Study of resonant states in nuclei via breakup reactions

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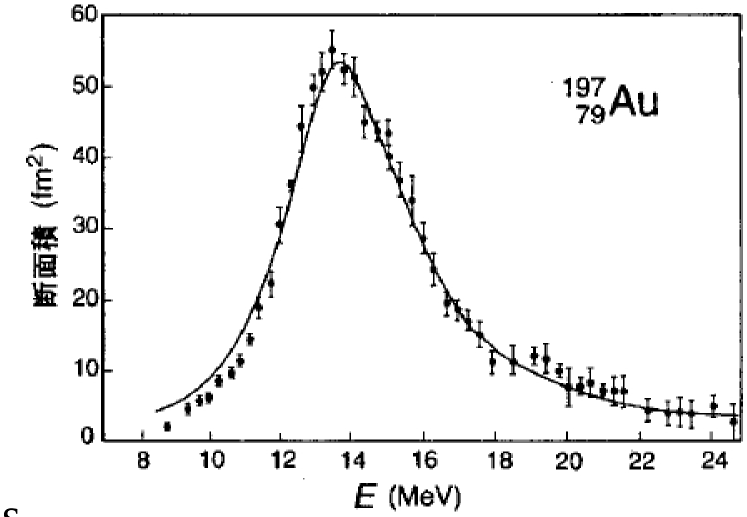
Few-Body systems in Hadron, Nuclei, Atomic and Molecular Physics

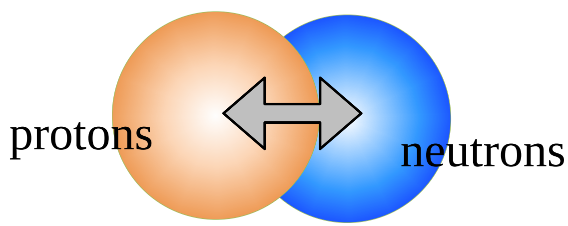
Introduction

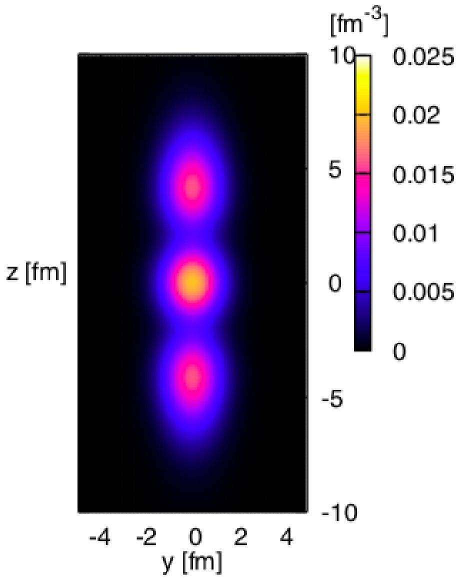
■Resonance in Nuclei

✓ Giant dipole resonance

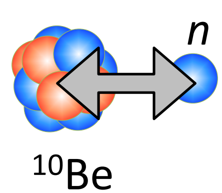


Corrective nuclear excitation

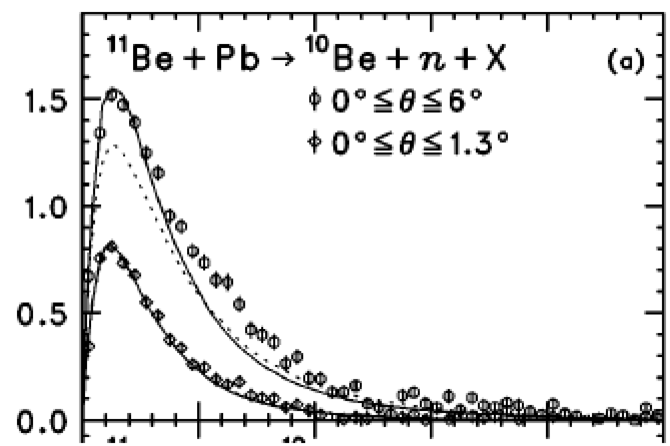




✓ Soft dipole resonance



N. Fukuda et al., PRC 70 054606 (2004)



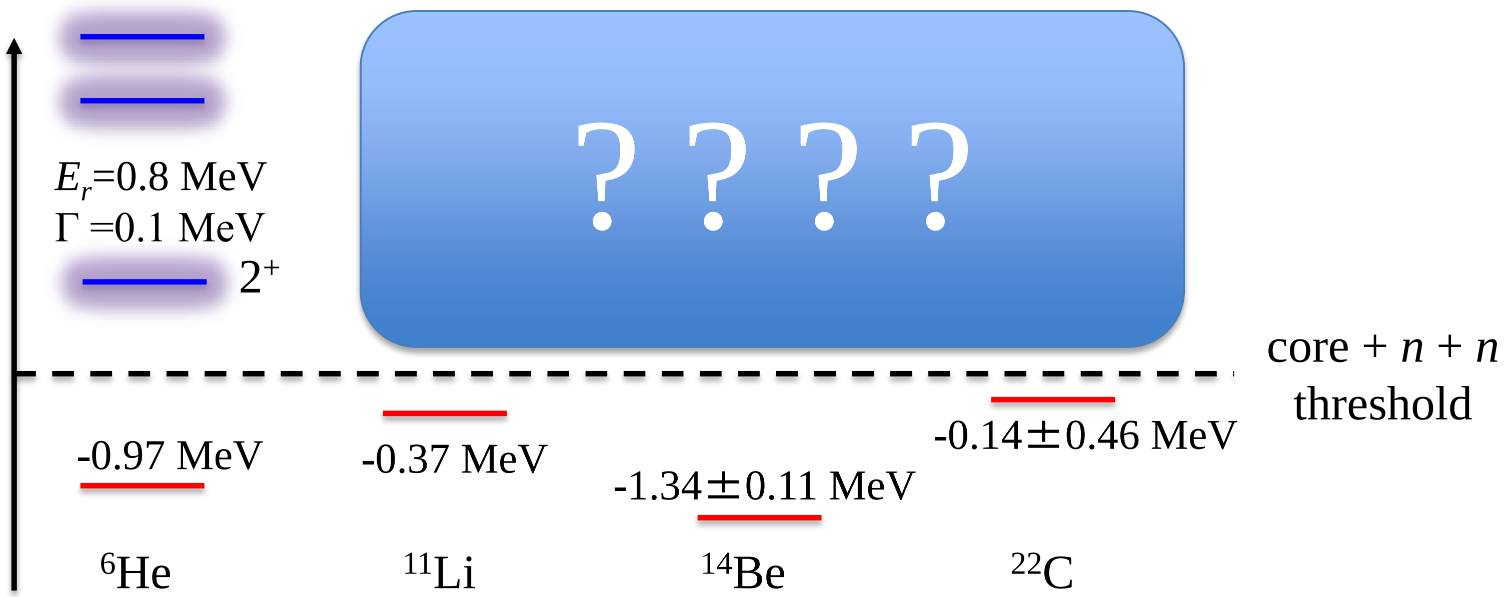
Y. Funaki, Phys. Rev. C **94**, 024344 (2016).

✓ Cluster resonance

Linear chain structure

Two-neutron halo nuclei

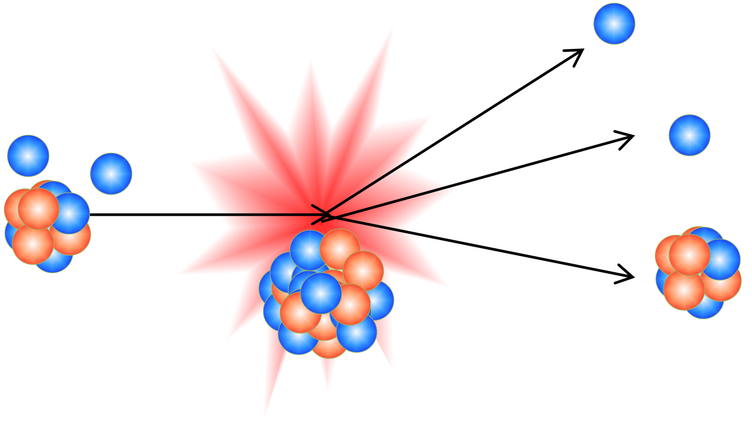
^{6}He, ^{11}Li, ^{14}Be, and ^{22}C are known as two-neutron halo nuclei consisting of a core nucleus and two loosely bound neutrons.



- ✓ Excited bound states do not exist.
- ✓ Except for ^{6}He, experimental information on resonances of two-neutron halo is very scarce.
- ✓ Existence of a resonance of ^{11}Li is a longstanding open question.

Breakup Reaction

◆ Breakup reactions are useful for investigating resonances.



Observable

➢ Breakup cross section for E_x

✓ *Resonance states*

→ *peak structure*

✓ *Excited modes*

◆ To extract properties of resonances, an accurate method for describing breakup processes is highly desired.

◆ Coulomb breakup with a heavy target (^{208}Pb, ^{209}Bi)

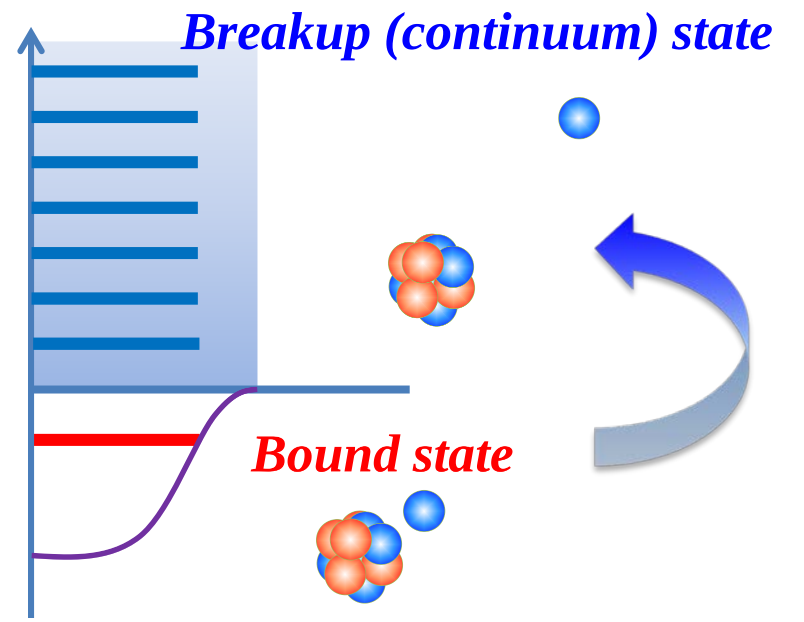
→ Coulomb interaction

◆ Nuclear breakup with a light target (p, ^{12}C)

→ Nuclear interaction

Continuum-Discretized Coupled-Channels

- **Breakup is effects of *coupling to continuum states*.**
- **In CDCC, breakup continuum states are assumed as *a finite number of discretized states*.**



- **Average method**: ➢ G. H. Rawitscher, Phys. Rev. C 9 (1974), 2210

$$\phi_i = N_i \int_{E_i}^{E_{i-1}} \psi(E)\,dE \qquad \psi(E): \text{continuum w.f.}$$

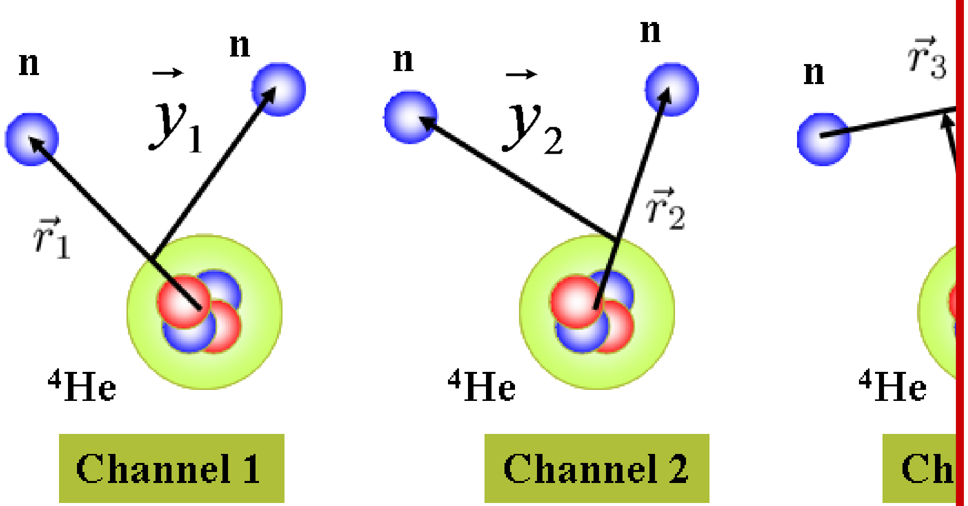
- **Pseudo-states method**: ➢R. C. Johnson and P. C. Tandy, Nucl. Phys. A 235 (1974), 56

$$\phi_i = \sum_{j=1}^{N} C_j^{(i)} \varphi_j \qquad \varphi_j: \text{Basis function}$$

Pseudo-state Discretization

Gaussian Expansion Method

E. Hiyama, Y. Kino, and M. K

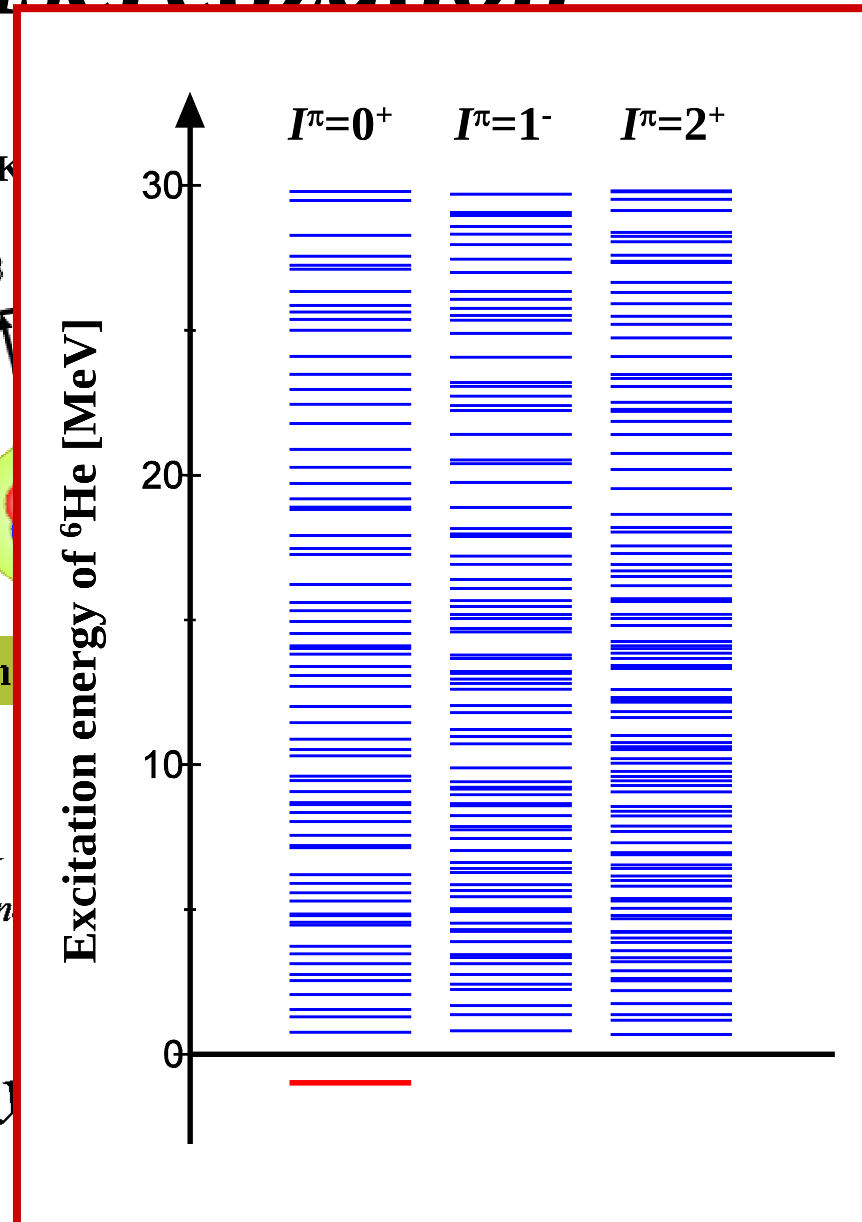


Three-body Hamiltonian

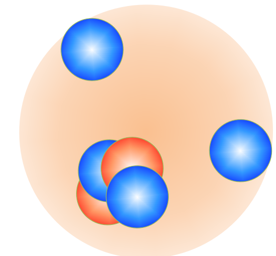
$$H = T_r + T_y + V_{nn} + V_{nc} + V_{n}$$

Gaussian basis functions

$$\phi_{\mathrm{Im}}(r,y) = \sum_{c=1}^{3} \sum_{nj\ell\lambda} A^{(c)}_{nj\ell\lambda} \varphi_{n\ell}(r_c) \varphi_{j\lambda}($$

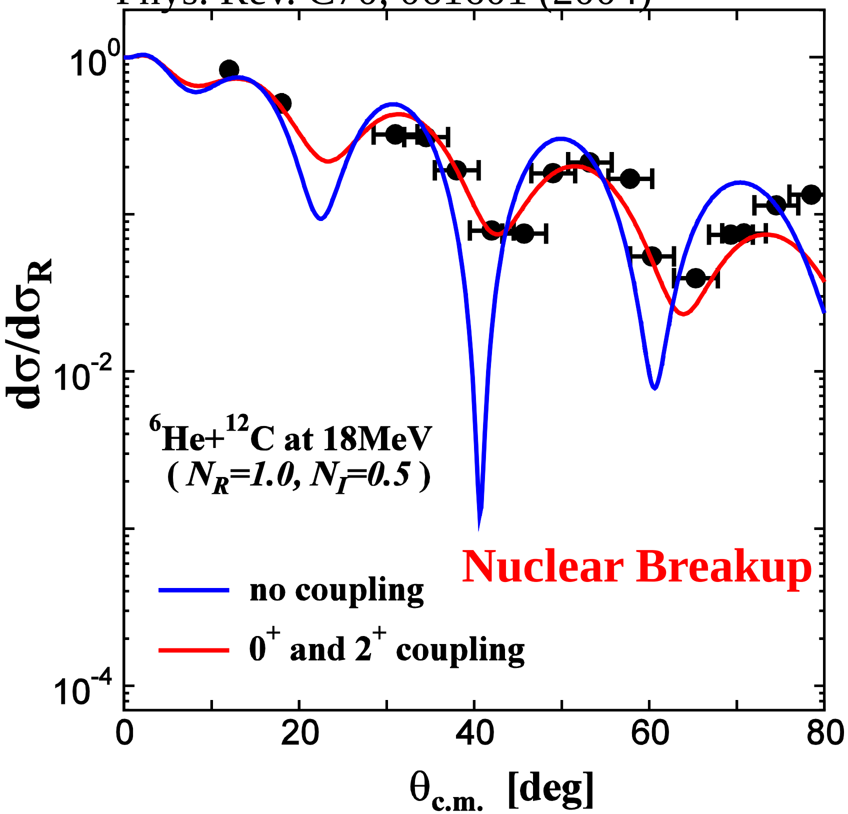


^{6}He Elastic Scattering

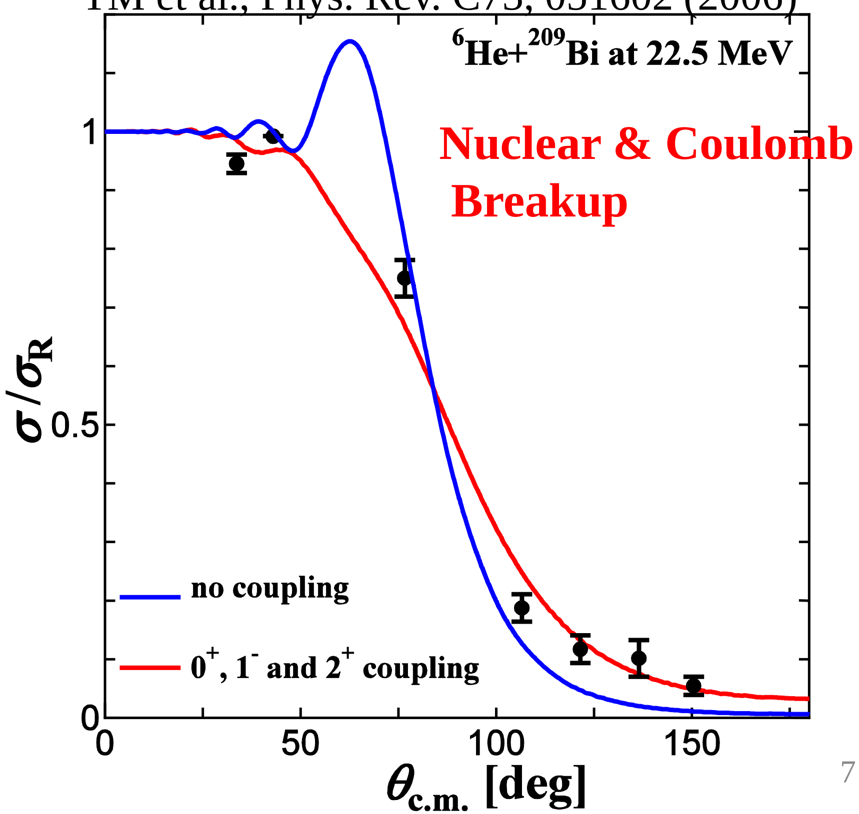


- ^{6}He
  - *A typical example of two-neutron halo*
  - *Described by n + n + ^{4}He three-body model*

TM, Hiyama, et al.
Phys. Rev. C70, 061601 (2004)



TM et al., Phys. Rev. C73, 051602 (2006)

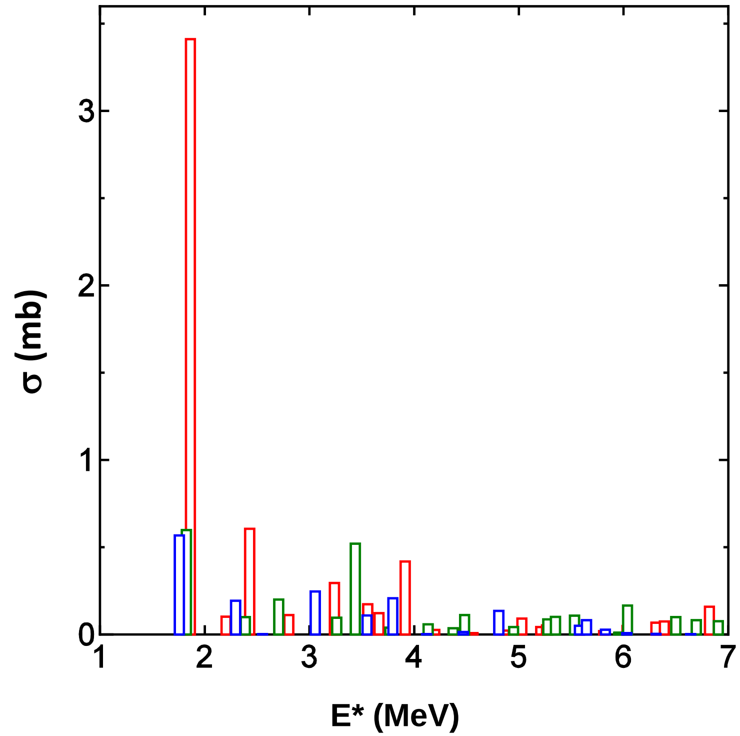


Breakup Cross Section

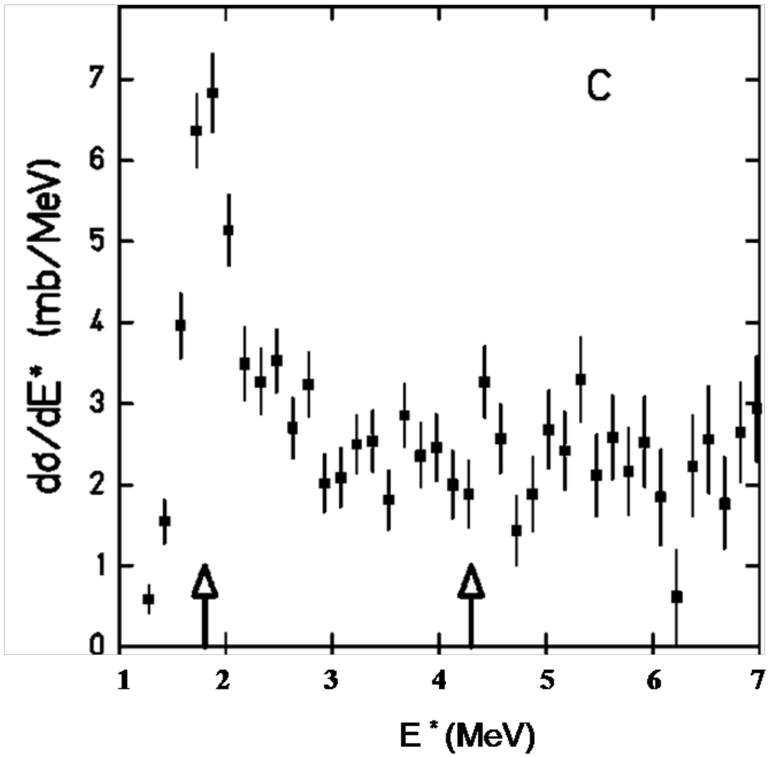
Breakup cross sections calculated by CDCC are discrete in the internal energy of the projectile.

$^{6}He+^{12}C$ scattering at 240 MeV/nucl.

4-body CDCC calc.



PRC59, 1252(1999), T. Aumann *et al*.



How to calculate the continuuous breakup cross section

Complex-Scaled Method

S. Aoyama, T. Myo, K. Kato, and K. Ikeda,
Prog. Theor. Phys. 116, 1 (2006)

Complex-scaling operator: U^{θ}

$$U^{\theta} f(r) = e^{i3/2\theta} f(re^{i\theta})$$

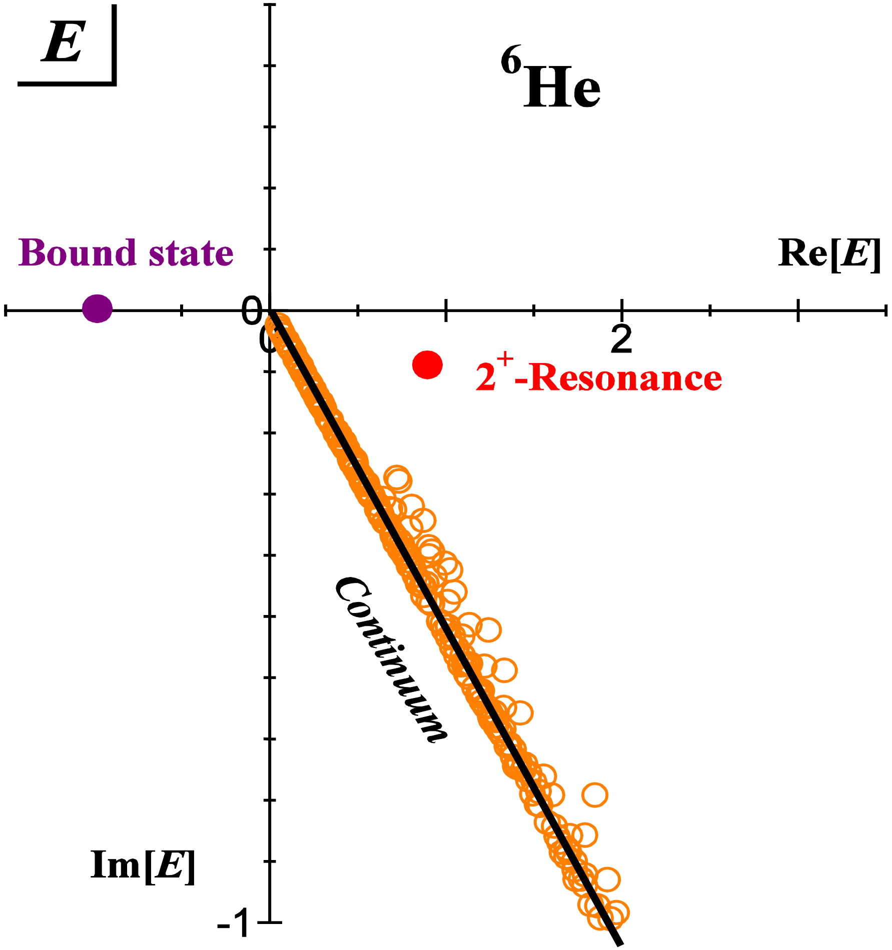
Coordinate: $r \rightarrow re^{i\theta}$

Momentum: $k \rightarrow ke^{-i\theta}$

Asymptotic form

$$e^{ikr} \longrightarrow e^{ikr\cos\theta} e^{-kr\sin\theta}$$

Useful for searching many-body resonances



Green's function with Complex-Scaling Method (CDCS Green's function)

$$\mathcal{G}^{(-)}(E,\xi,\xi') = \frac{1}{E - H - i\epsilon} \approx \sum_{\nu} U^{-\theta} \frac{|\Phi_{\nu}^{\theta}\rangle\langle\tilde{\Phi}_{\nu}^{\theta}|}{E - E_{\nu}^{\theta}} U^{\theta}$$

New Smoothing Procedure with *CSM*

$$\frac{d\sigma}{dE} = \int T^\dagger(E')T(E')\delta(E-E')dE' = \frac{1}{\pi}\mathrm{Im}\mathcal{R}(E)$$

$$T(E) = \langle\psi^{(-)}(E,\xi)\chi_C^{(-)}(\mathbf{R})|V|\Psi^{(+)}(\xi,\mathbf{R})\rangle$$

Response function

Final state of the projectile

$$\mathcal{R}(E) = \int d\xi d\xi' \langle\Psi^{(+)}(\xi,\mathbf{R})|V^*|\chi_C^{(-)}(\mathbf{R})\rangle_{\mathbf{R}}\mathcal{G}^{(-)}(E,\xi,\xi')\langle\chi_C^{(-)}(\mathbf{R})|V|\Psi^{(+)}(\xi,\mathbf{R})\rangle_{\mathbf{R}}$$

Green's function with Complex-Scaling Method (CDCS Green's function)

$$\mathcal{G}^{(-)}(E,\xi,\xi') = U^{-\theta}\frac{1}{E-H^\theta-i\epsilon}U^\theta \approx \sum_\nu U^{-\theta}\frac{|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|}{E-E_\nu^\theta}U^\theta$$

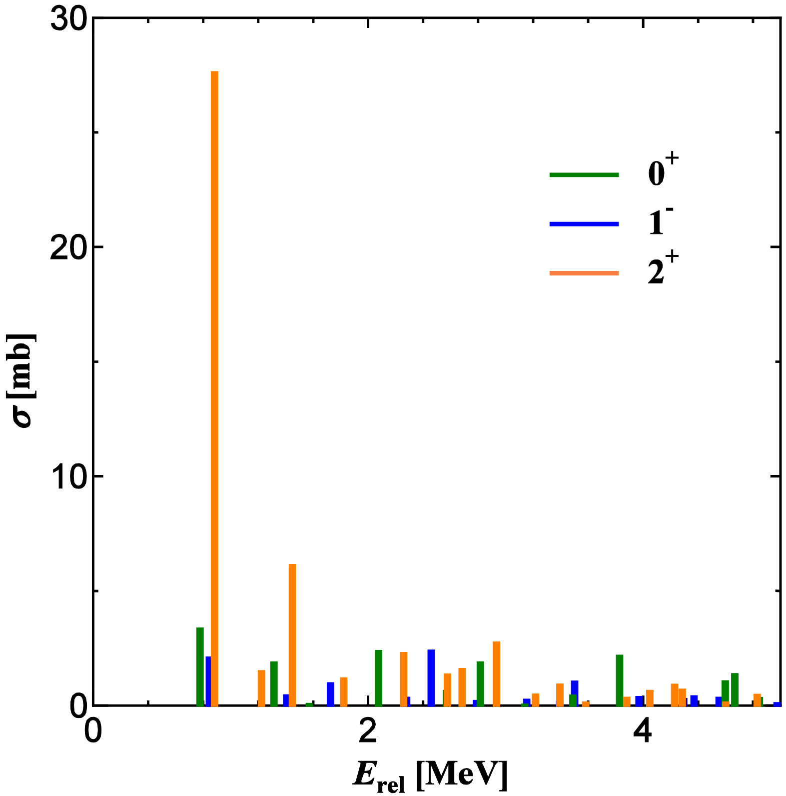
$$\mathcal{G}^{(-)}(E,\xi,\xi') \approx \sum_\nu\sum_{i,j}|\Phi_i\rangle\frac{\langle\Phi_i|U^{-\theta}|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|U^\theta|\Phi_j\rangle}{E-E_\nu^\theta}\langle\Phi_j|$$

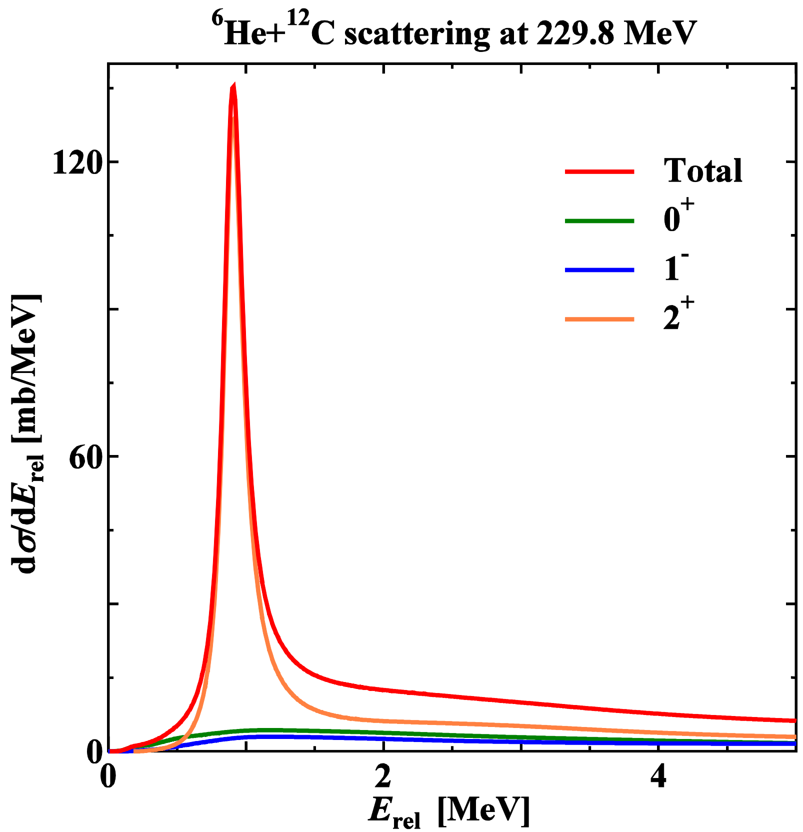
$$\mathcal{R}(E) = \sum_\nu\sum_{i,j}\langle\Psi^{(+)}|V^*|\chi_C^{(-)}\Phi_i\rangle\frac{\langle\Phi_i|U^{-\theta}|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|U^\theta|\Phi_j\rangle}{E-E_\nu^\theta}\langle\Phi_j\chi_C^{(-)}|V|\Psi^{(+)}\rangle$$

T-matrix calculated by CDCC

Differential Breakup Cross Section

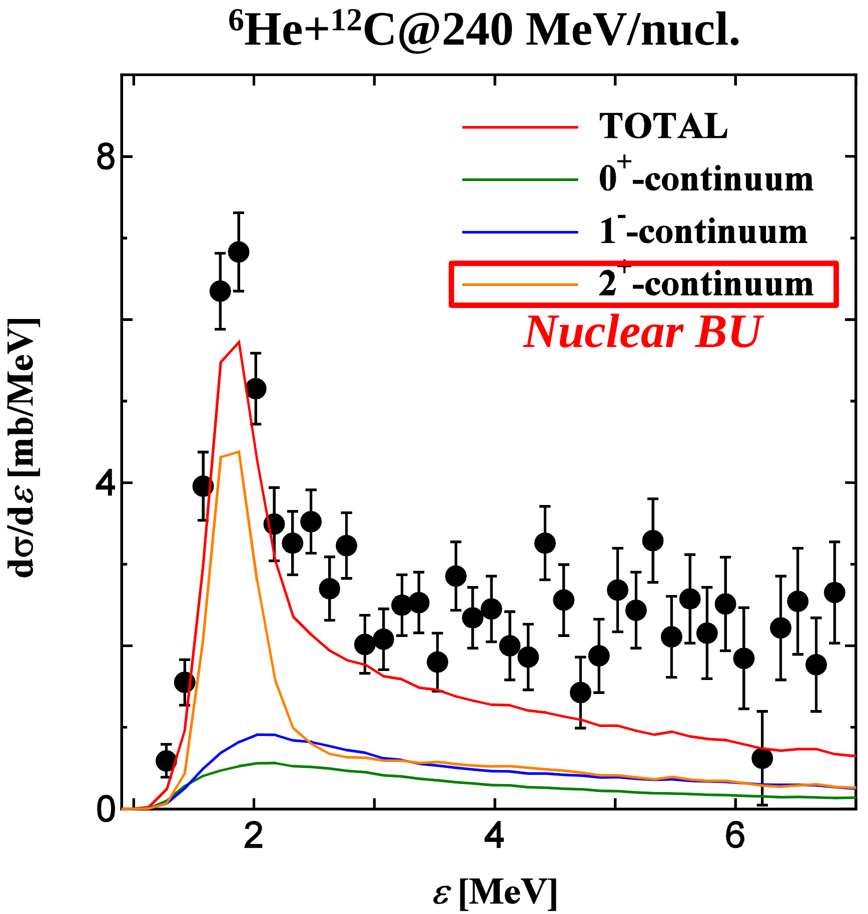
$$\frac{d\sigma}{dE} = \frac{1}{\pi}\mathrm{Im}\sum_{\nu}\sum_{i,j} T_i^{\mathrm{CDCC}\dagger}\frac{\langle\Phi_i|U^{-\theta}|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|U^\theta|\Phi_j\rangle}{E-E_\nu^\theta}T_j^{\mathrm{CDCC}}$$

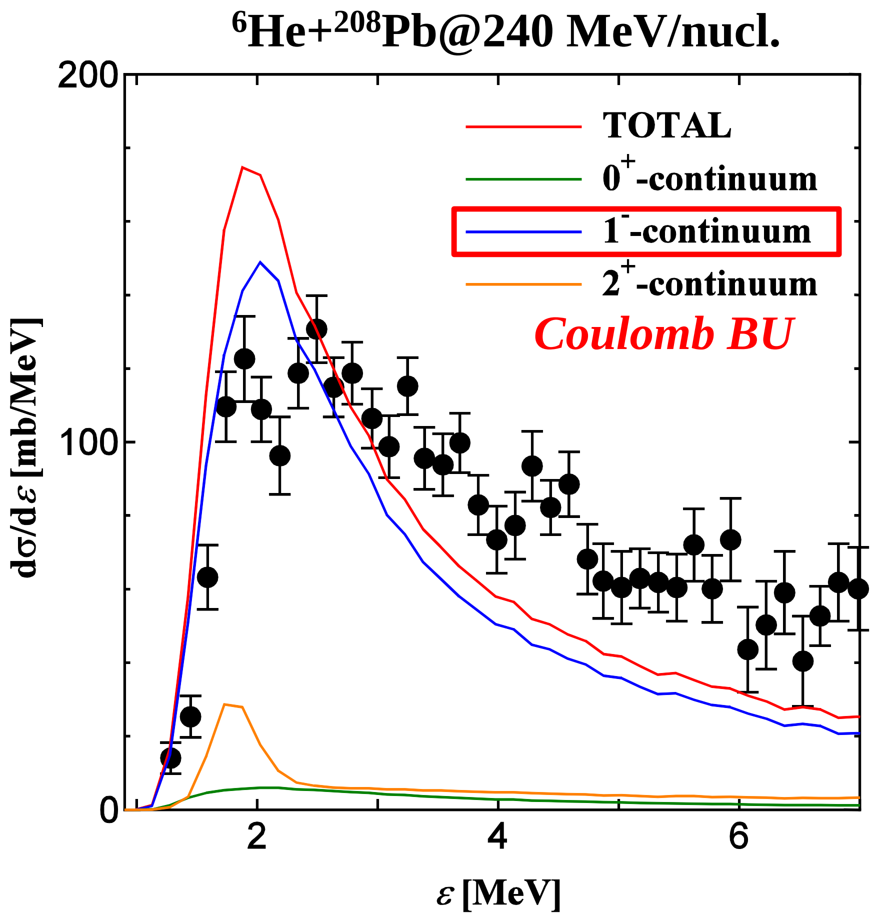




^{6}He *Breakup Reaction*

TM, Yahiro, and Kato, PRC82, 051602 (2010)



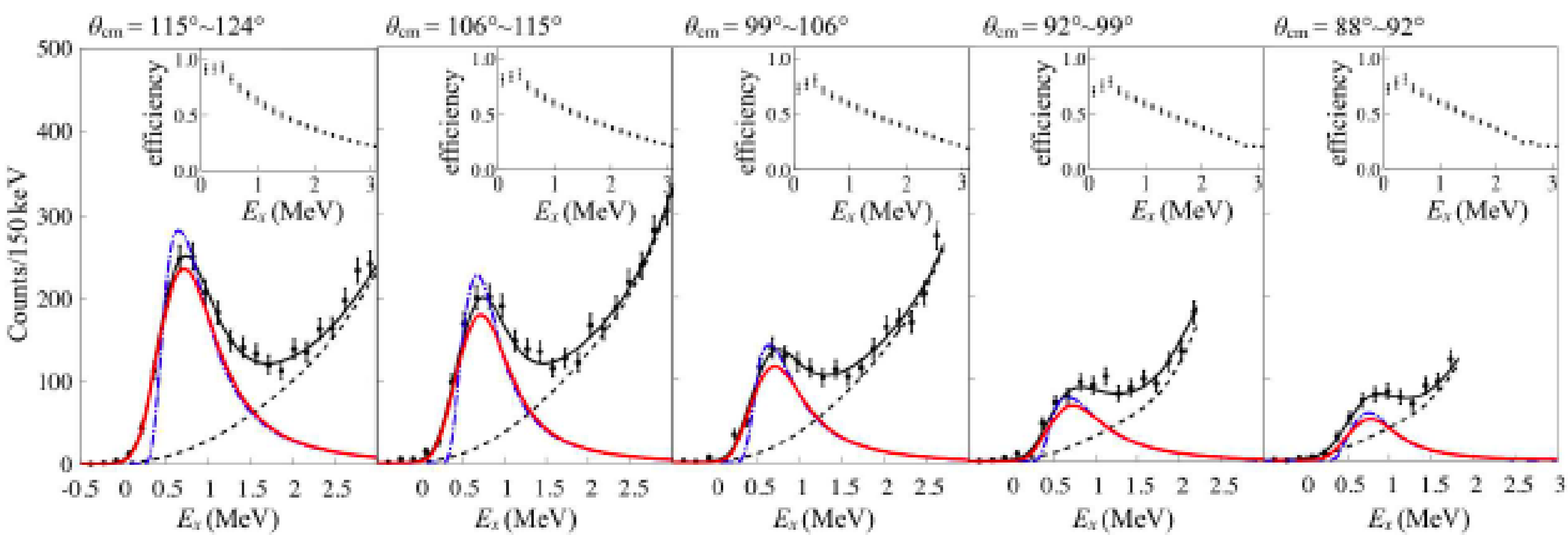


Exp. data from PRC59, 1252 (1999), T. Aumann *et al.*

Recent experiment of ^{11}Li

- Measurement of the ^{11}Li(p, p') reaction at 6 MeV/nucleon with high static and high resolution has been performed, and a low-lying excited state of ^{11}Li has clearly been identified.

J. Tanaka et al., Phys. Lett. B774, 268 (2017).



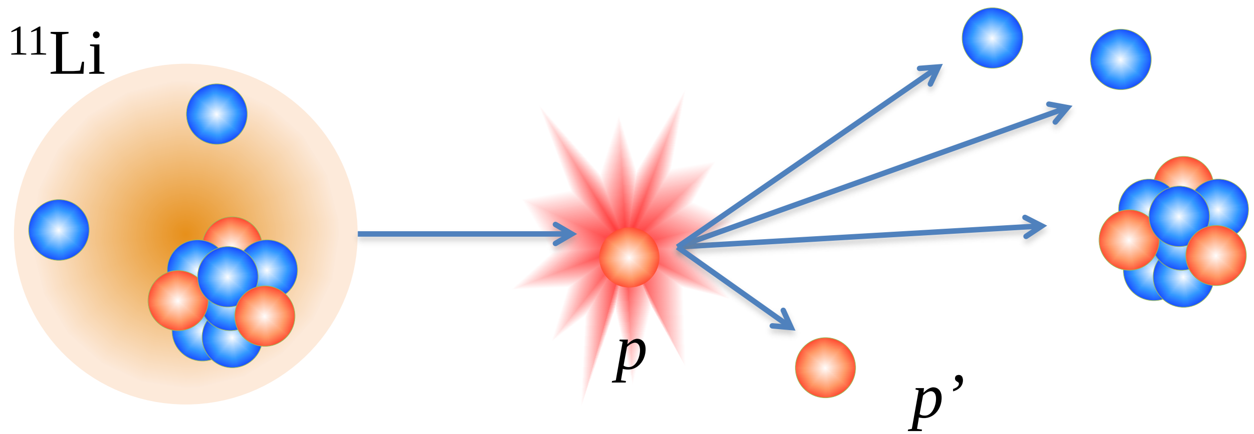
- The purpose of this work is to analyse the reaction with a microscopic reaction model.

^{11}Li(*p*, *p'*) @ 6MeV/*nucl*

^{11}Li

✓ Borromean

✓ $S_{2n} \sim 0.37$ MeV



^{11}Li Breakup

→ ^{11}Li + *p* = *n* + *n* + ^{9}Li + *p*

→ Continuum-Discretized Coupled-Channels (CDCC)

Yahiro, Ogata, TM, Minomo,
Prog. Theor. Exp. Phys. 2012, 01A206 (2012).

Coupling Potential of ^{11}Li-*p*

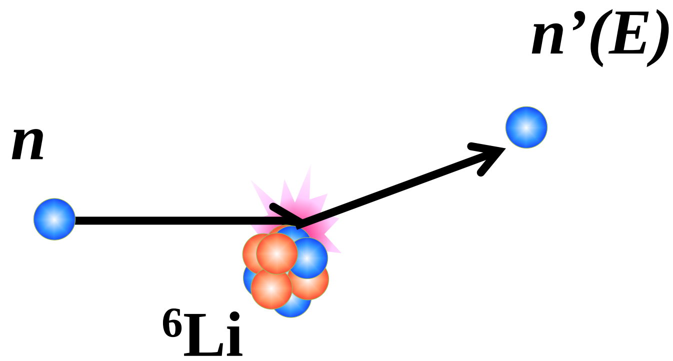
→ Folding with JLM interaction

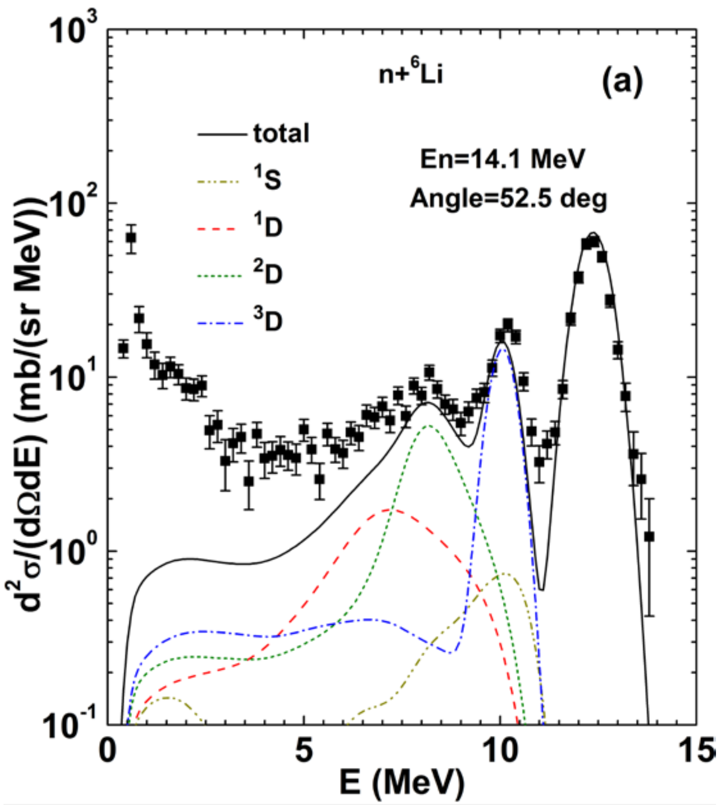
Jeukenne, Lejeune, Mahaux,
Phys. Rev. C16, 80 (1977).

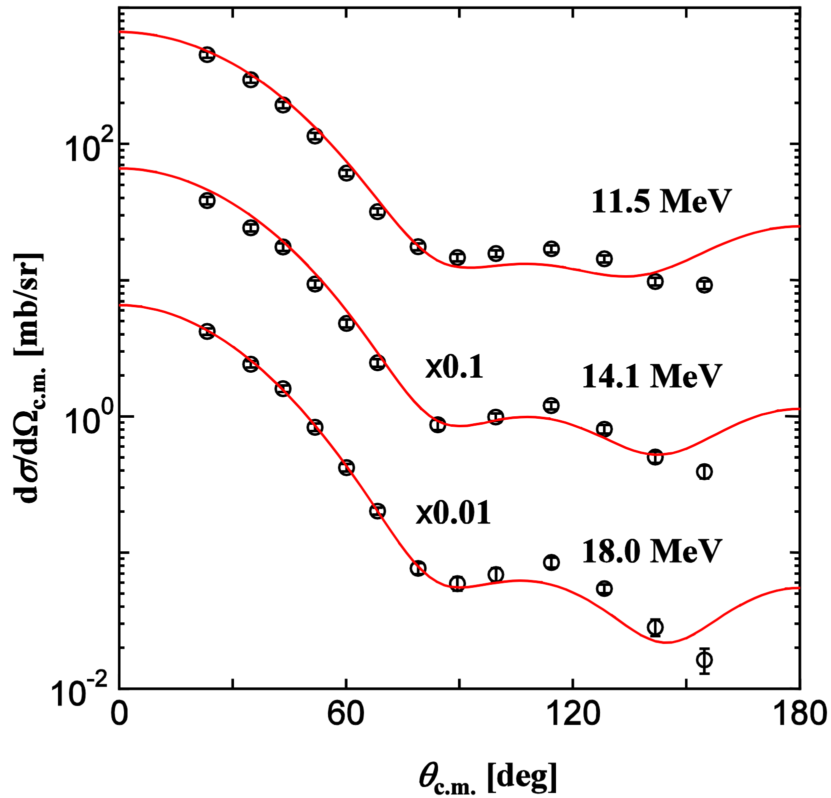
CDCC with JLM

T.M., Ichinkhorloo, Hirabayashi, Kato, Chiba, Phys. Rev. C 83, 064611 (2011).

Analysis of ^{6}Li(n,n')



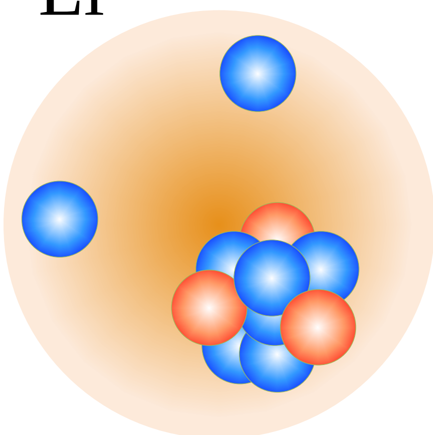




- ◆ ^{6}Li = $d + \alpha$
- ◆ CDCC with JLM
  - ✓ Elastic cross section
  - ✓ DDX

^{11}Li Three-body model

^{11}Li

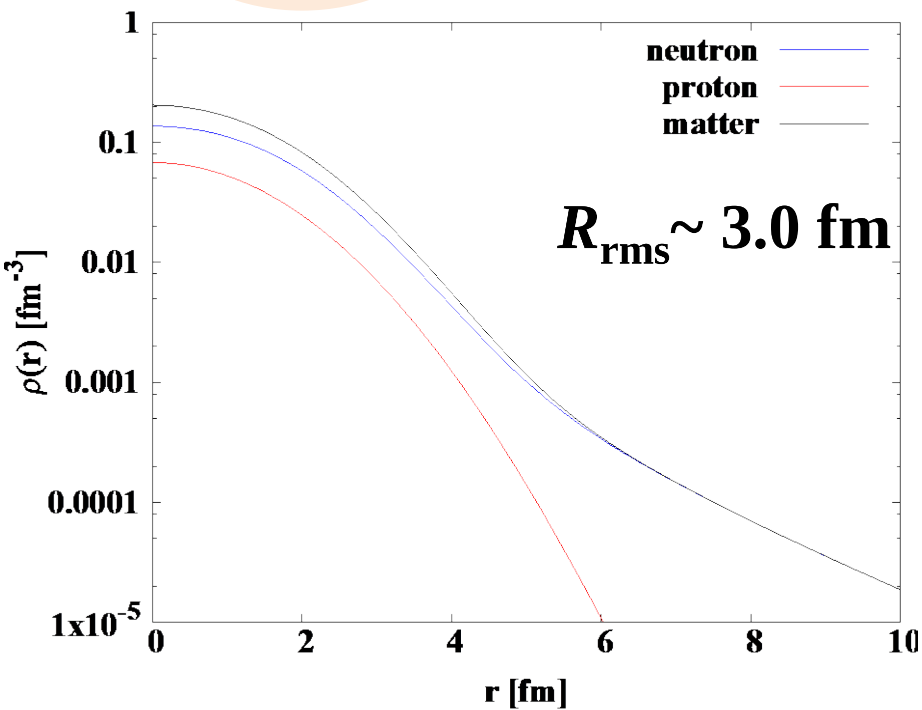


^{11}Li : $n + n + {}^{9}$Li (spinless)

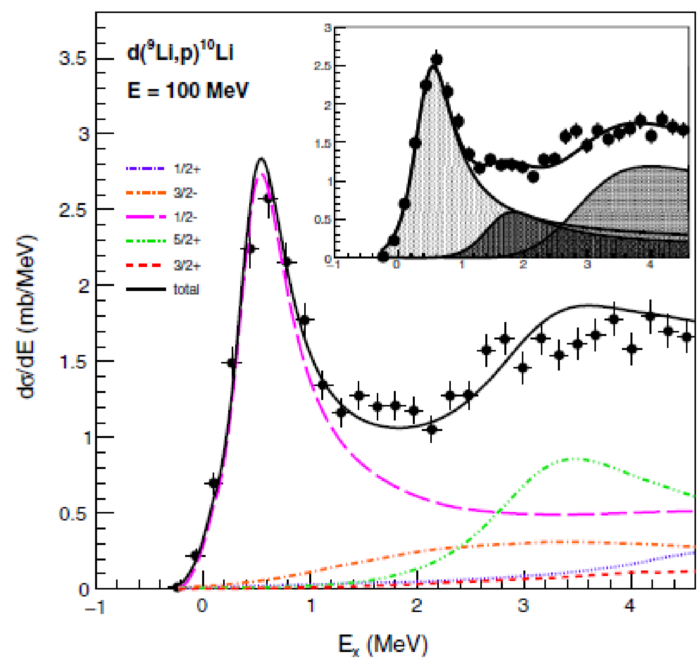
V_{NN} : Minnesota interaction

V_{NC} : Esbensen and Bertsch, NPA 542, 310

V_{NNC}: to optimize S_{2n}~ 0.37 MeV



^{10}Li resonance ~ 0.5 MeV



M.Cavallaro et al., PRL 118,012701 (2017)

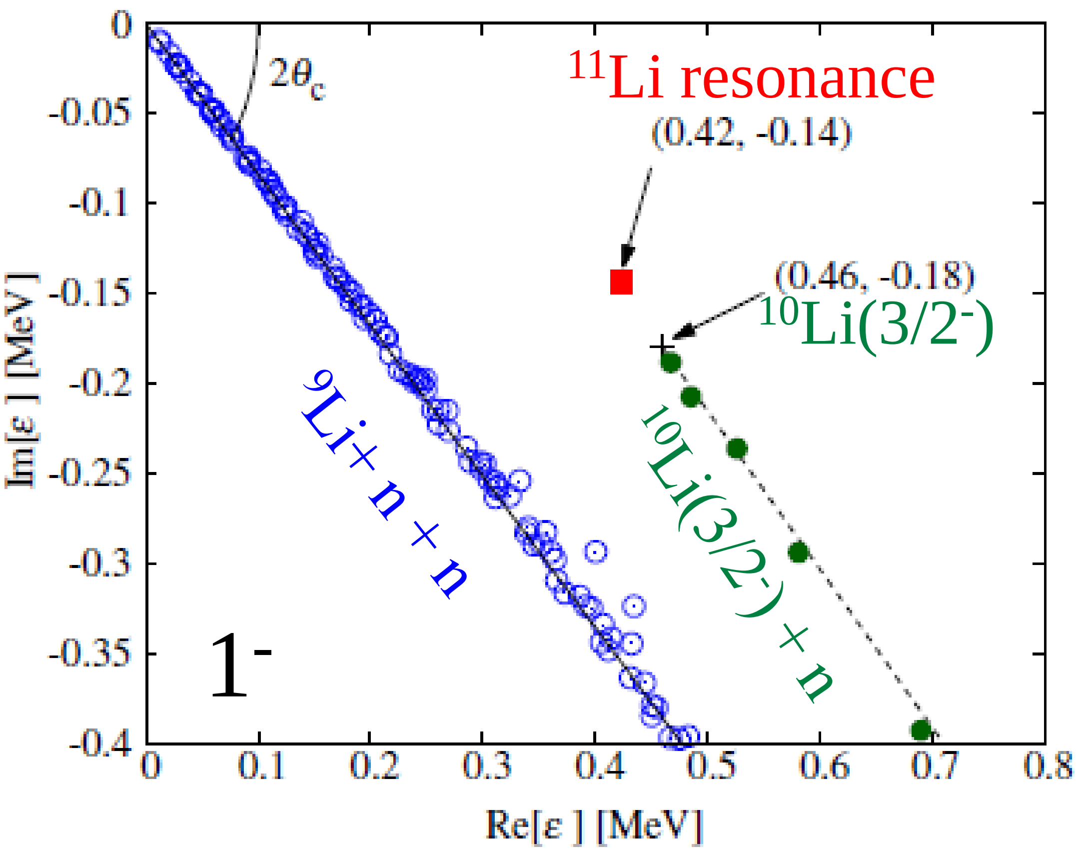
^{11}Li *Resonance*

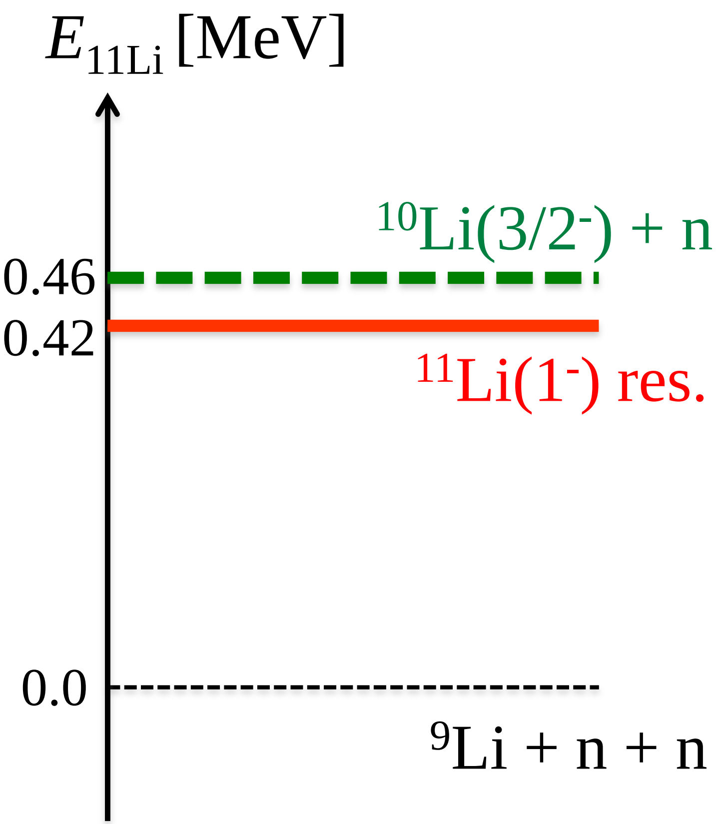
- Complex-scaling method:

  Aoyama, Myo, Kato, and Ikeda, Prog. Theor. Phys. 116, 1 (2006)

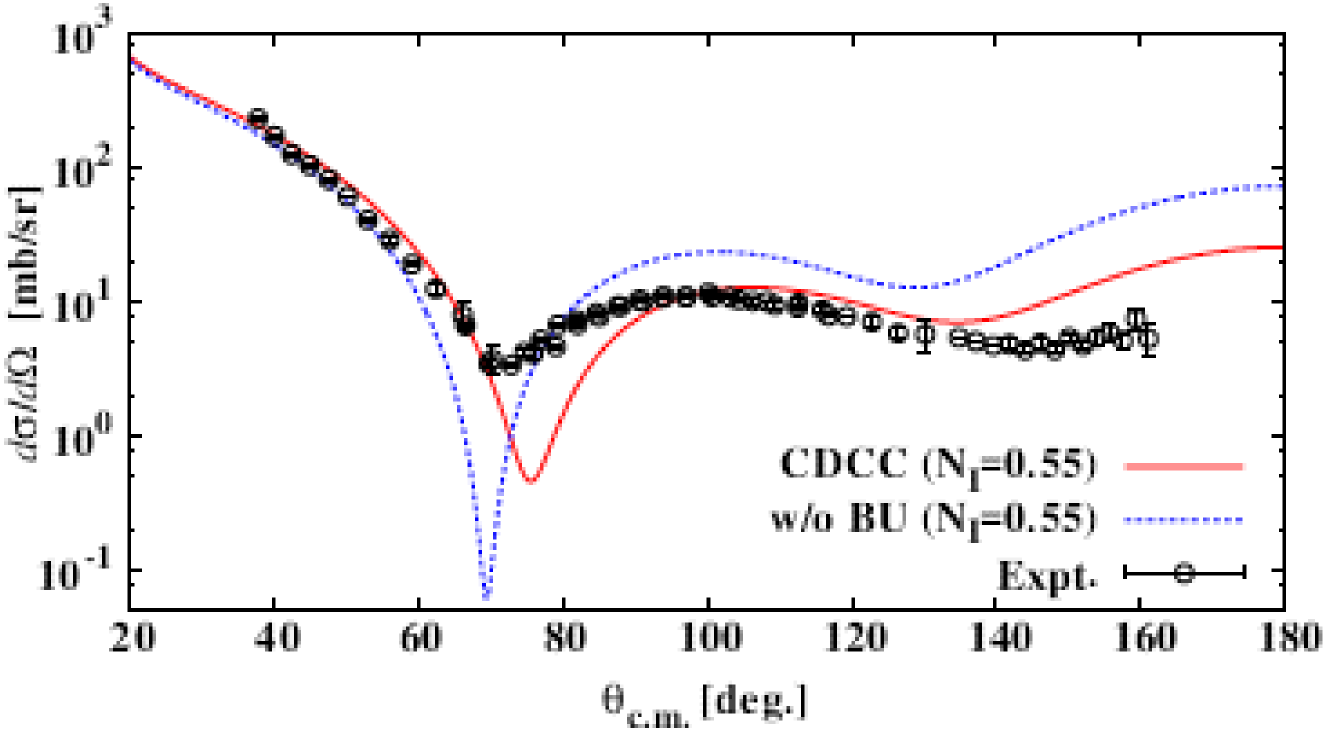
- ^{11}Li resonance: S. N. Ershov et al., Phys. Rev. C 70, 054608 (2004).

  E. C. Pinilla et al., Phys. Rev. C 85, 054610 (2012).



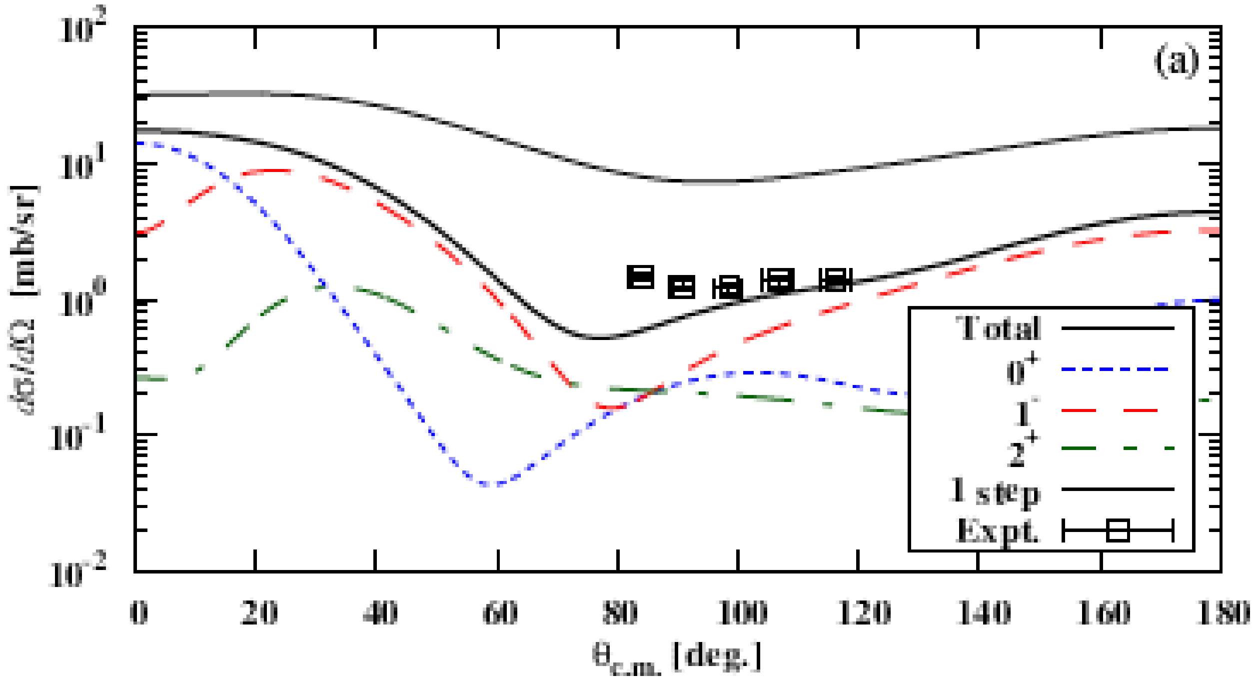


Elastic Cross Section



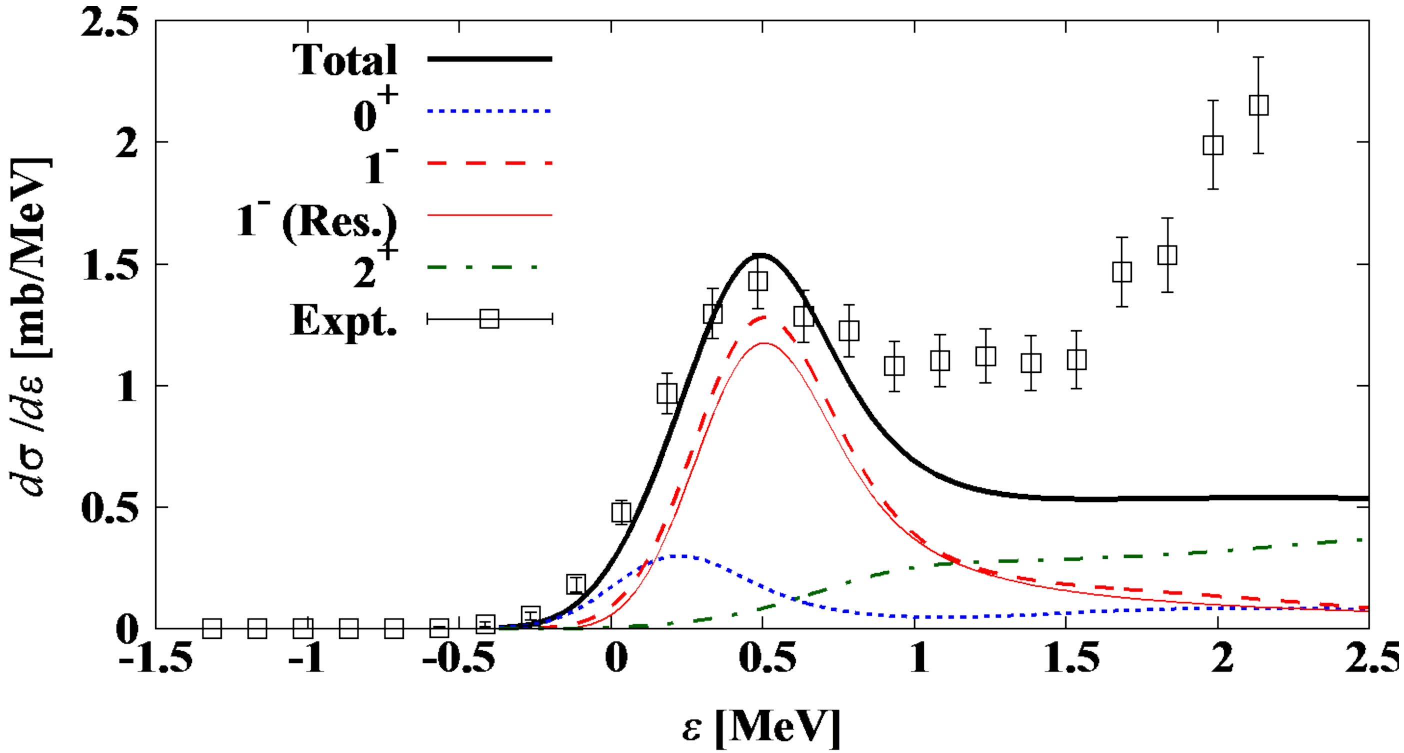
- **The four-body CDCC calculation reproduces the experimental data reasonably well.**
- **Breakup effects are significant.**

Breakup Cross Section



- **The breakup cross section is integrated up to 1.5 MeV for excited energy of ^{11}Li so as to cover well the low-lying peak structure.**
- **The 1-step calculation w/o coupling effects is over estimated the experimental data.**

Energy Spectrum



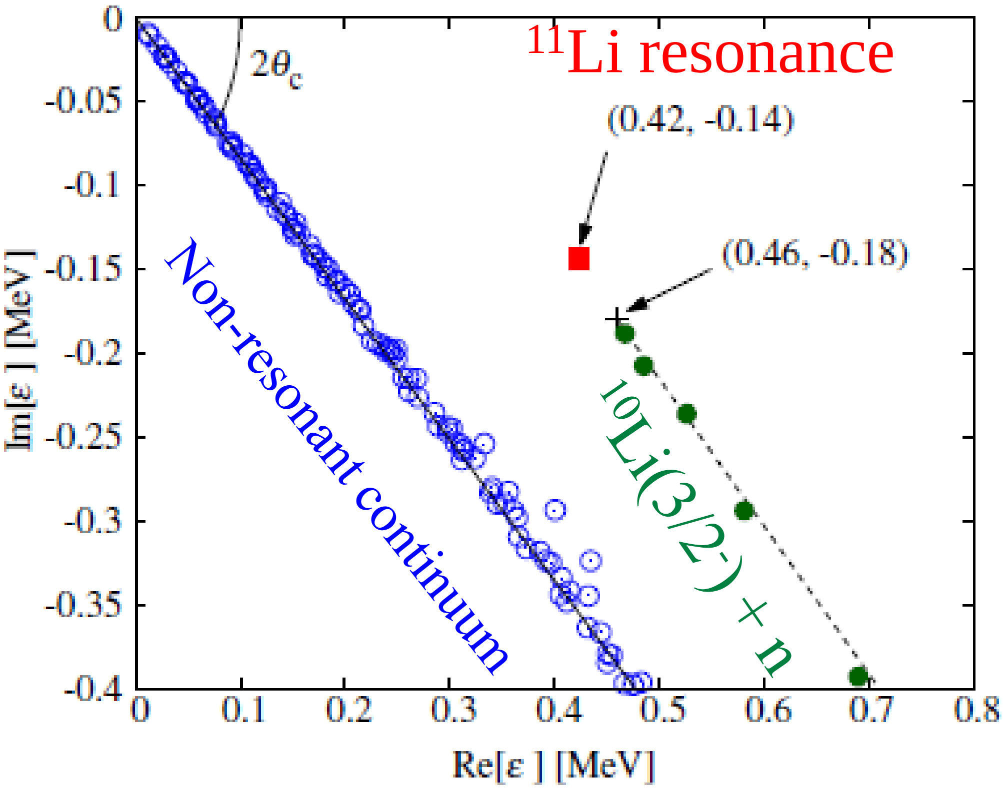
- **The contribution of the dipole resonance dominates the low-lying peak.**
- **The width of the low-lying peak is reproduced by taking into account non-resonant components.**

Wave Function of ^{11}Li Resonance

- Probability of ^{10}Li resonance in ^{11}Li

$$\alpha_n^\theta = 2\left\langle \Phi_n^\theta \middle| \underline{\phi_{res}^\theta \right\rangle \left\langle \phi_{res}^\theta} \middle| \Phi_n^\theta \right\rangle$$

^{10}Li res. w.f.



- Non-resonant continuum

  Re[α_n] ~ 0.0

- ^{10}Li(3/2$^-$) + n continuum

  Re[α_n] ~ 0.9

- ^{11}Li resonance

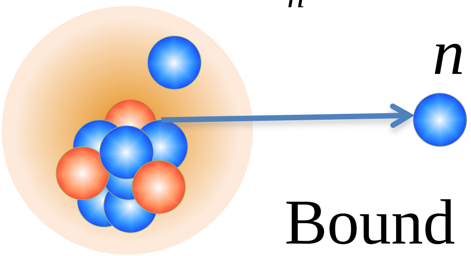
  Re[α_n] ~ 0.9

Borromean Feshbach Resonance

$$\psi_{res}({}^{11}Li) = \left[\phi_{res}({}^{10}Li) \otimes \chi_n(\ell=0)\right]$$

0.42 MeV 0.46 MeV -0.04 MeV

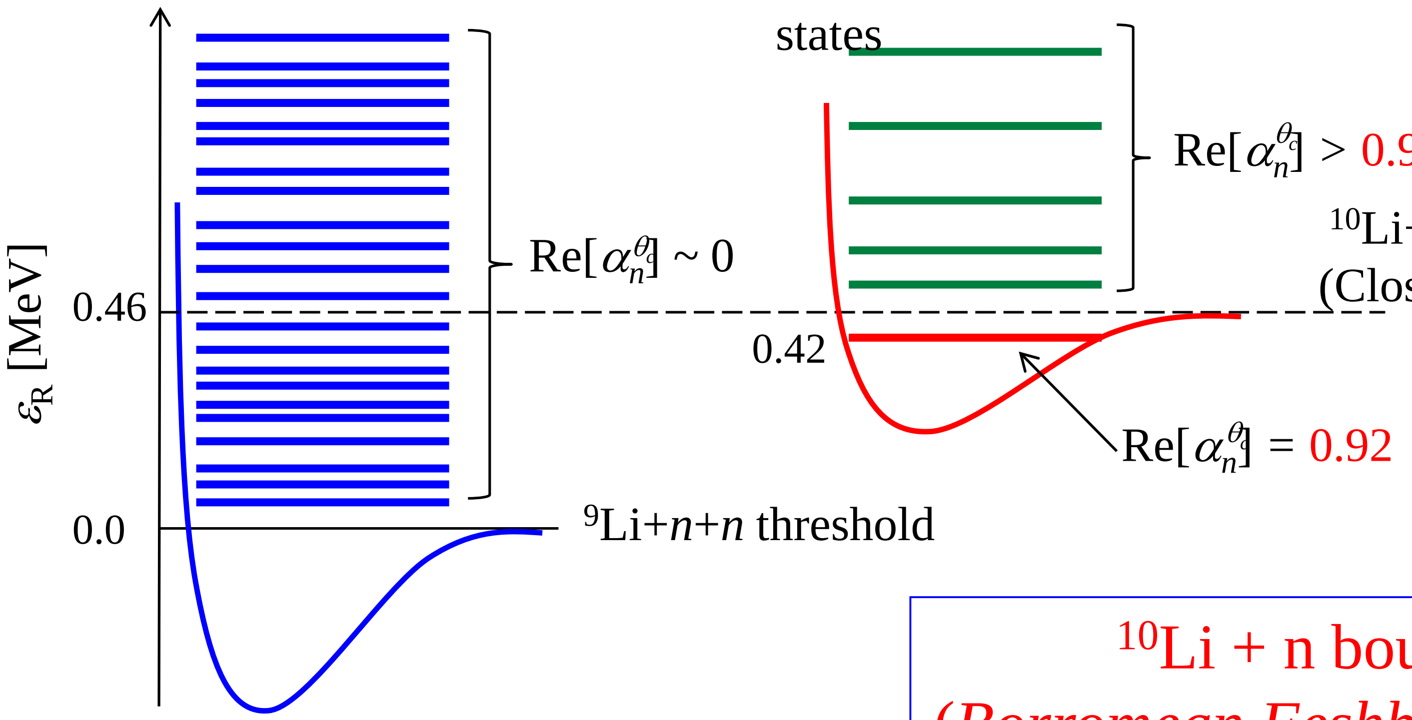
^{10}Li S_n~0.04 MeV



Bound state
(*s*-wave)

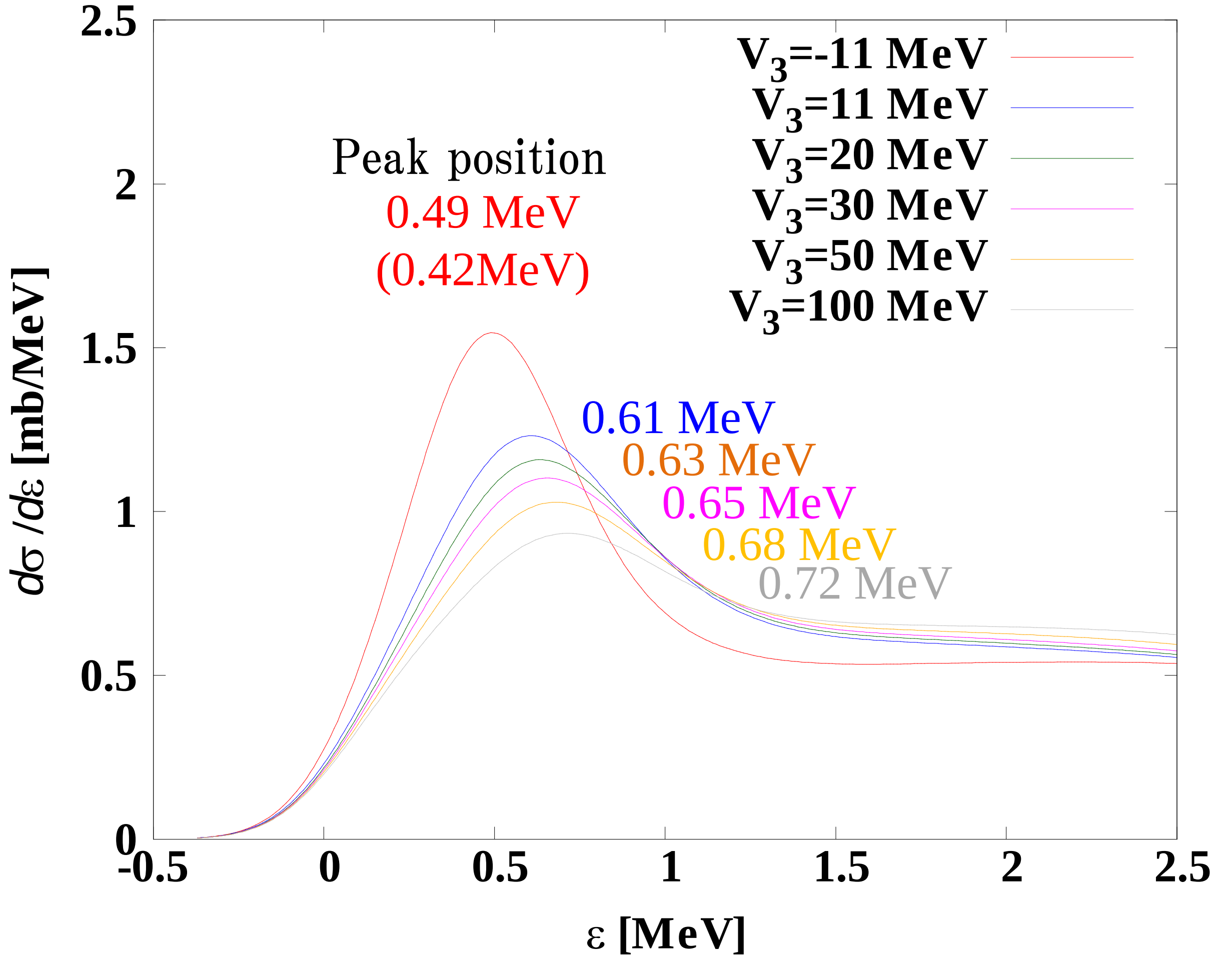
^{9}Li+n+n nonresonant continuum

^{10}Li+n bound and continuum states



^{10}Li + n bound state
(*Borromean Feshbach resonance*)

Resonance effect on $d\sigma/d\varepsilon$



Summary of ^{11}Li

- **We found a dipole resonance in ^{11}Li at 0.42 MeV with the width of 0.28 MeV.**

- **The three-body model of ^{11}Li with the resonance has been validated by the good agreement between the results of four-body CDCC and the recent measurement of ^{11}Li(*p*,*p'*).**

- **The resonance of ^{11}Li is interpreted as a bound state of ^{10}Li + n system, that is, a *Borromean Feshbach resonance*.**

http://arxiv.org/abs/1711.07209

Perspective

✓ **Three-body calculation of ^{11}Li with ^{9}Li spin**