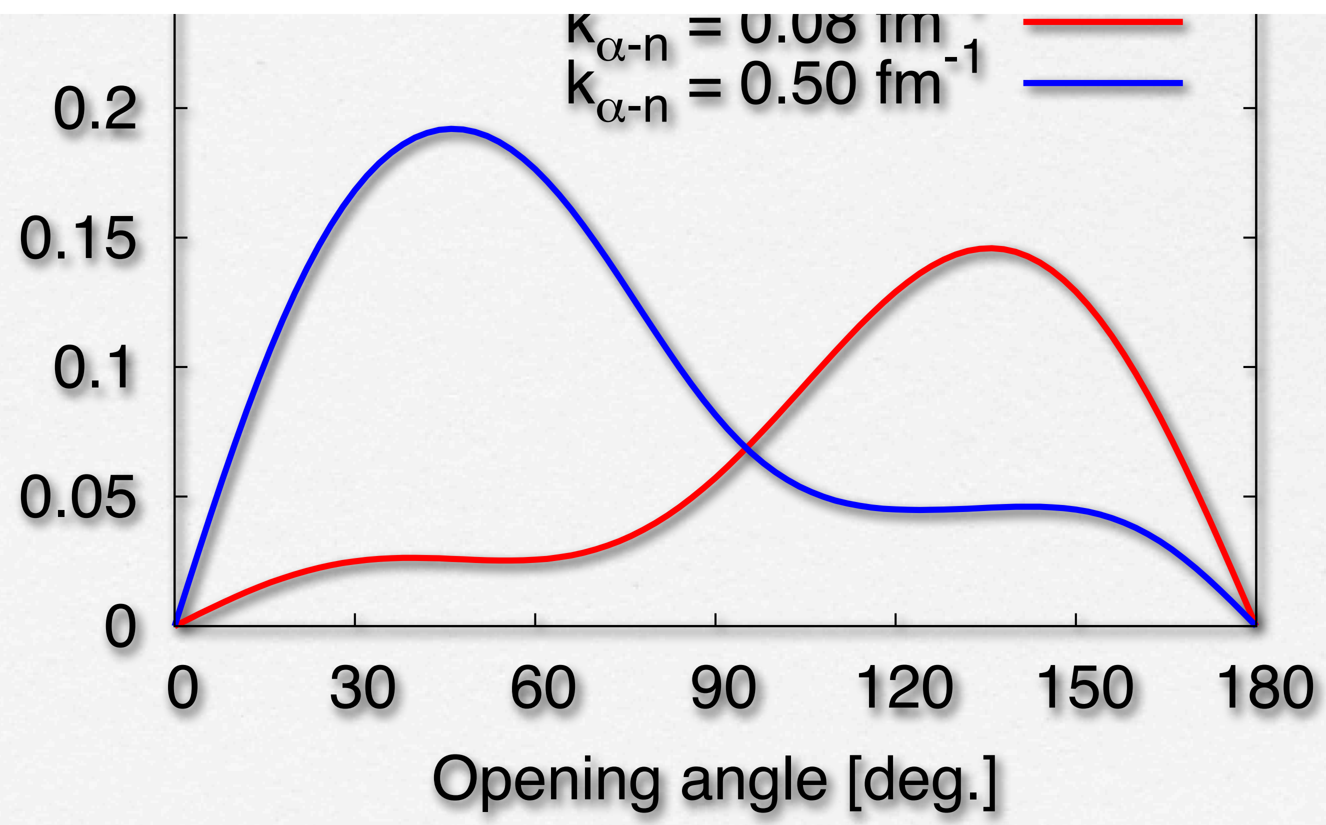
By measuring the lower momentum part of off-resonance region, we can see a clear evidence of dineutron.



Summary

- To investigate the dineutron in the ground and excited states of ^{6}He, we investigated two types of reactions.
  - For the excited state, we calculated the breakup reaction by ^{12}C at 240 MeV/nucleon, in which the 2^+_1 state is populated in final states.
    - We clarified the decay mode of 2^+_1, and found that the genuine three-body decay is dominant in the decay from 2^+_1.
    - The IMS for n-n shows the specific back-to-back emission of two neutrons, which can be a possible signature of dineutron.
  - For the ground state, we calculated the quasi-free knockout reaction.
    - We found that the process via the ^{5}He resonance drastically changes the angular correlation in the knockout reaction.
    - By selecting the off-resonance region in calculating the angular correlations, we can see a clear signature of dineutron as a huge enhancement at large angle.