チャネル結合^{9}Li+n+n模型を用いた ^{11}Liのクーロン分解反応の分析

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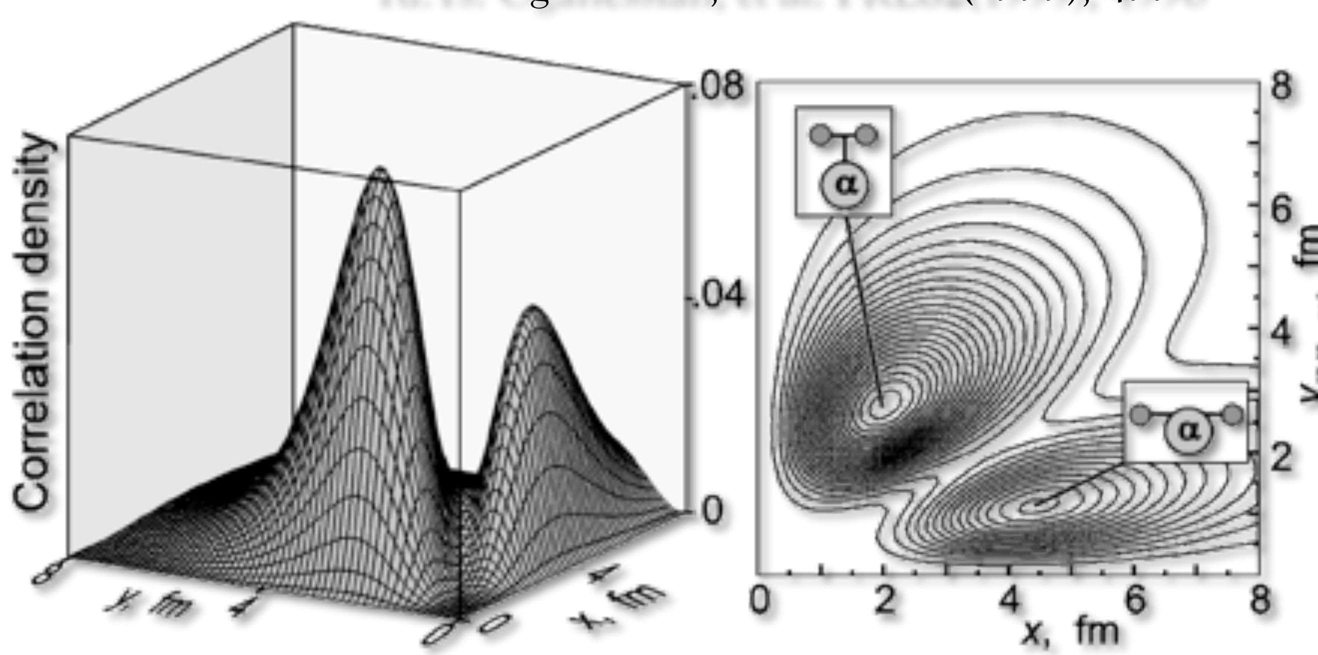
published in PRC87, 034606 (2013).

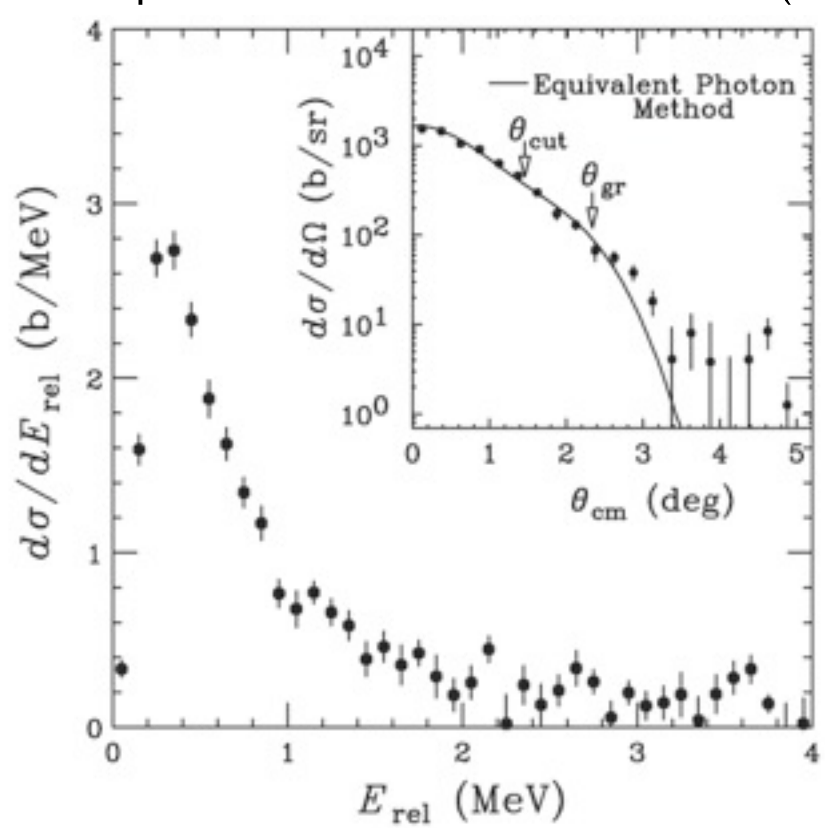
2n halo nuclei and their Coulomb breakups

- Theoretical studies based on core+2n picture
  - "dineutron" correlation
- Experiments using Coulomb breakup reactions
  - Low-lying enhancement above the breakup threshold
  - Related to dineutron?

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



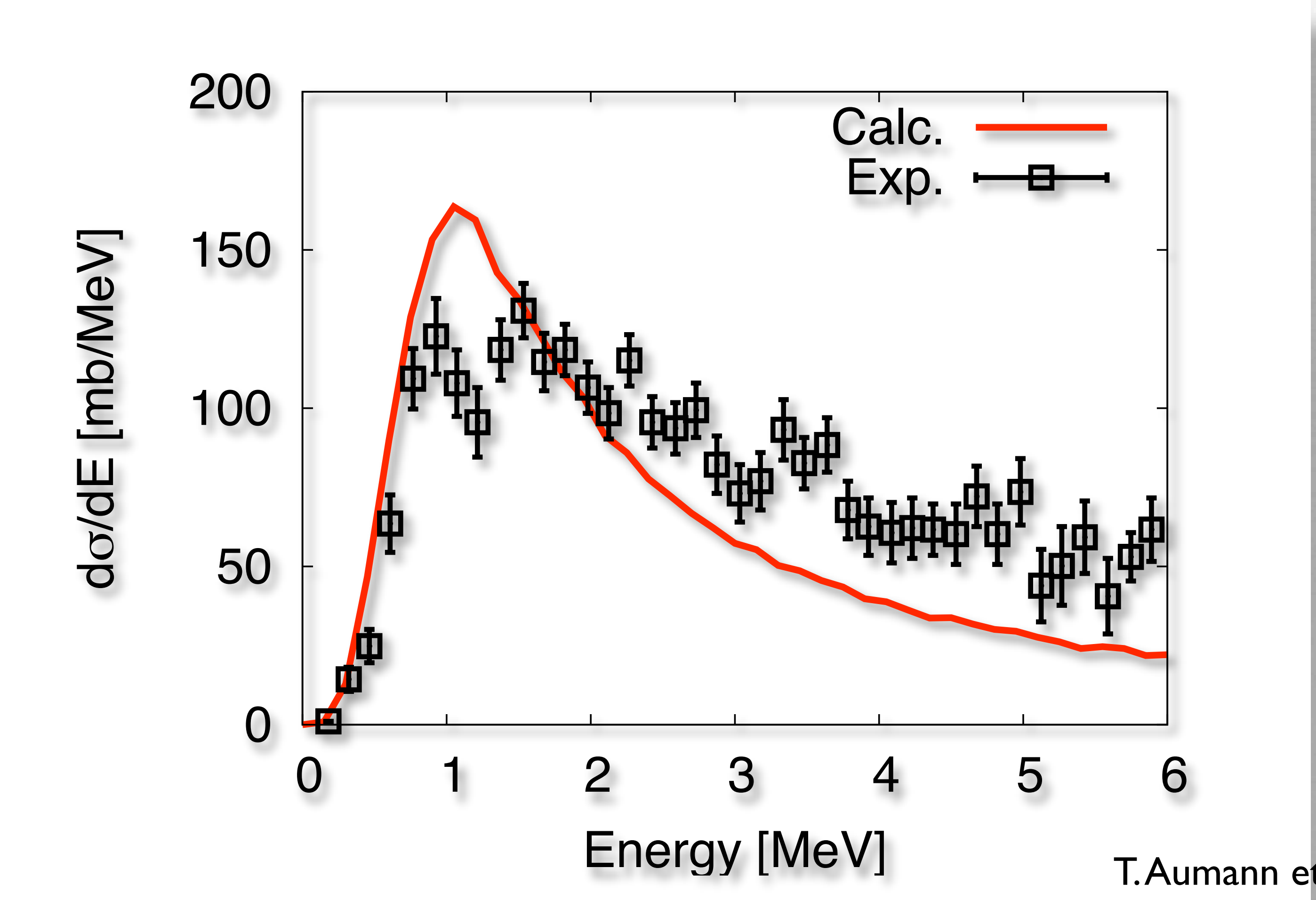
[11]Li breakup: T. Nakamura et al., PRL 96, 252502 (2006).



YK et al., PTP 122, 499 (2009).
YK et al., PRC 81, 044308 (2010).

Coulomb breakup reaction of ^{6}He

- Our previous analysis based on α+n+n three-body model
  - Good agreement with the observed cross section
  - Dominance of FSI
    - ^{5}He(3/2$^-$) resonance & n-n virtual state
    - The information on g.s. structure is masked



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

Exotic properties of ^{11}Li

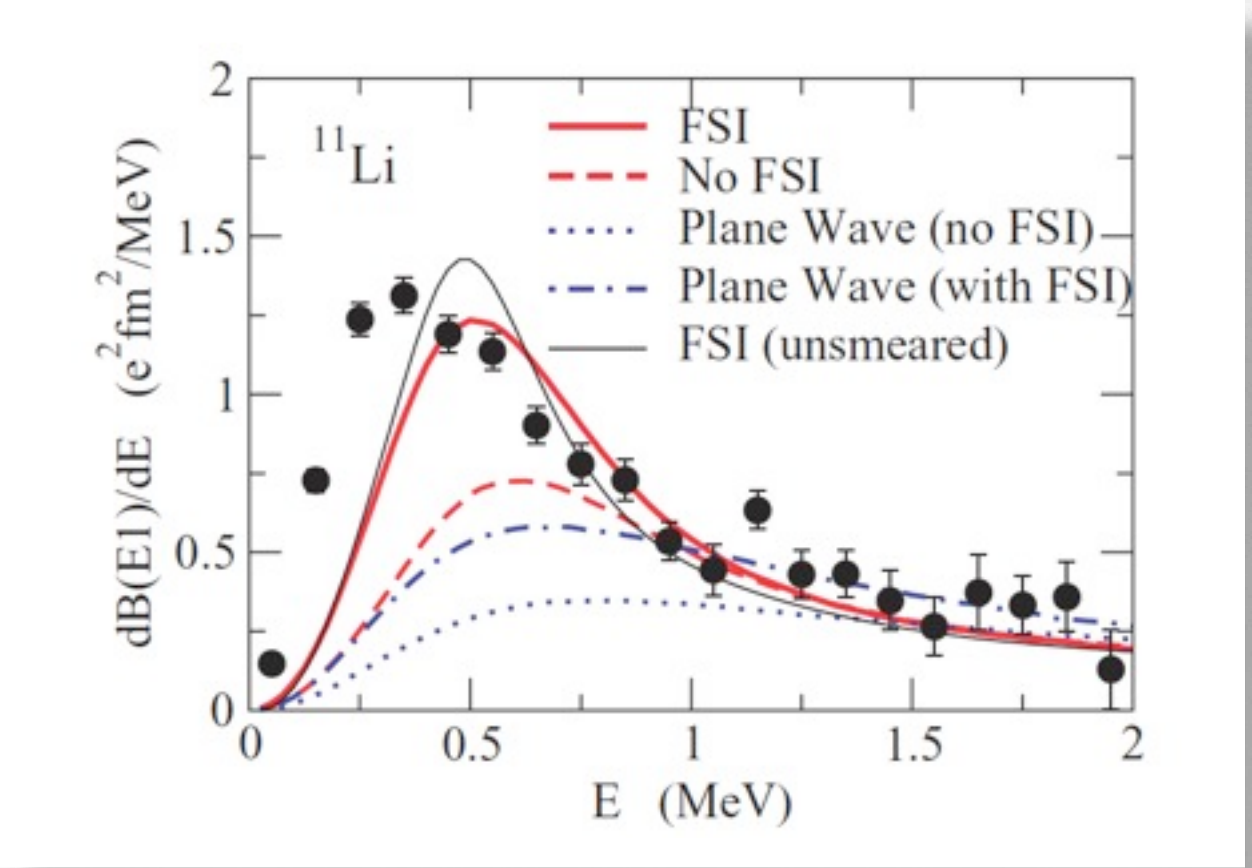
- Breaking of the N=8 magic number
  - Large $(s_{1/2})^2$ component of halo neutron comparable to the $(p_{1/2})^2$ one
  - Such a large s-wave mixing causes the well-developed halo structure.

- Suggested point from the simple model assuming the inert ^{9}Li core
  - Difficult to explain the charge radius and the dipole strength in ^{11}Li simultaneously*.

K. Hagino et al., PRC80, 031301(R) (2009).
*H. Esbensen et al., PRC76, 024302 (2007).

Theory
$(1s_{1/2})^2$ component = 20.6 %
scattering length for ^{9}Li-n = −5.6 fm

Expt.
$(1s_{1/2})^2$ component = 45±10%
scattering length for ^{9}Li-n ~ −30 fm



In this talk...

- We investigate the Coulomb breakup mechanism of ^{11}Li.
- We calculate the cross section by using the coupled-channel ^{9}Li+n+n three-body model, in which the coupling between the relative motion of halo neutrons and the excitations of ^{9}Li core is taken into account.
- We discuss the following points:
  - Effects of FSI
  - Binary subsystem correlations
  - Effects of ^{9}Li core excitation

- Our approach T. Myo et al., PTP119, 561 (2008).
  - 2p-2h excitations due to tensor and pairing correlations in ^{9}Li (TOSM)

    ➡ well reproduce the observed quantities in g.s. and E1 strength

Coupled-channel ^{9}Li+n+n three-body model

- We take into account the coupling between the relative motion of halo neutrons and the excitation of the ^{9}Li core.
  - Hamiltonian

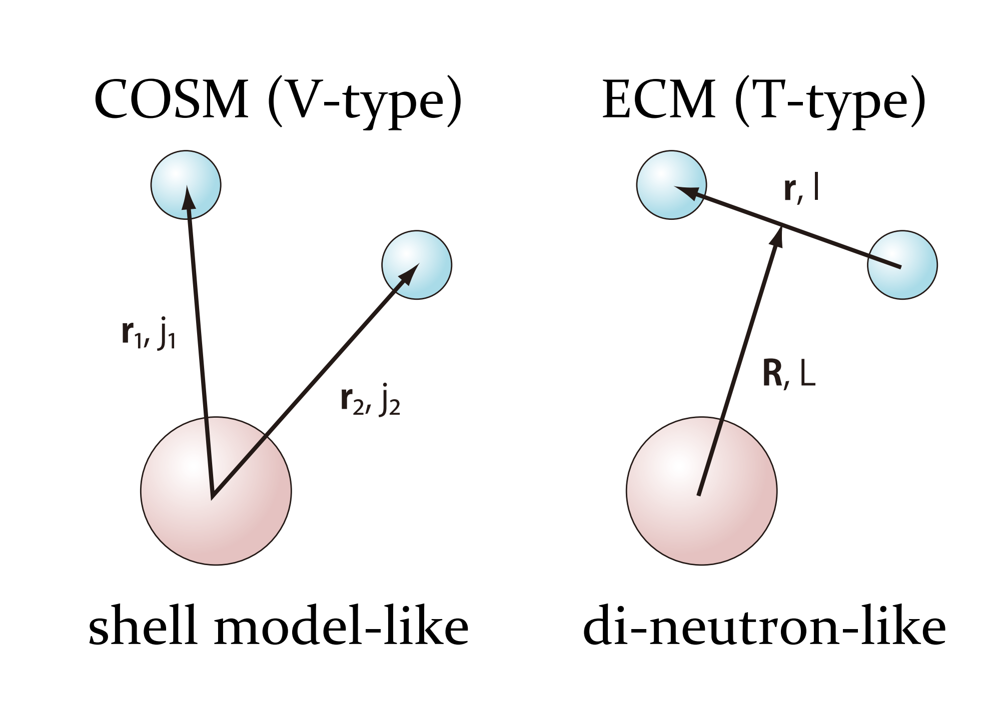
$$\hat{H} = \sum_{i=1}^{3} t_i - T_{\rm cm} + \sum_{i=1}^{2} V_{^9\text{Li-}n}(\mathbf{r}_i) + V_{n\text{-}n} + \lambda|\Phi_{\rm PF}\rangle\langle\Phi_{\rm PF}| + h(^9\text{Li})$$

$V_{^9\text{Li-}n}$: folded MHN potential $\quad V_{n\text{-}n}$: Argonne v8'

  - Wave function

$$\Phi^{J^\pi}(^{11}\text{Li}) = \sum_i C_i \left[\Phi_i(^9\text{Li}) \otimes \chi_{nn}\right]_{J^\pi}$$

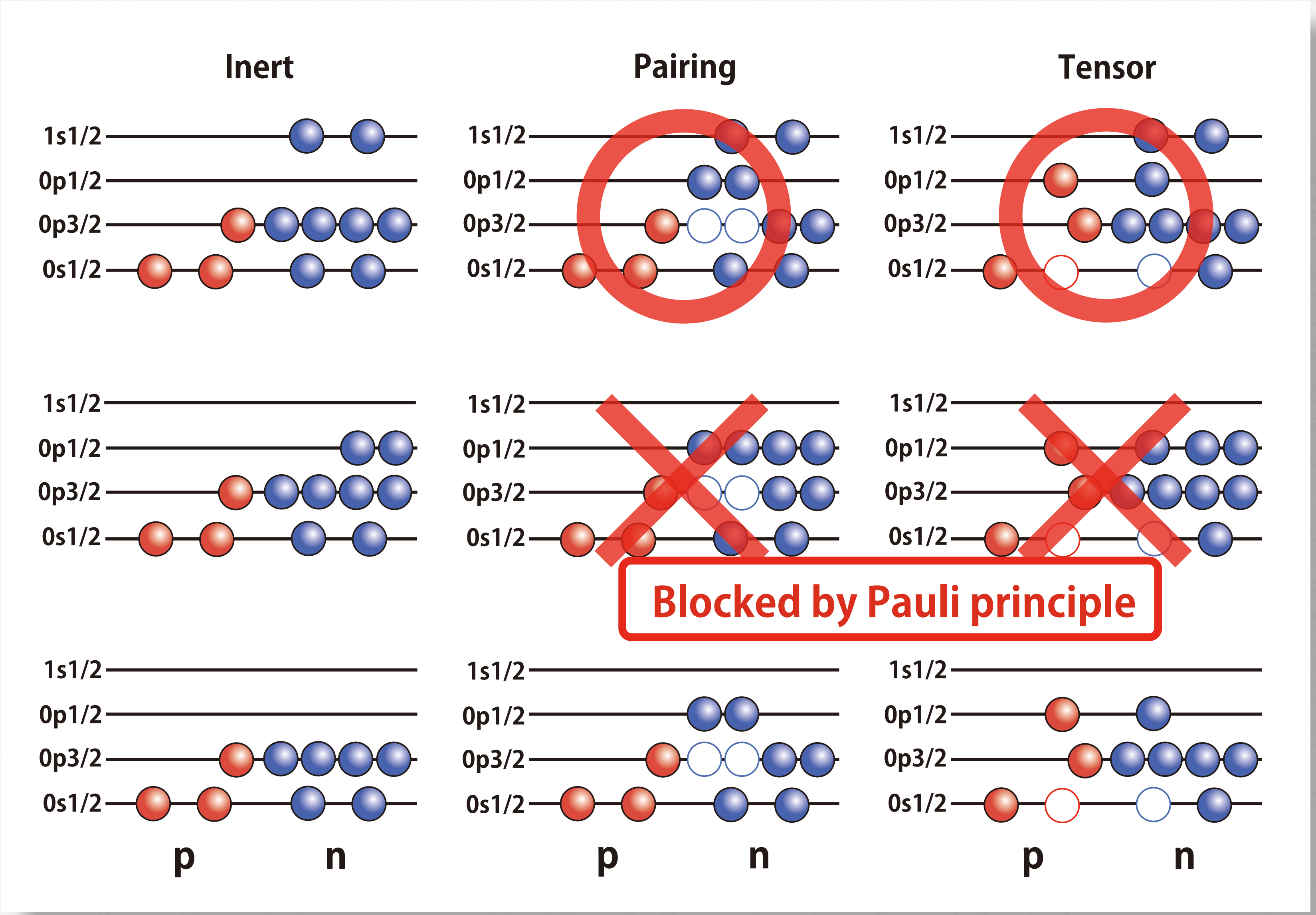
0p-0h & 2p-2h configurations



2p-2h excitations in ^{9}Li core

- The 2p-2h configurations make the single-particle energy of the $p_{1/2}$ orbit pushed up by the Pauli blocking effect.
  → Large $(s_{1/2})^2$ mixing & well-developed halo structure

T. Myo et al., PTP119, 561 (2008).



Properties of ^{11}Li and ^{10}Li with coupled-channels

- For ^{11}Li
  - Large s-wave mixing of 44.0% (45±10% in Exp.)
- For ^{10}Li
  - large s-wave scattering length → ^{10}Li virtual state
  - Two p-wave resonances @ E_r = 275 keV and 506 keV

For ^{11}Li

	Theor.	Exp.
S_{2n} (keV)	377	378 ± 5^{a}
R_m (fm)	3.39	3.12 ± 0.16^{b}
		3.53 ± 0.06^{c}
		3.71 ± 0.20^{d}
R_{ch} (fm)	2.43	2.467 ± 0.037^{e}
		2.423 ± 0.034^{f}
$P((s_{1/2})^2)(\%)$	44.0	45 ± 10^{g}
$P((p_{3/2})^2)(\%)$	2.5	–
$P((p_{1/2})^2)(\%)$	46.9	–
$P((d_{5/2})^2)(\%)$	3.1	–
$P((d_{3/2})^2)(\%)$	1.7	–

For ^{10}Li

	1^+	2^+	1^-	2^-	Exp.
Energy (keV)	275	506			
Width (keV)	150	388			
a_s (fm)			-6.8	-45.0	-30^{+12a}_{-31}

Coulomb breakup cross section

- Equivalent photon method

$$\frac{d^6\sigma}{d\mathbf{k}d\mathbf{K}} = \frac{16\pi^3}{9\hbar c} \cdot N_{E1}(E_\gamma) \cdot \frac{d^6B(E1)}{d\mathbf{k}d\mathbf{K}}$$

$$\frac{d^6B(E1)}{d\mathbf{k}d\mathbf{K}} = \frac{1}{2J_{\rm gs}+1} \left| \langle \Psi^{(+)}(\mathbf{k},\mathbf{K}) || \hat{O}(E1) || \Phi_{\rm gs} \rangle \right|^2$$

- For scattering states:
  Complex-scaled solutions of the Lippmann-Schwinger equation (CSLS)
  - Interaction region
    - Few-body technique similar to the bound states
  - Boundary conditions
    - Complex scaling method

Complex-scaled solutions of LS equation (CSLS)

- Formal solution of LS equation

$$\Psi^{(\pm)} = \Phi_0 + \lim_{\varepsilon \to 0} \frac{1}{E - \hat{H} \pm i\varepsilon} \hat{V} \Phi_0$$

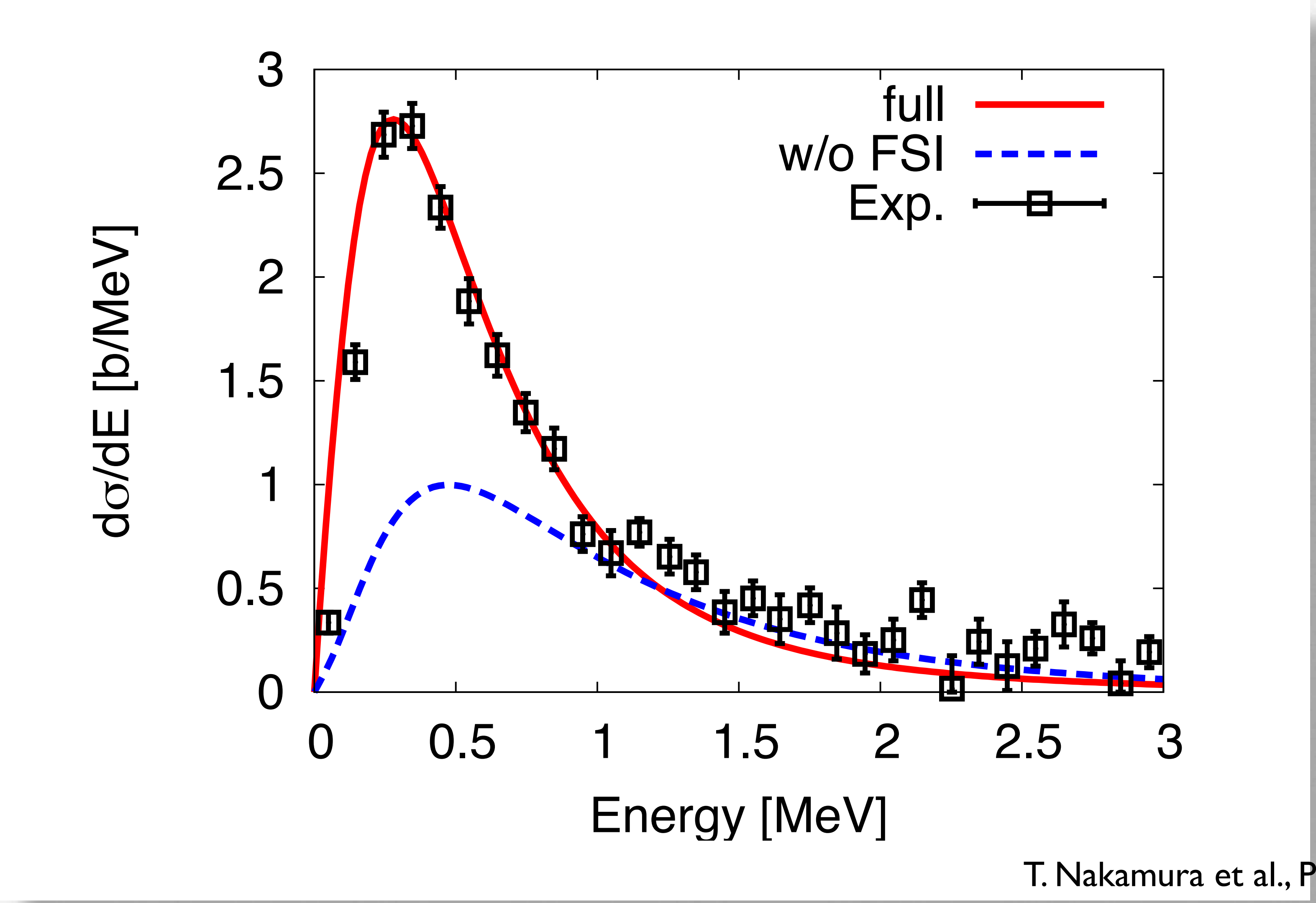
- Complex-scaled Green's function

$$\lim_{\varepsilon \to 0} \frac{1}{E - \hat{H} + i\varepsilon} = U^{-1}(\theta) \frac{1}{E - \hat{H}^\theta} U(\theta) = \sum_n U^{-1}(\theta) |\chi_n^\theta\rangle \frac{1}{E - E_n^\theta} \langle \tilde{\chi}_n^\theta | U(\theta)$$

  - Expand with complete set constructed by the eigenstates of H^θ
  - Coupling b/w relative motion of halo neutrons and excitation of ^{9}Li core

Coulomb breakup cross section of ^{11}Li

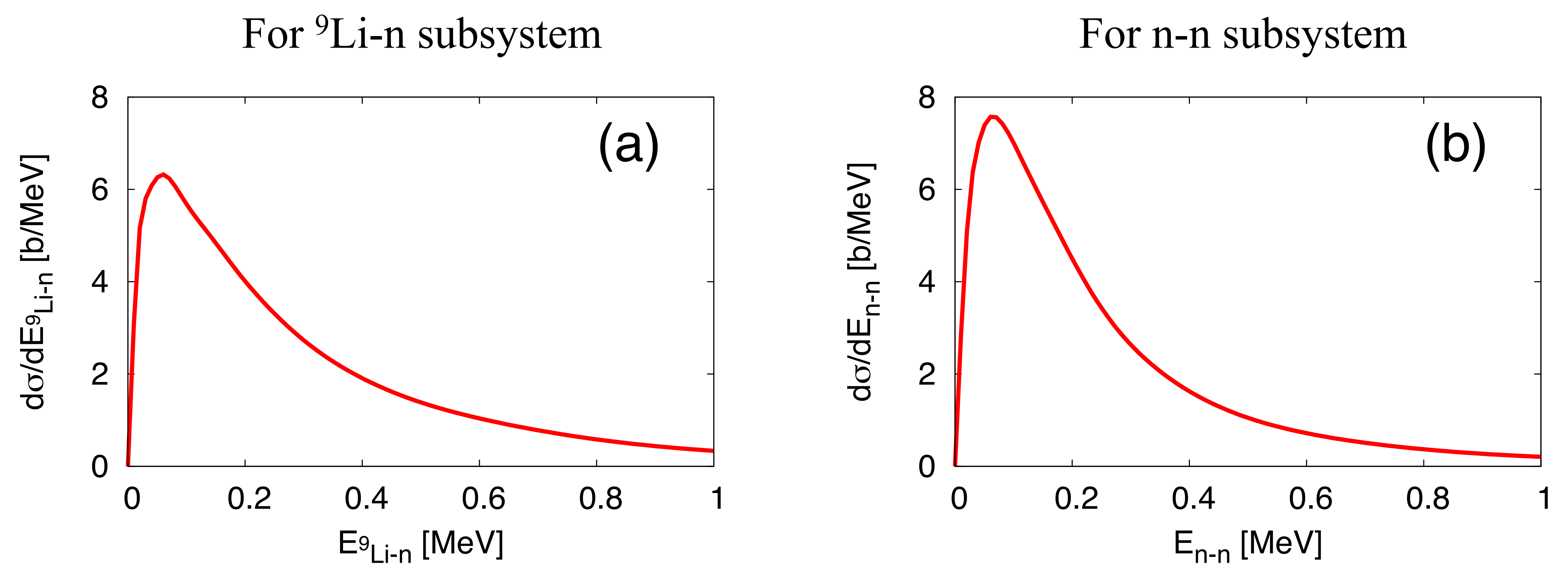
- Calculated differential cross section with respect to total excitation energy.
  - Perfect agreement with the experiment in whole energy region.
  - Low-lying enhancement comes from FSI → similar to the ^6He case.



T. Nakamura et al., PRL 96, 252502 (2006).

Breakup mechanism of ^{11}Li Coulomb breakup

- Invariant mass spectra for binary subsystems
  - ^{10}Li and n-n virtual states
  - p-wave resonances of ^{10}Li → not identified



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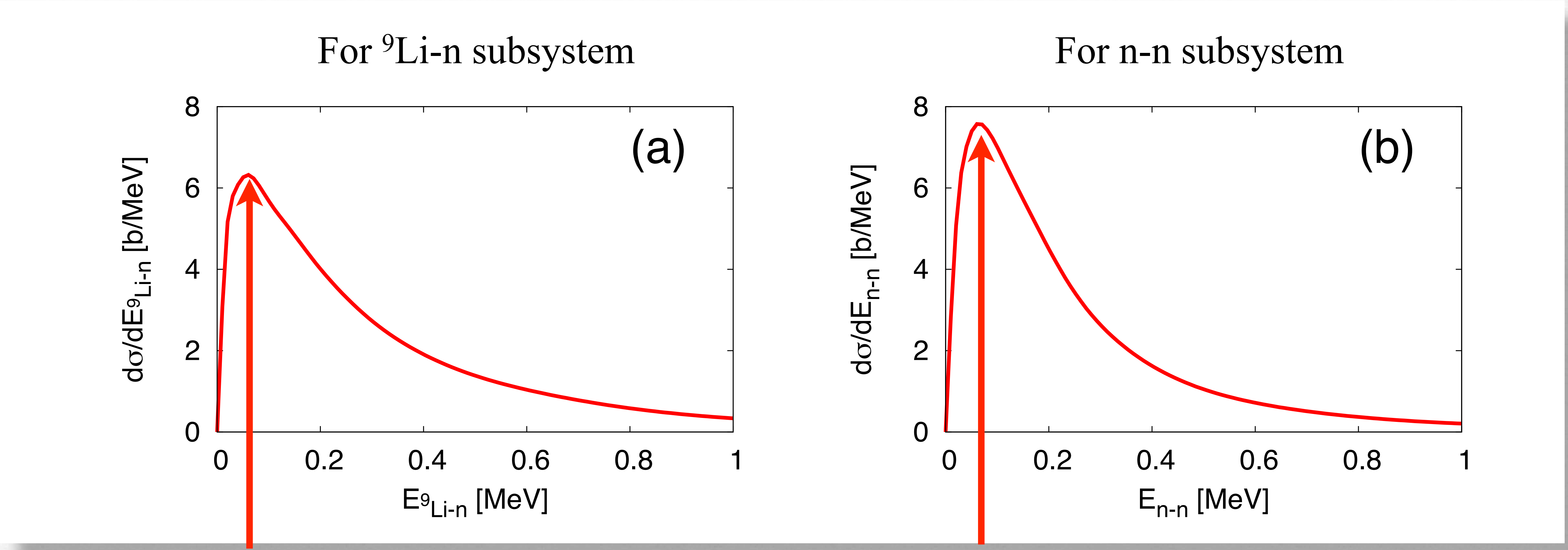

^{10}Li virtual state **n-n virtual state**

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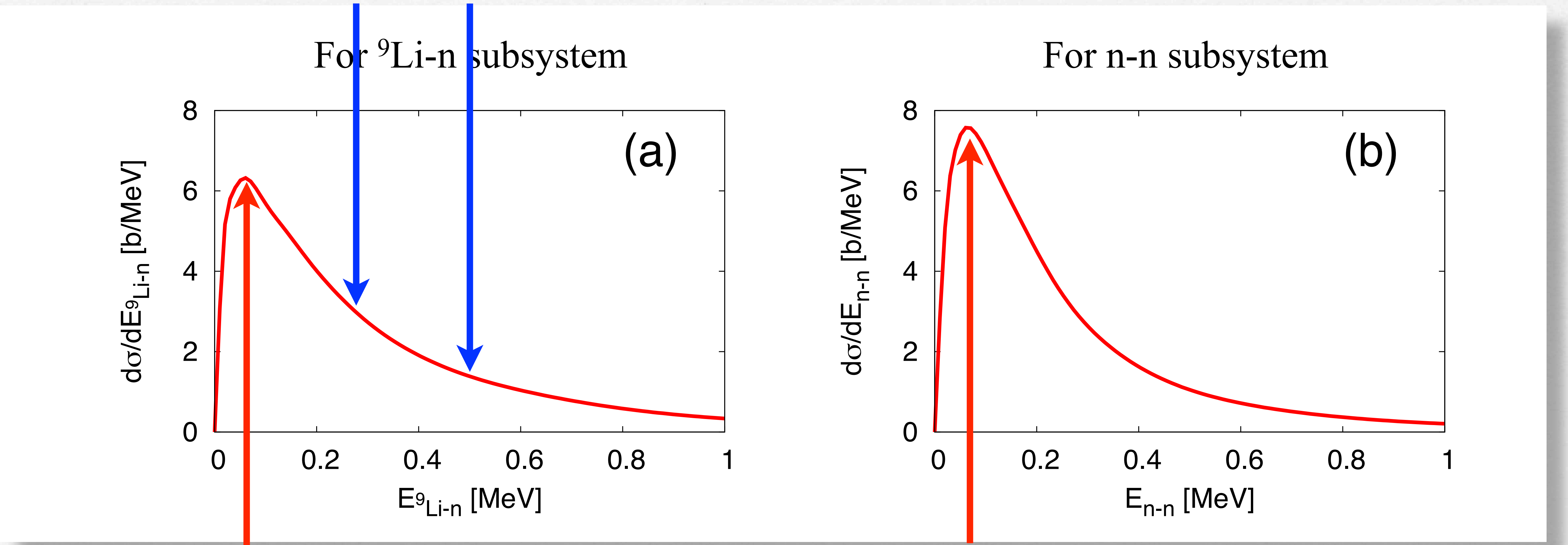
p-wave resonances



^{10}Li virtual state

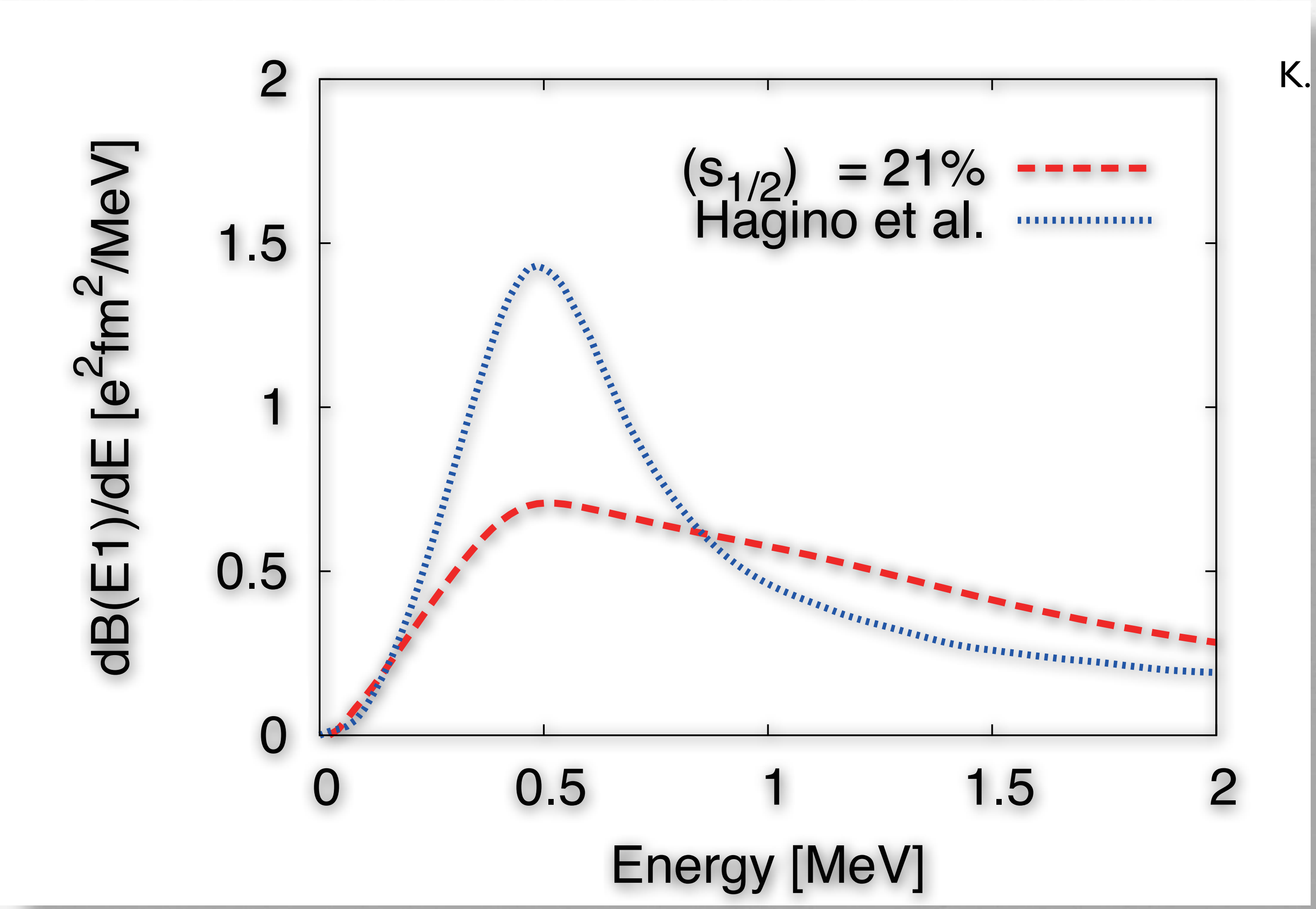
n-n virtual state

Effects of ^{9}Li core excitation on the cross section

- To see the effects of the excitation of the ^{9}Li core
  - For comparison...
    1. Our model including only pairing-type 2p-2h excitation
       - V_{core-n} is tuned to reproduce the g.s. binding energy
       - $(s_{1/2})^2$ component = 21.0 %
    2. Simple model assuming inert ^{9}Li core   Hagino et al., PRC80, 031301(R) (2009).
       - Using different V_{core-n} for even- and odd-parity states
       - $(s_{1/2})^2$ component = 20.6 %

Effects of ^{9}Li core excitation on the cross section

- ^{9}Li core excitation
  ➡ Effect on shape & sum rule reduction ~ 15 %



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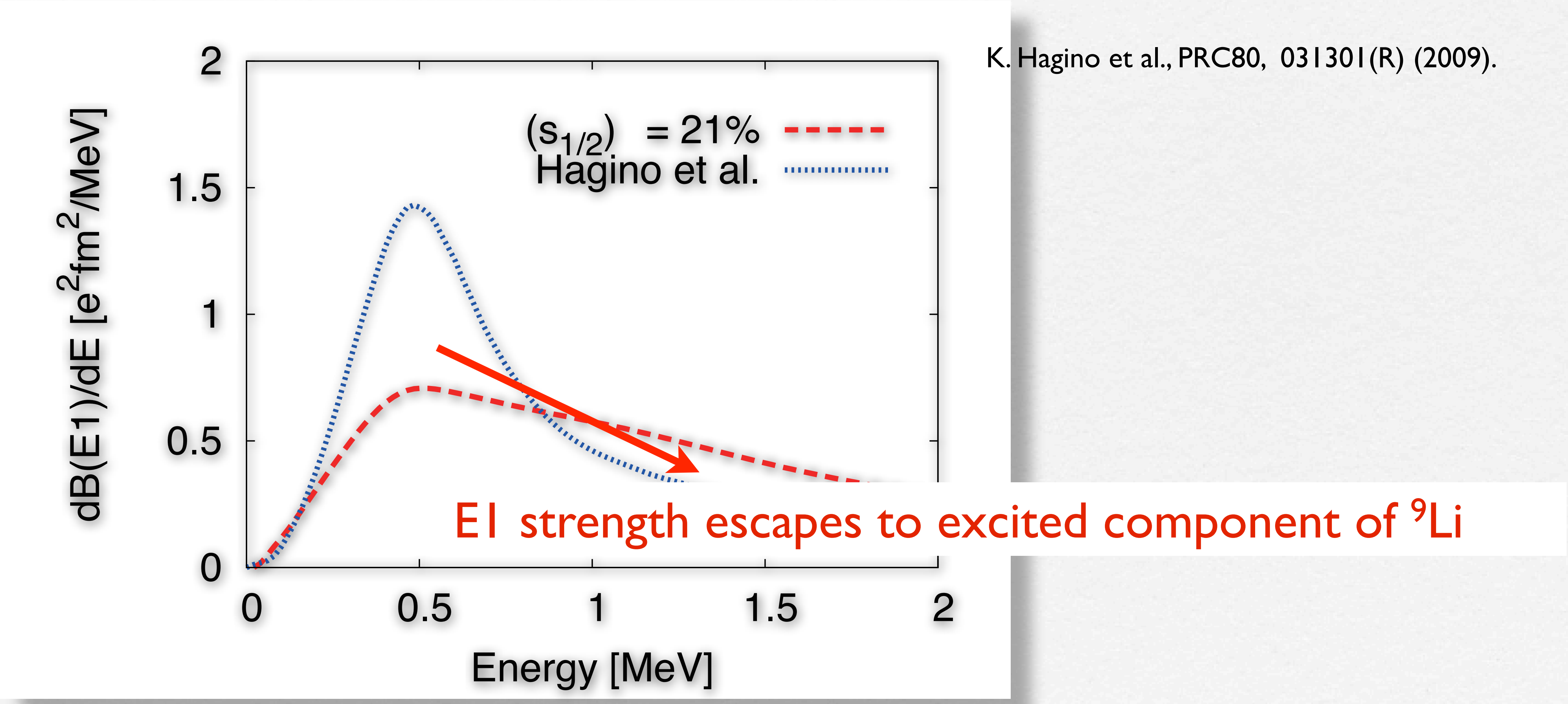

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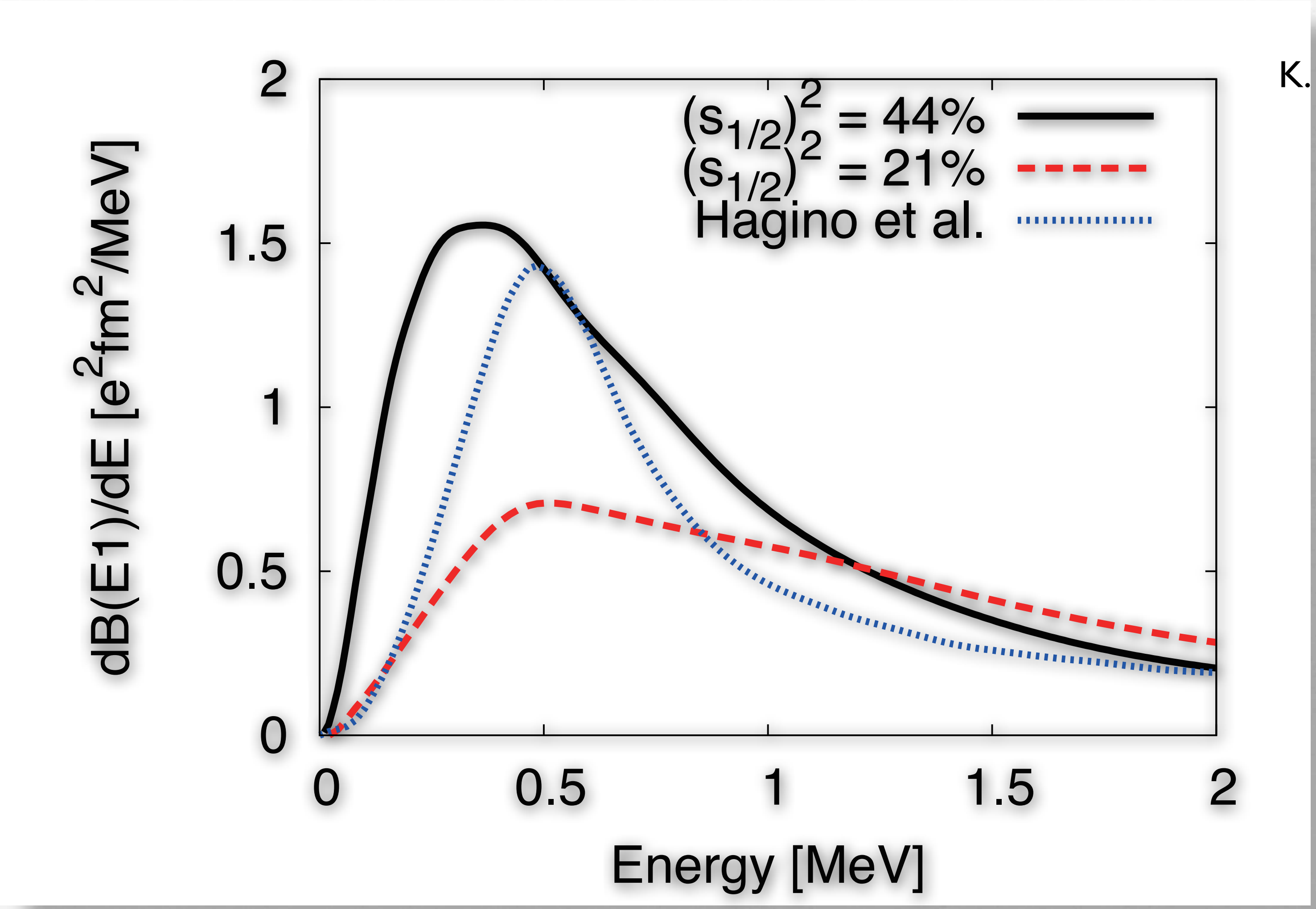
Effects of ^{9}Li core excitation on the cross section

- ^{9}Li core excitation
  - ➡ Effect on shape & sum rule reduction ~ 15 %
- Large s-wave mixing
  - ➡ Enhances the strength at low energy



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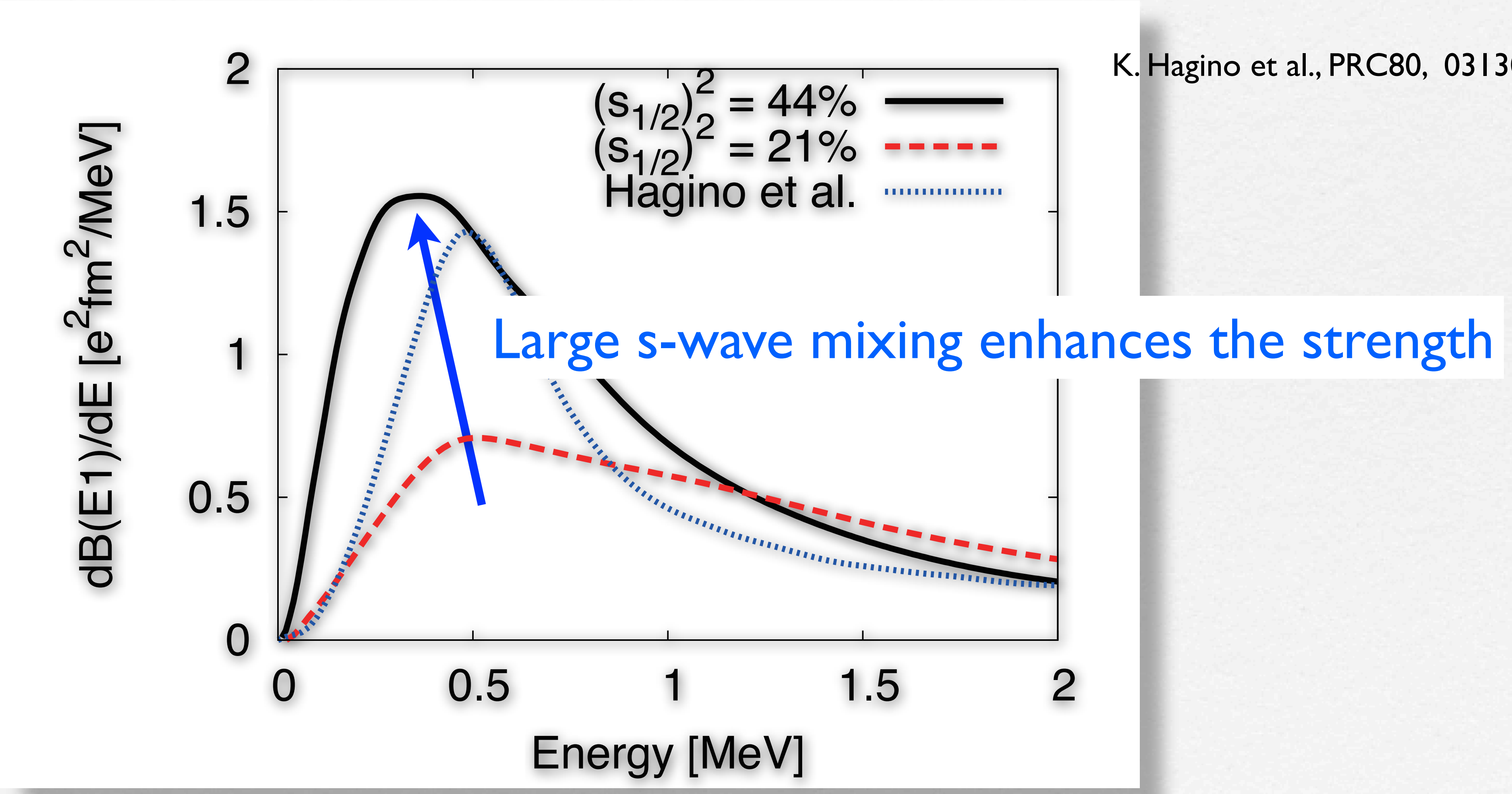

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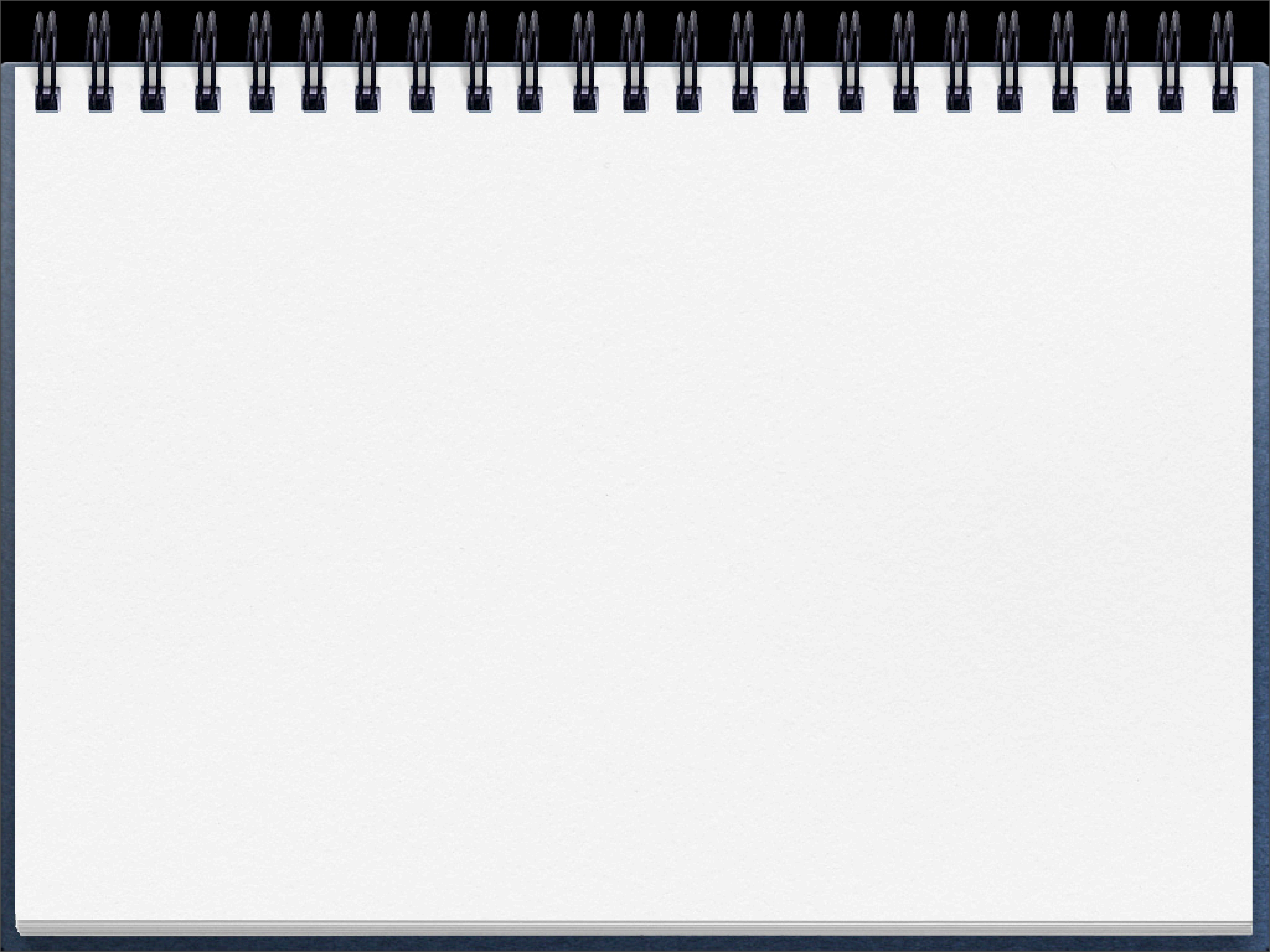
Summary

- We investigated the Coulomb breakup mechanism of ^{11}Li.
- We calculated the cross section by using the coupled-channel ^{9}Li+n+n three-body model.

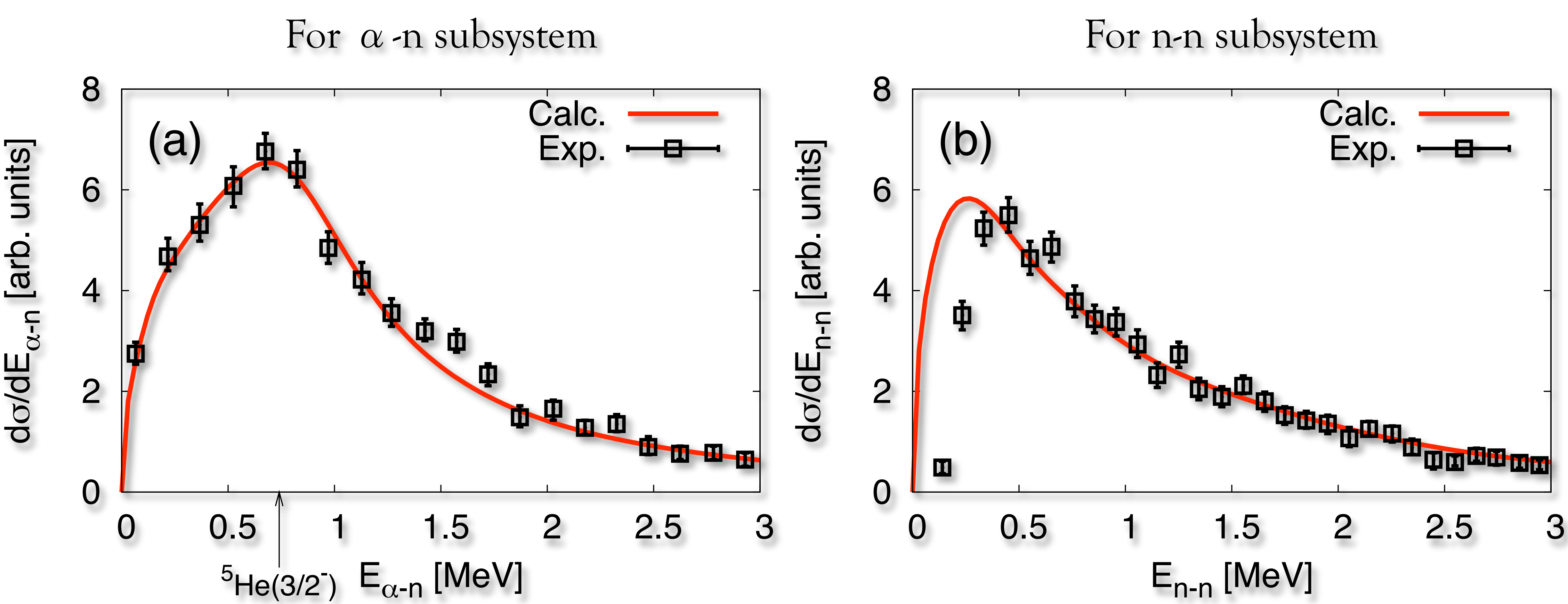
  ➡ Perfect agreement with the observed cross section
- We discussed the following points:
  - Effects of FSI ➡ Dominated the cross section
  - Binary subsystem correlations ➡ ^{10}Li & n-n virtual states
    ^{10}Li p-wave resonances are not identified
  - Effects of ^{9}Li core excitation ➡ 15 % reduction of E1 sum rule

2p-2h excitation due to the tensor and pairing correlations in ^{9}Li is a key to reproduce the observed quantities.



Results - Application to ^{6}He -

- What kinds of FSI are important?
  - We calculate invariant mass spectra as functions of energies of binary subsystems.
  - For ^{4}He-n, the spectra has a peak, whose position corresponds to resonance energy of ^{5}He(3/2-).
  - For n-n, the spectra has a sharp peak in low-energy region, which comes from the virtual s-state of n-n system.



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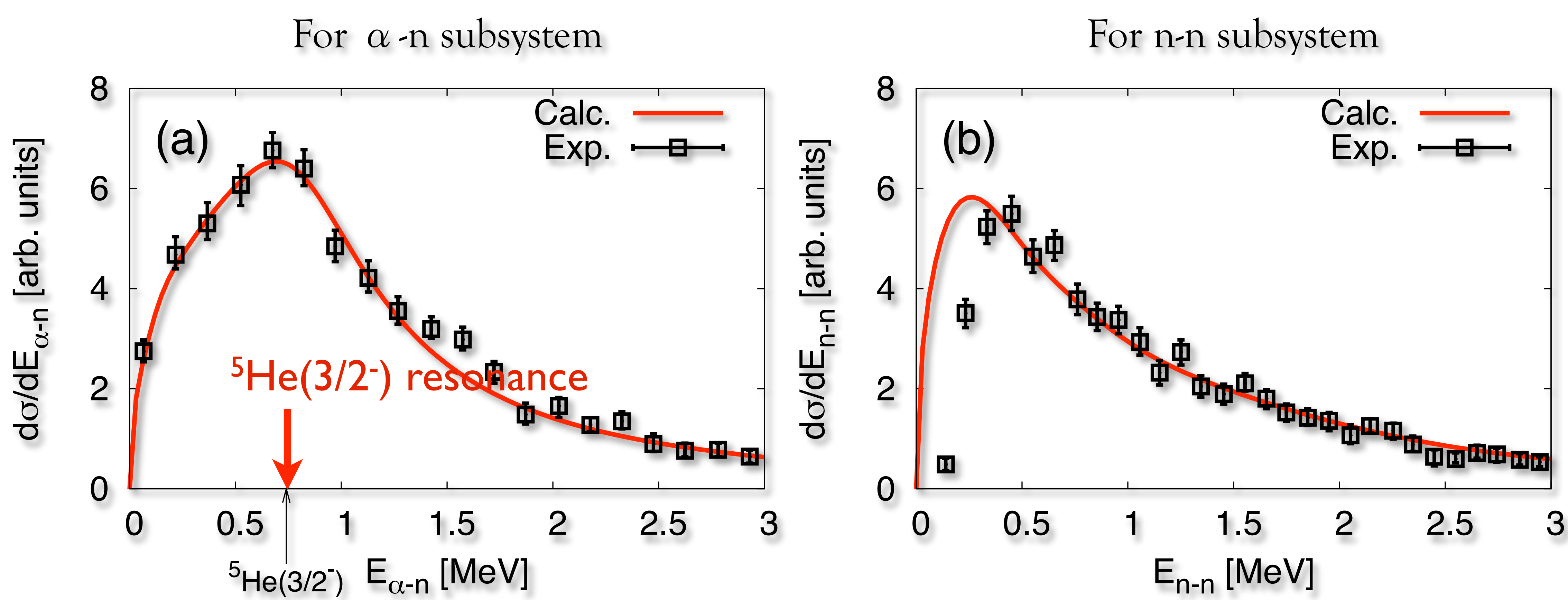

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