

# Exotic molecular states in the $\alpha+{}^{6,8}\text{He}$ resonant scattering

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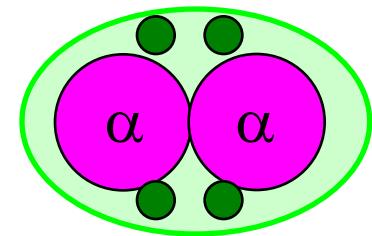
# Nuclear clustering in N-rich nuclei

## 1. $\alpha$ -clustering in stable nuclear systems

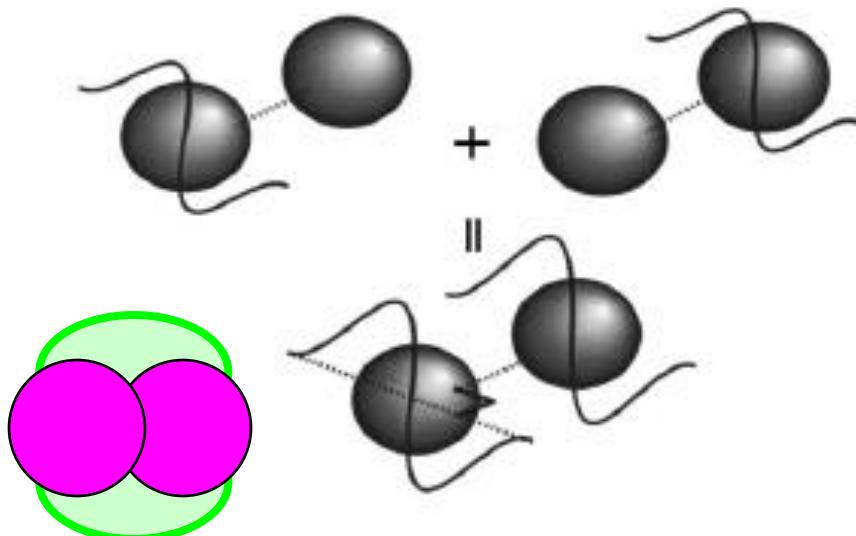
$$^8\text{Be} = 2\alpha, ^{12}\text{C} = 3\alpha, ^{16}\text{O} = \alpha + ^{12}\text{C}, ^{20}\text{Ne} = \alpha + ^{16}\text{O}$$

## 2. Clustering in N-rich systems : Clusters + XN

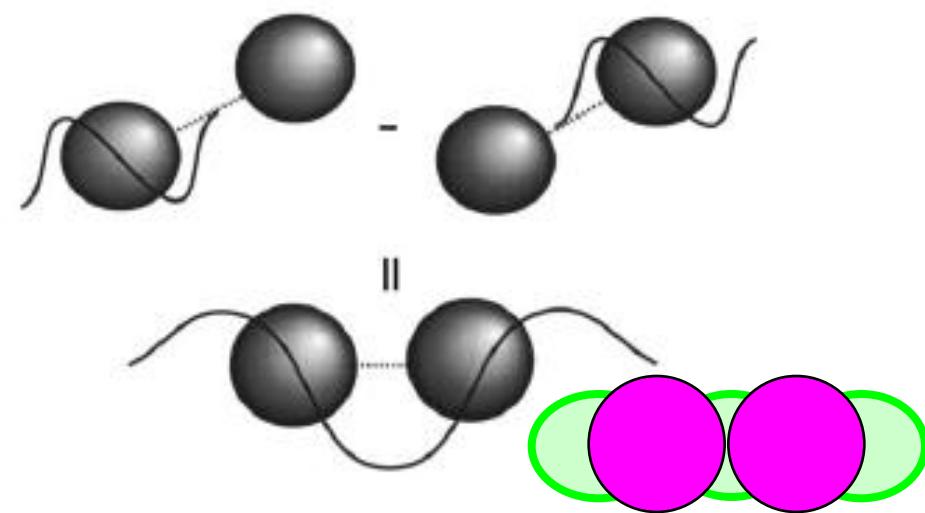
Example : Be isotopes =  $2\alpha + \text{XN}$



(a)  $\pi$ -orbit



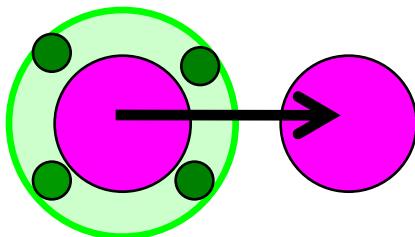
(b)  $\sigma$ -orbit



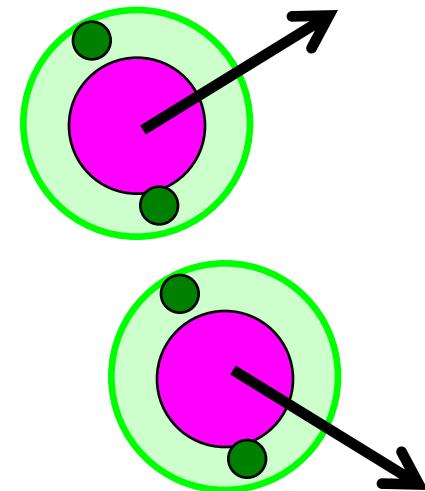
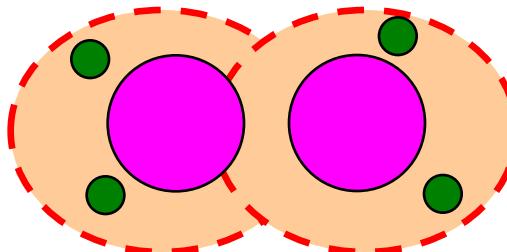
Molecular Orbital model : N. Itagaki et al., PRC61,62 (2000)

# Studies on neutron-rich systems in 3-dimensional space

Slow RI beam



Resonance Reactions



Today's report

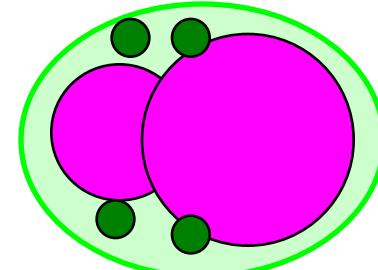
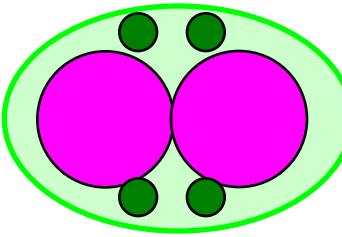
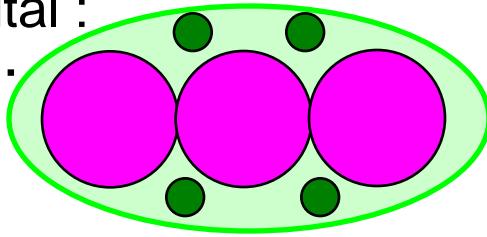
Structure :  $^{10}\text{Be}$   
scattering :  $\alpha + ^6\text{He}$

Ex. energy

Structural  
Change

Transfer,  
Inelastic

Low-lying  
Mol. Orbital :  
 $\pi^-$ ,  $\sigma^+$  ...

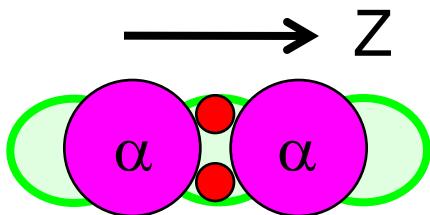


↔

( N, Z ) : Two Dimension

## Formulation

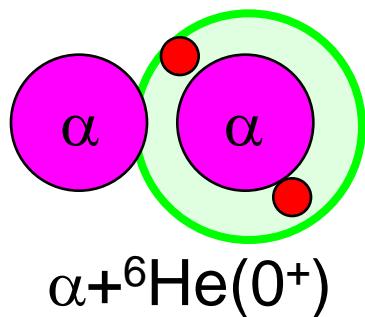
Linear Combination of  
Atomic Orbital (LCAO)



$$(\sigma^+)^2 = (P_z(L) - P_z(R))^2$$

$$= P_z(L) \cdot P_z(L) + P_z(R) \cdot P_z(R) - 2P_z(L) \cdot P_z(R)$$

${}^6\text{He} + \alpha$                      $\alpha + {}^6\text{He}$                      ${}^5\text{He} + {}^5\text{He}$



$$= P_x(R) \cdot P_x(R) + P_y(R) \cdot P_y(R) + P_z(R) \cdot P_z(R)$$

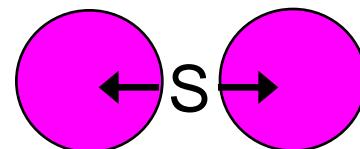
$\alpha + {}^6\text{He}(0^+)$

Total wave function

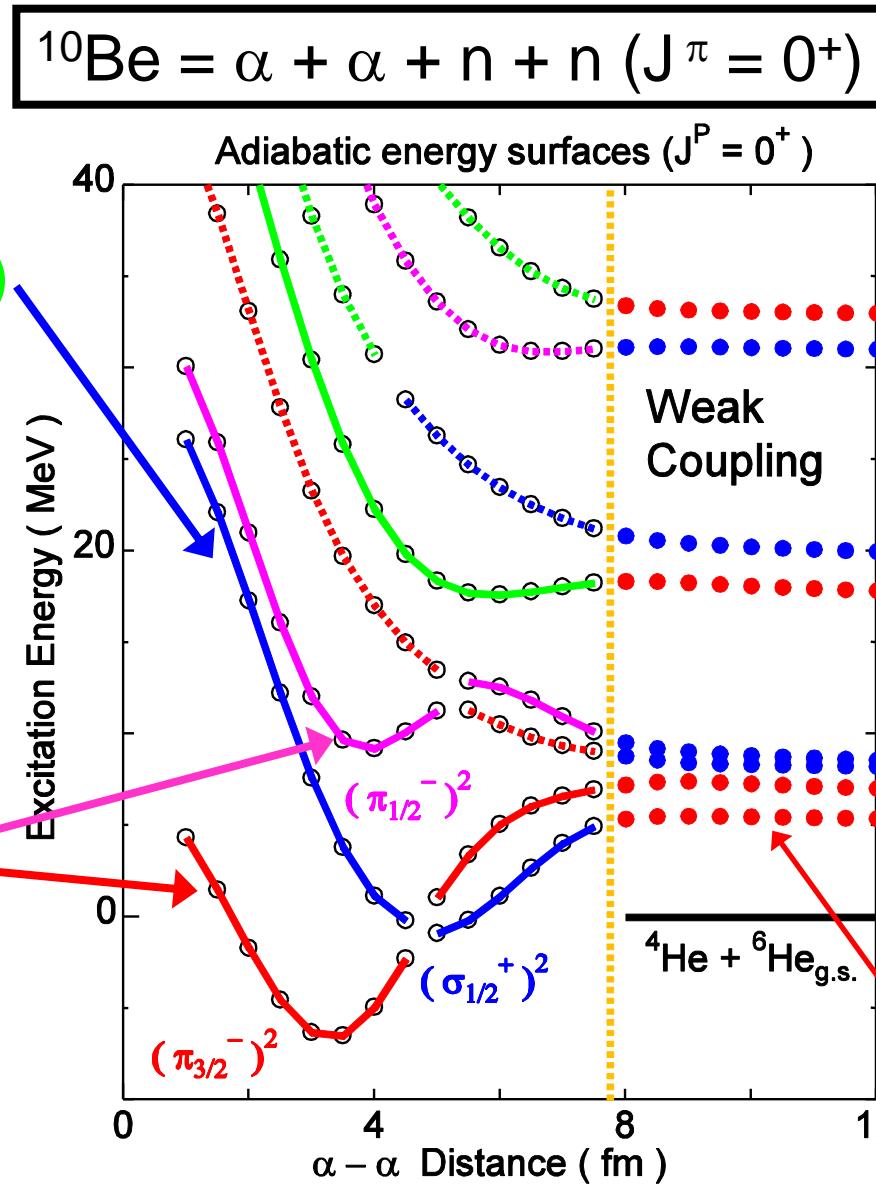
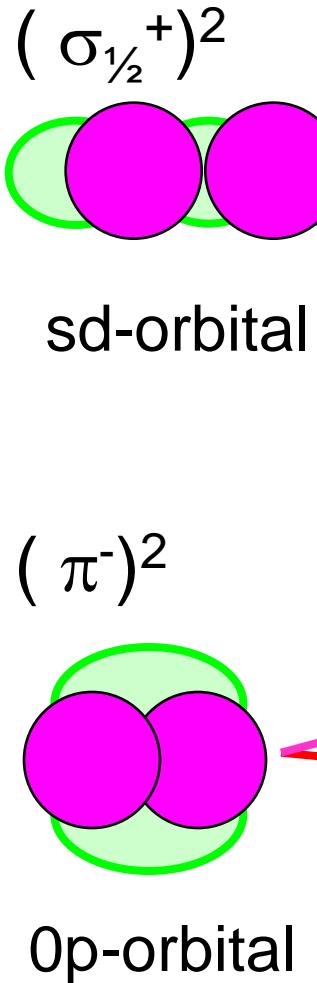
$$\Psi = \sum_{\beta, S} \underline{C(\beta, S)} P_m(a) \cdot P_n(b)$$

Variational PRM

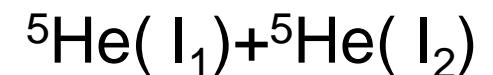
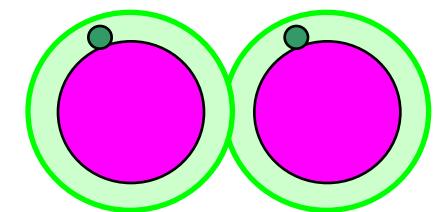
$(m, n) = x, y, z$      $(a, b) = L, R$



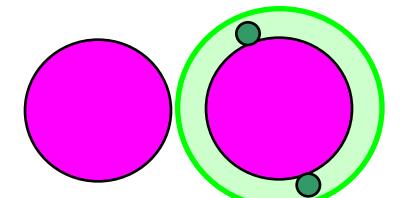
# Adiabatic Energy surfaces : NN int. $\Rightarrow$ Volkov No.2 + G3RS



Blue Dots

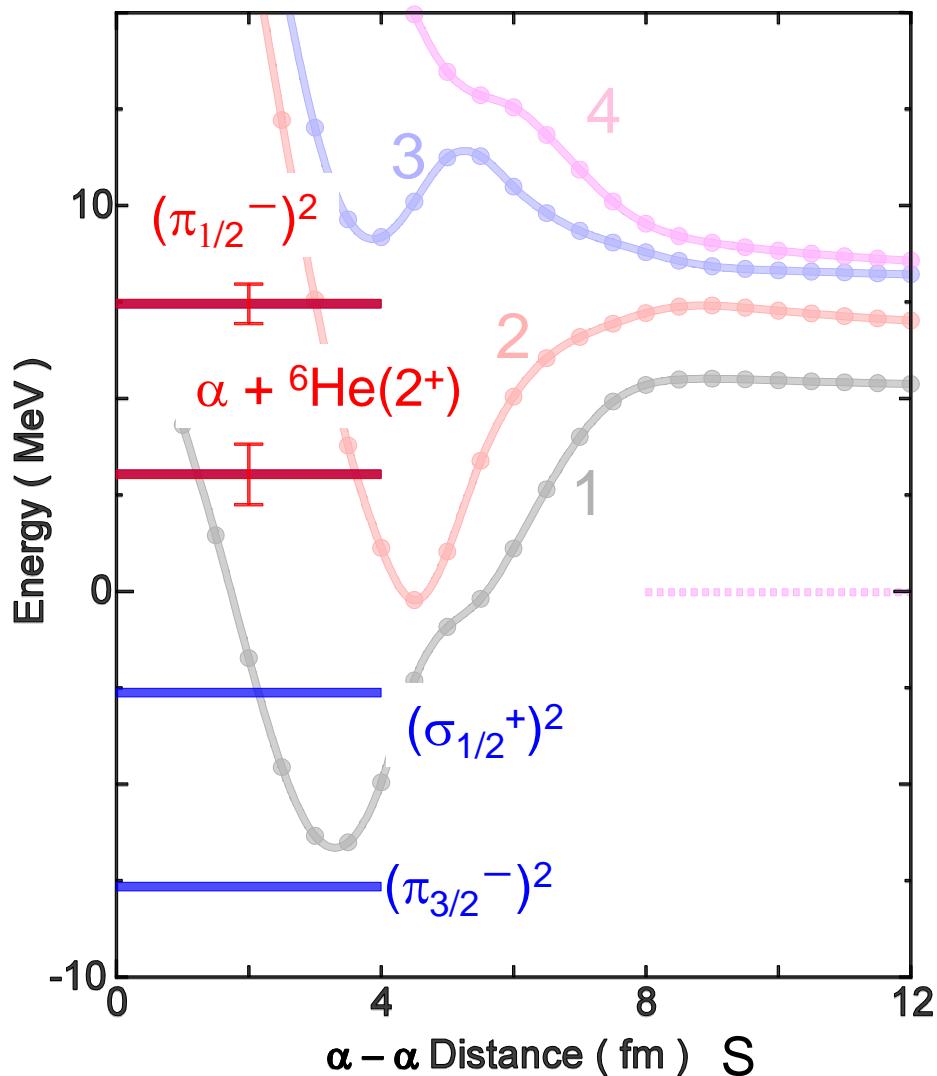


Red Dots



## Coupled channels with the adiabatic states

Energy spectra of  $^{10}\text{Be}$



Adiabatic basis

$$\Psi = \sum_{k,S} f(k,S) \Phi^{AD}(k,S)$$

$$k = 1, 2, 3, 4, \dots$$

$$H = \sum_i t_i + \sum_{i>j} v_{i,j}$$

$$(H - E)\Psi = 0$$

Bound,  
Resonant  
B.C.

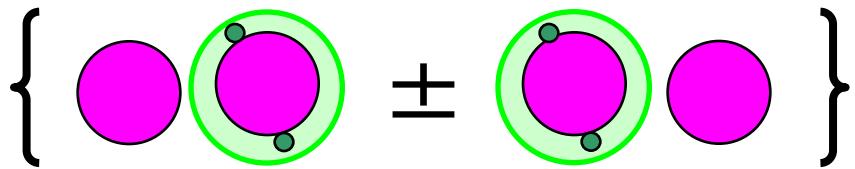
Scattering  
B.C.

Energy spectra

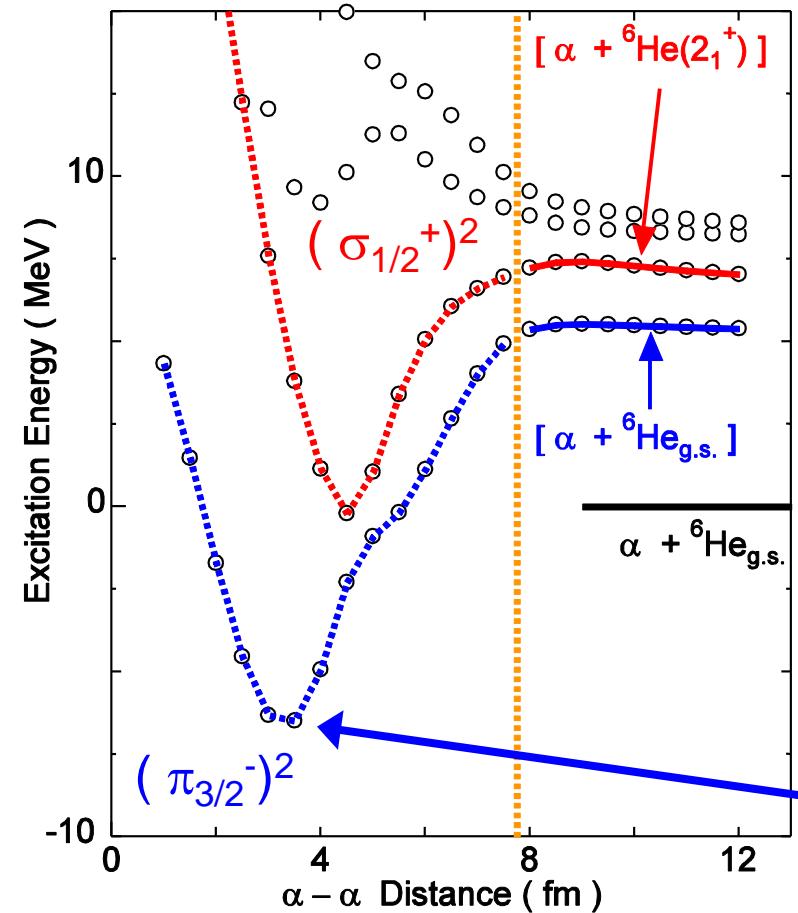
$\alpha + {}^6\text{He}$  scattering

# Parity doublet formation in adiabatic energy surfaces

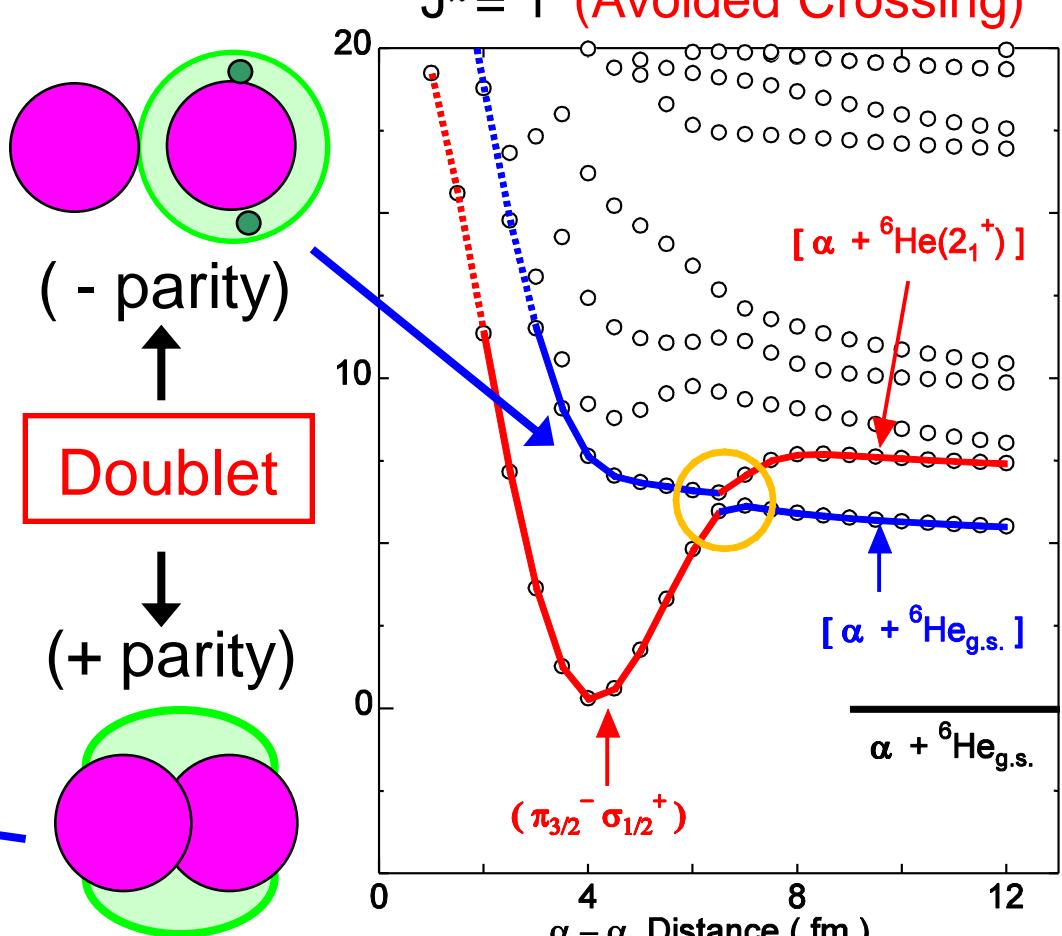
P-Doublet :  $\Psi^{(\pm)} =$



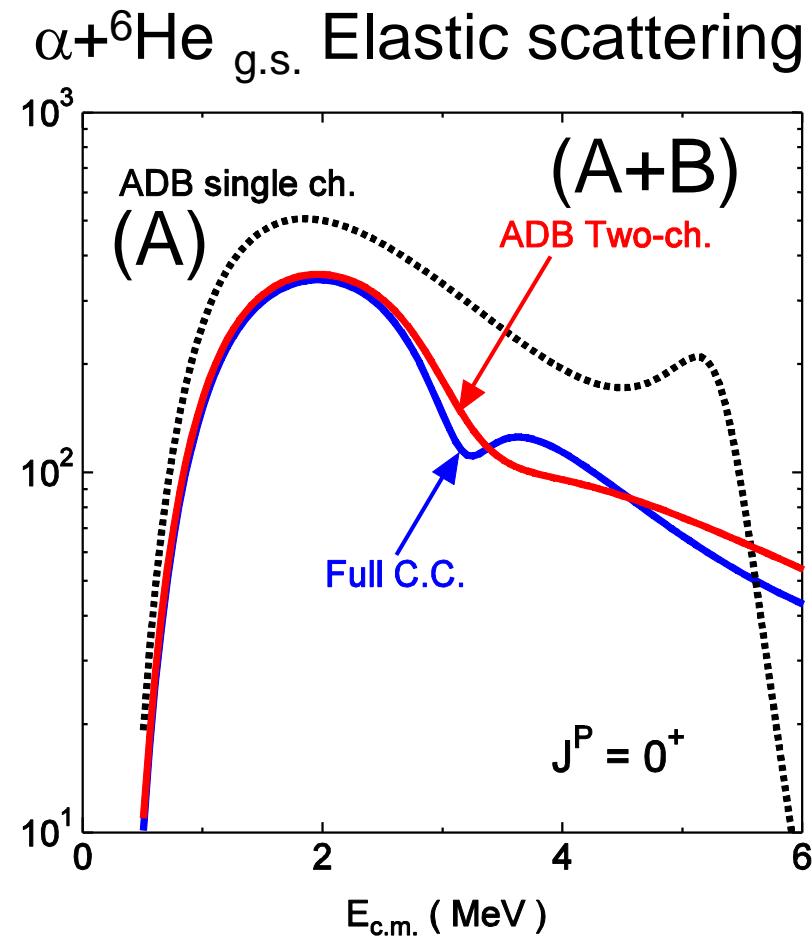
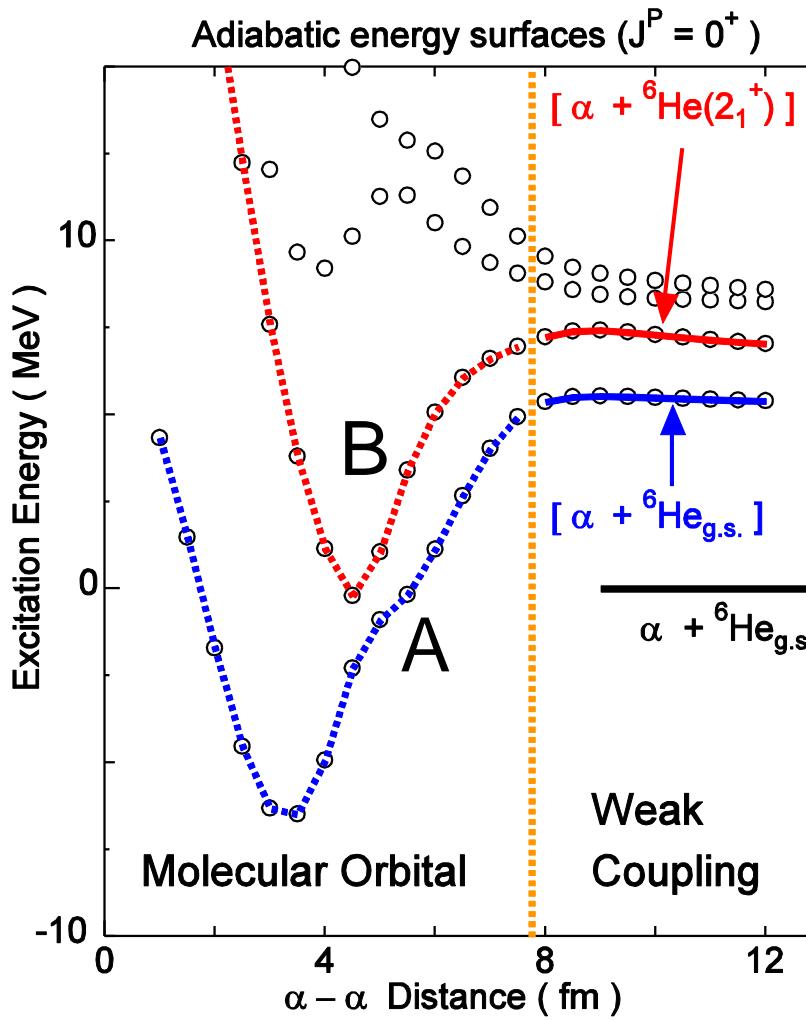
$J^\pi = 0^+$  (Long range coupling)



$J^\pi = 1^-$  (Avoided Crossing)

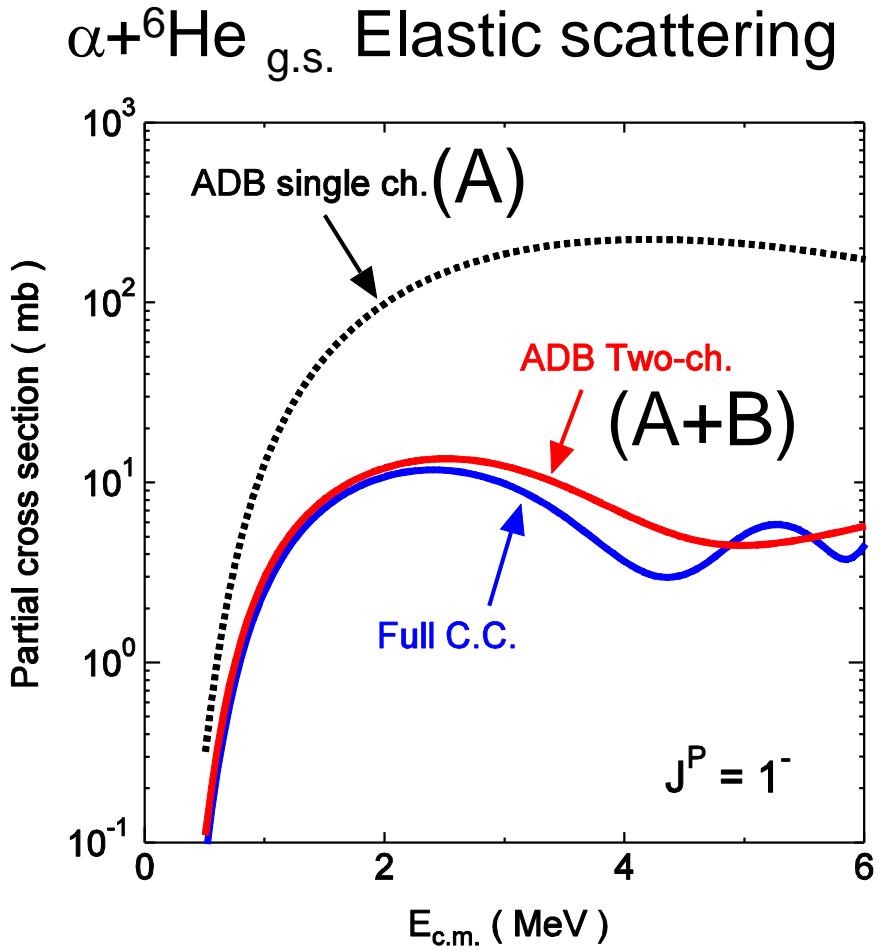
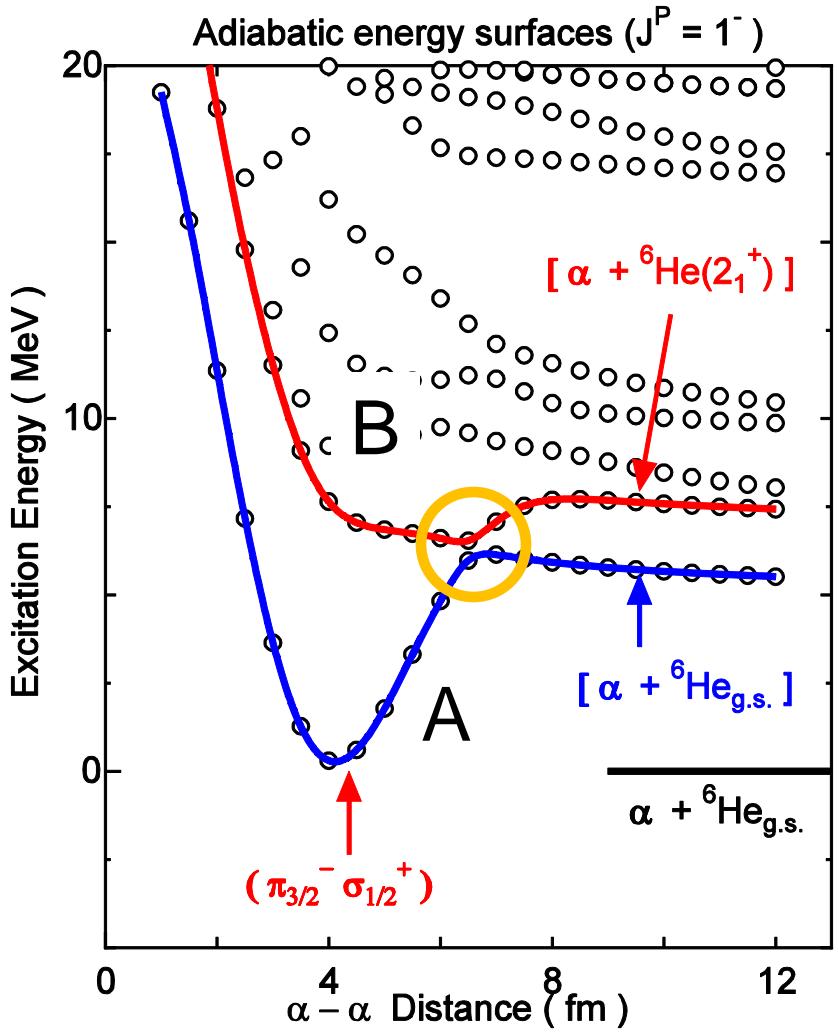


# Coupled channels in $\alpha + {}^6\text{He}$ elastic scattering ( $J^\pi = 0^+$ )



Adiabatic approximation is good.

# Coupled channels in $\alpha + {}^6\text{He}$ elastic scattering ( $J^\pi = 1^-$ )



Non-adiabatic transition strongly occurs.

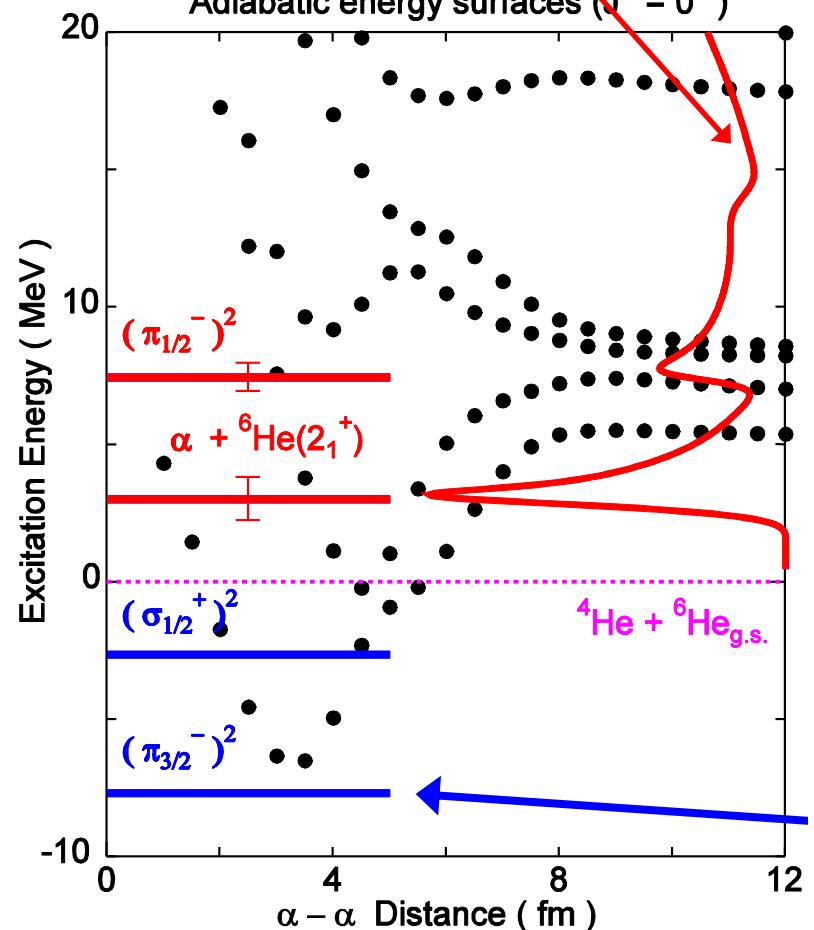
# Enhancements in $\alpha + {}^6\text{He}$ inelastic scattering

(B. Imanisi et al., Phys. Rep. 155)

$J^\pi = 0^+$  Resonance Poles



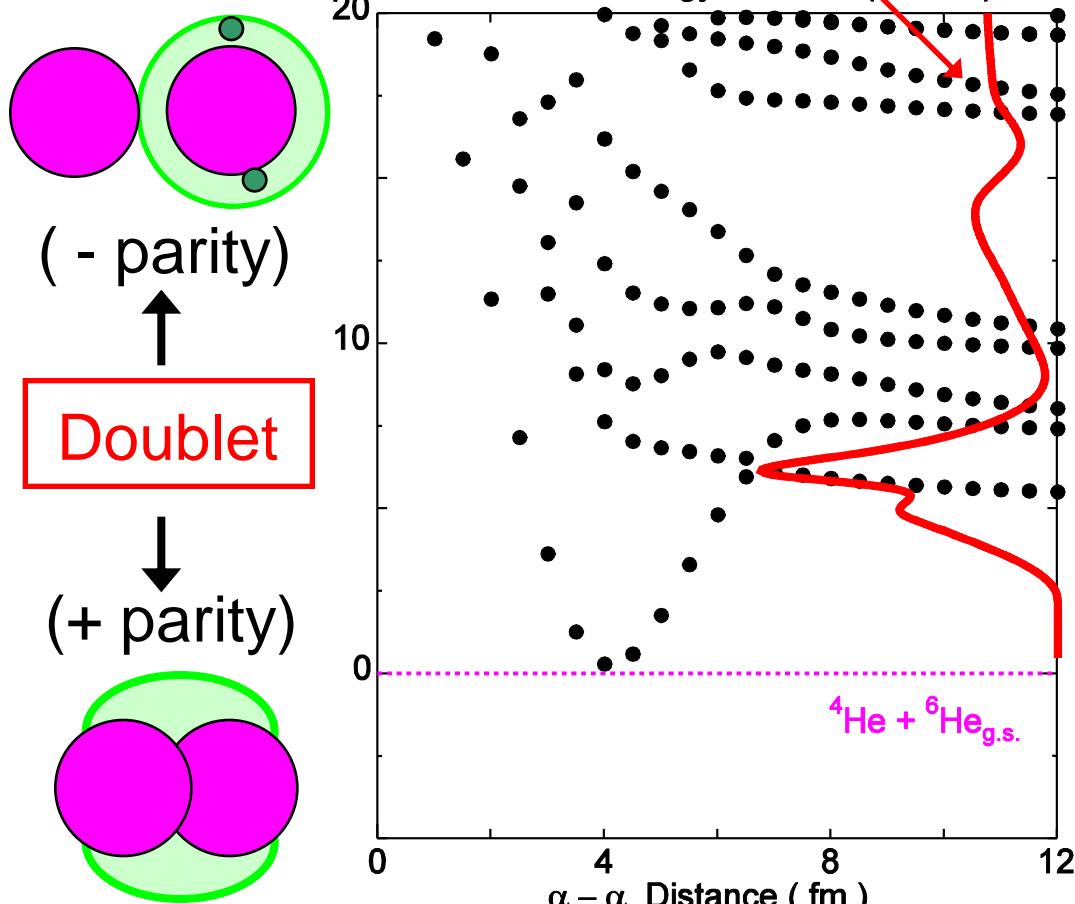
Adiabatic energy surfaces ( $J^P = 0^+$ )



$J^\pi = 1^-$  L-Z level crossing

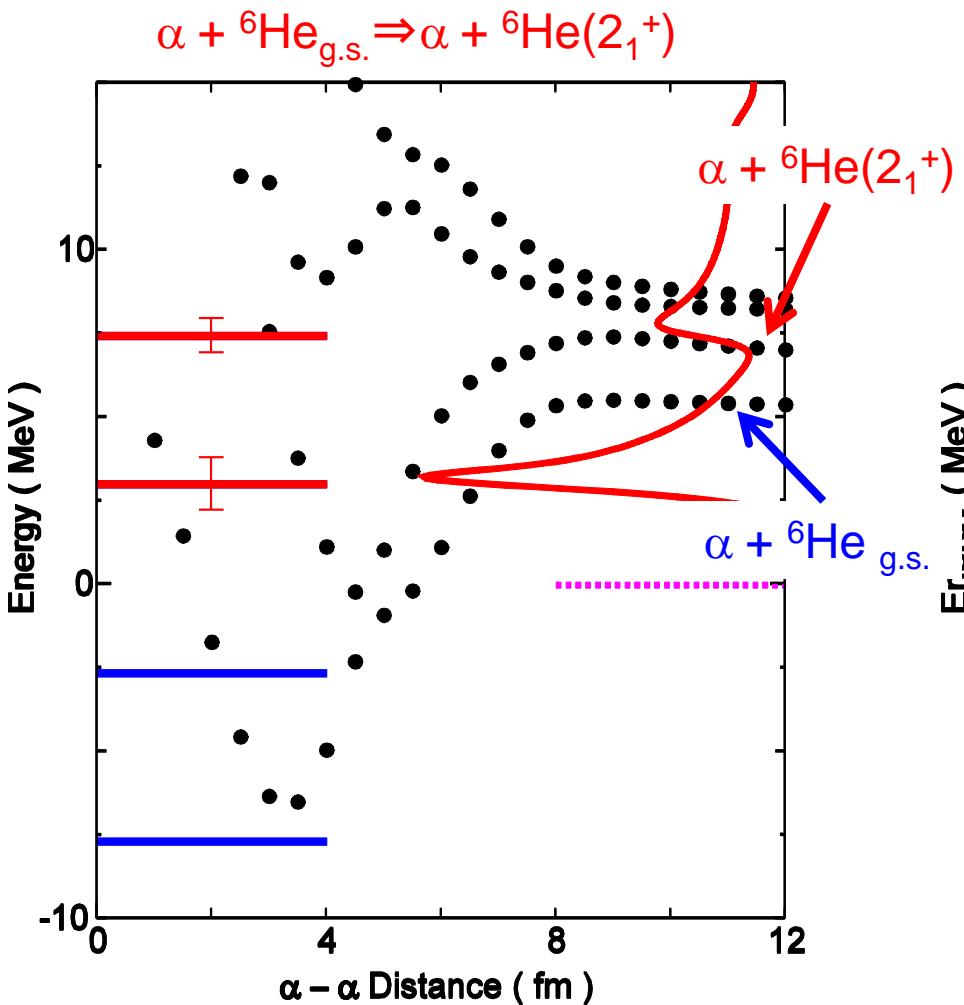


Adiabatic energy surfaces ( $J^P = 1^-$ )

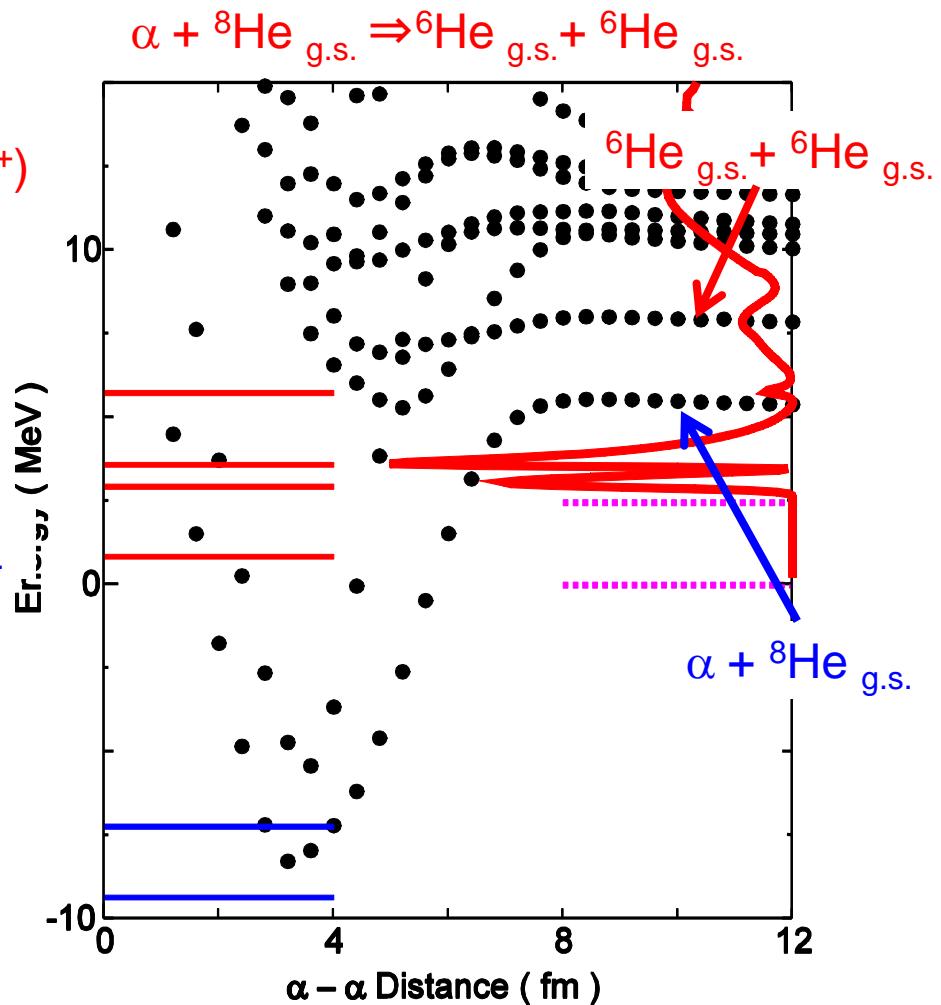


## Comparison between $\alpha + {}^6\text{He}$ and $\alpha + {}^8\text{He}$ scattering

${}^{10}\text{Be}(0^+)$  : Res. in Inel. Scatt.



${}^{12}\text{Be}(0^+)$  : Res. in Transfer ch.



## Summary

1. Studies on N-rich systems in (N,Z,E) space is very interesting.
2. Unified description of structures and reaction becomes quite important.
3. We show some enhancements in the  $\alpha+^6\text{He}$  and  $\alpha+^8\text{He}$  scattering.

## Results of $^{10}\text{Be}$

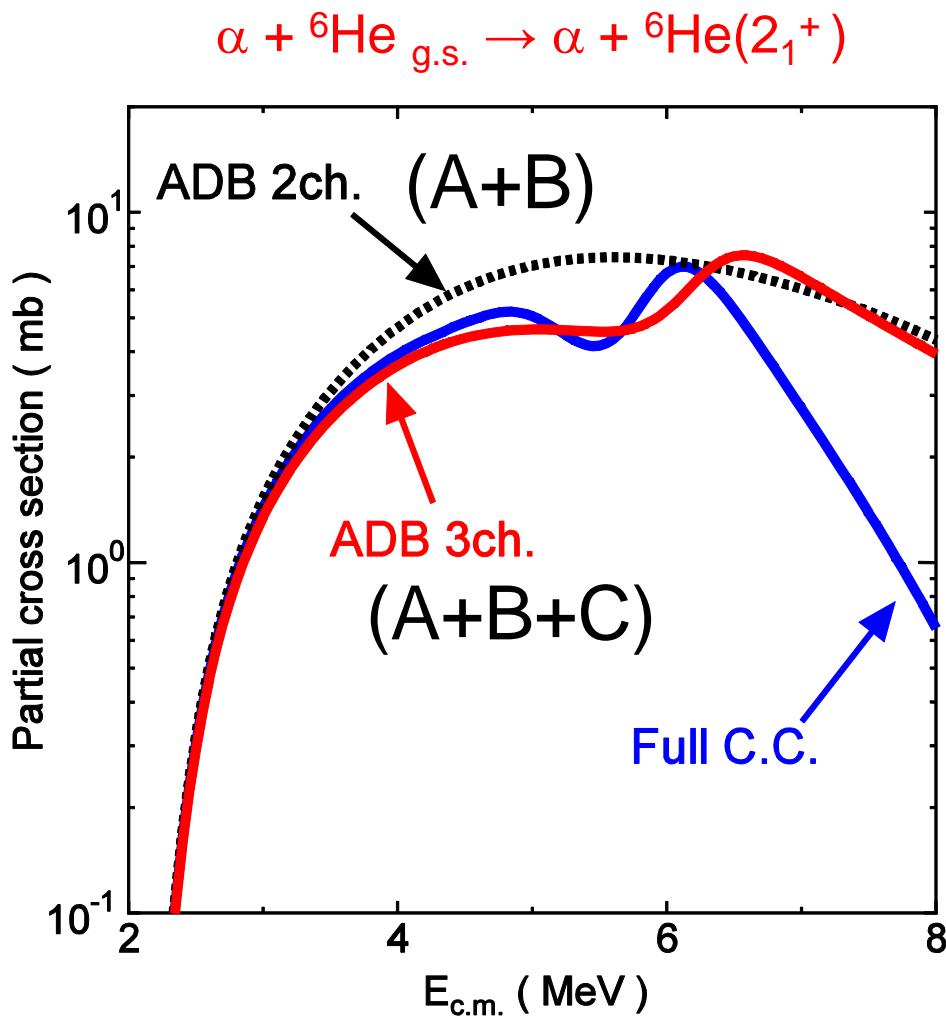
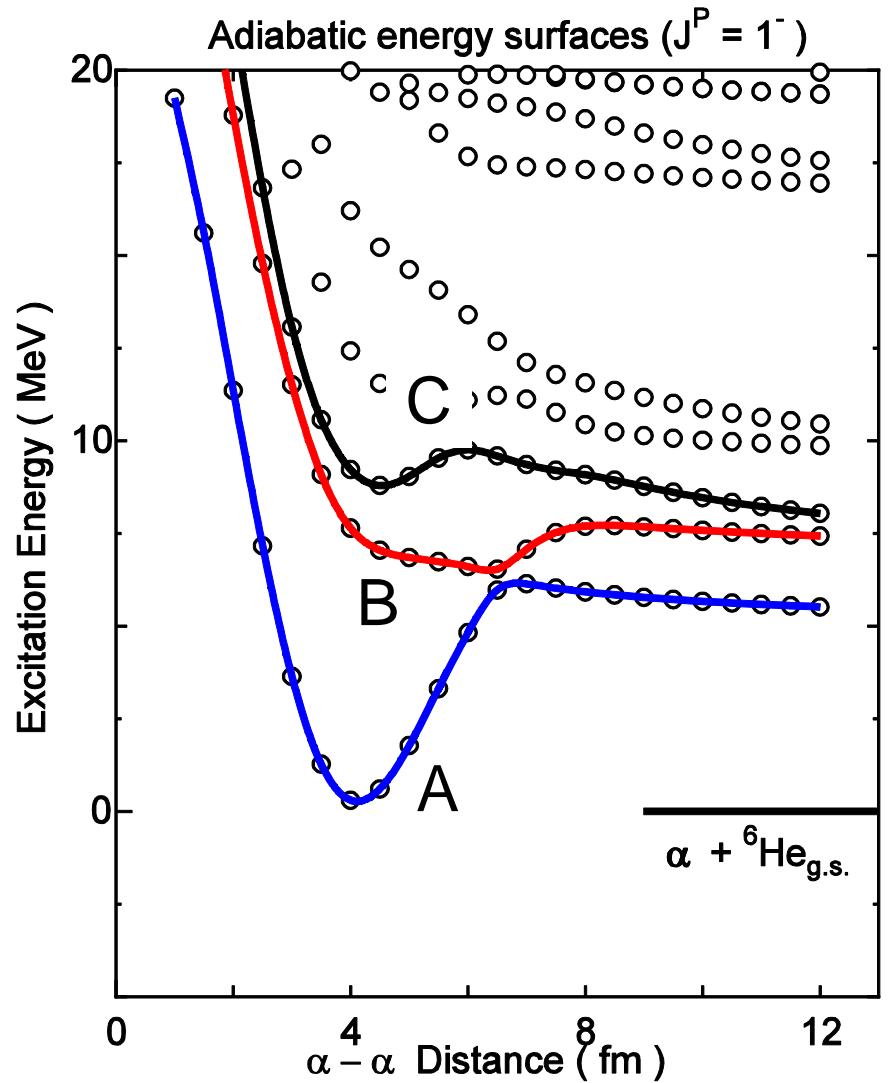
1. Molecular and atomic states coexist in this system.
2. Reaction process is different between the positive parity and the negative one.
3. L-Z transition is predicted in connection to the Parity doublet.

## Results of $^{12}\text{Be}$

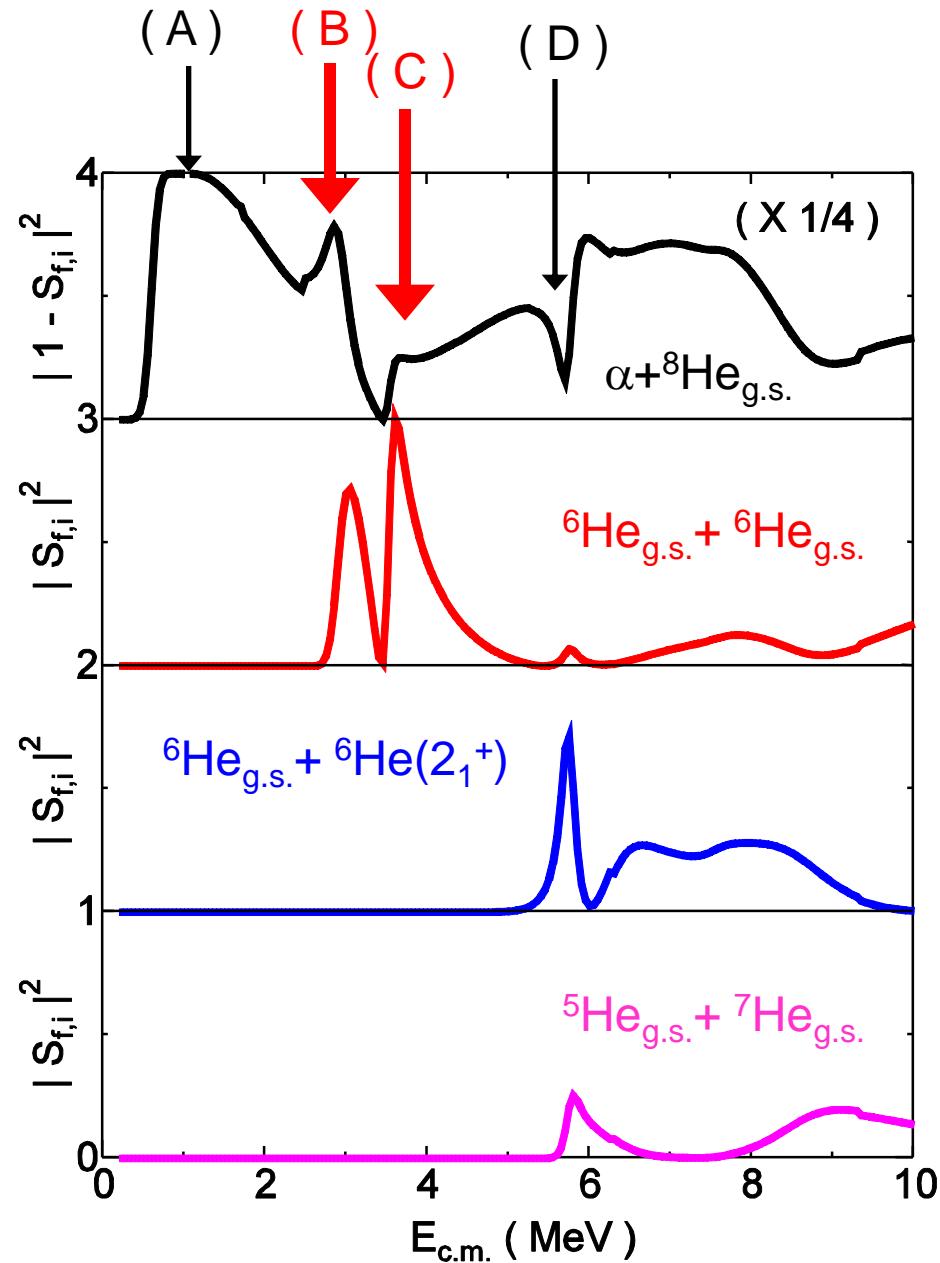
1. Resonances will be observed in two neutron transfers.
2. Exotic structures are excited. (I will report at YITP post symposium.)



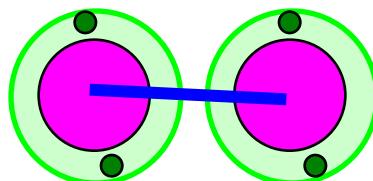
## Coupled channels with the adiabatic states



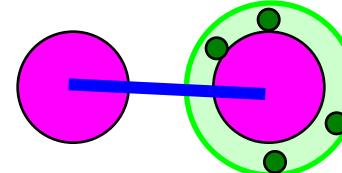
## Resonances in $\alpha + {}^8\text{He} \Rightarrow {}^x\text{He} + {}^y\text{He}$



(B) Two nucleon transferred state

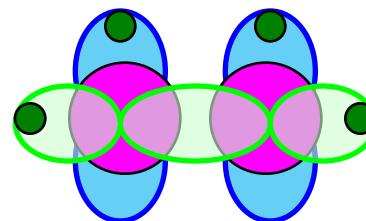


${}^6\text{He}_{\text{g.s.}} + {}^6\text{He}_{\text{g.s.}}$  Open



$\alpha + {}^8\text{He}_{\text{g.s.}}$  Open

(C) Atom-Molecule hybrid state

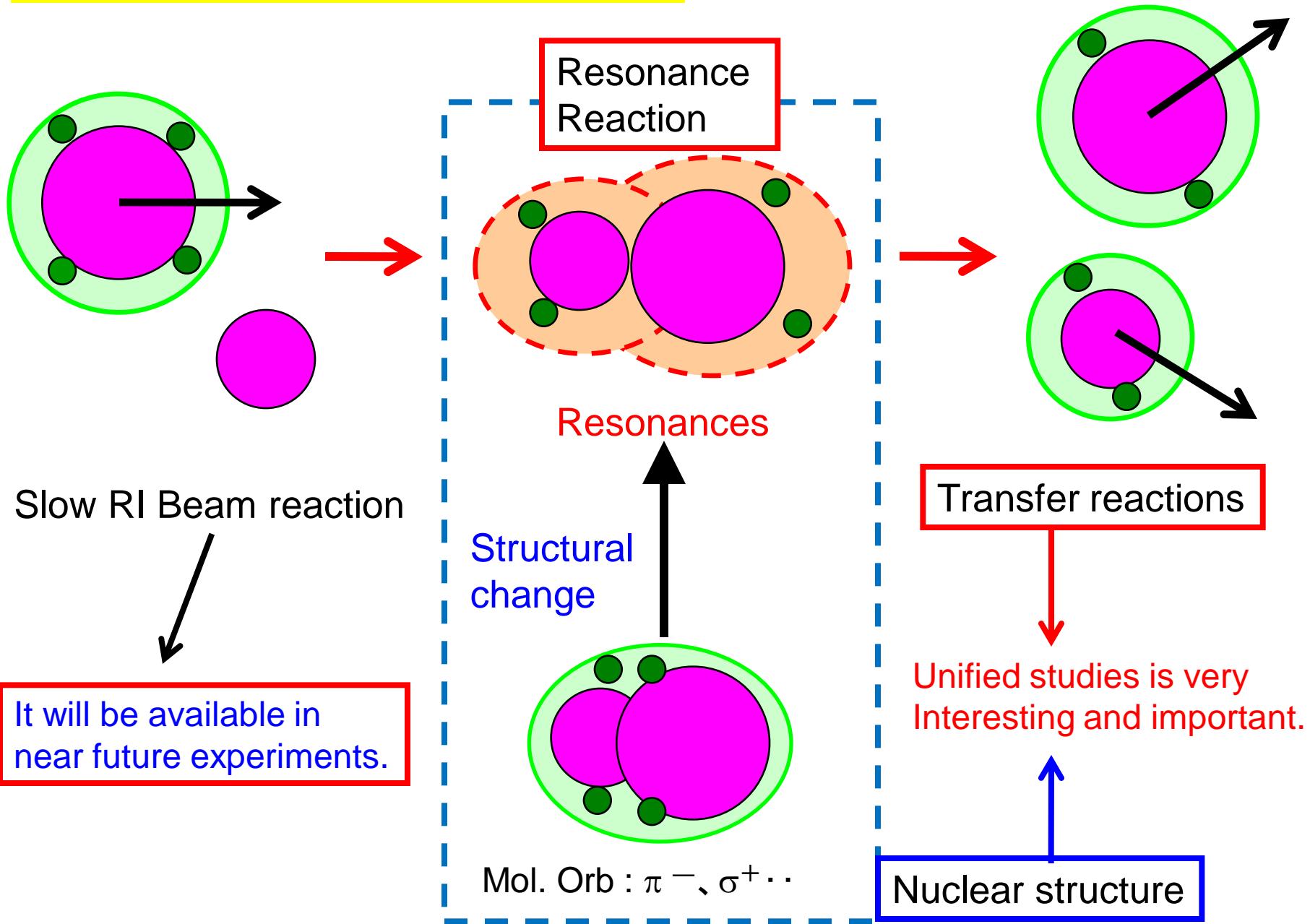


${}^6\text{He} + {}^6\text{He}$  Open

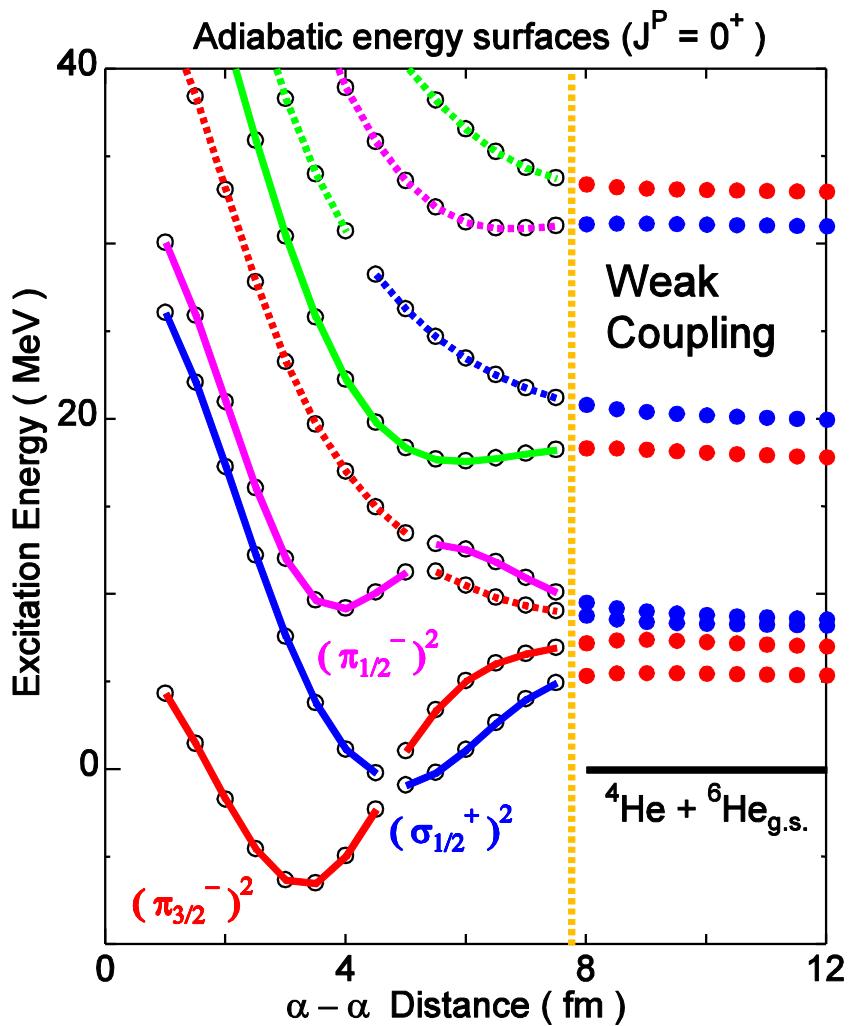
${}^5\text{He} + {}^7\text{He}$  Closed

Decay scheme depends on  
the intrinsic structure

## Unified studies in neutron-rich system



## Coupled channels with the adiabatic states



$$u^{rel}(\alpha, R, S) \varphi^{in}(\alpha, \xi_\alpha)$$

$$\Phi^{AD}(i, S) = \sum_\beta C_\beta(i) u^{rel}(\beta, R_\beta, S) \varphi^{in}(\beta, \xi_\beta)$$

$$u^{rel}(\beta, R_\beta, S) \propto \exp[-\nu(R_\beta - S)^2]$$

$$u^{rel}(\alpha, R_\alpha, S) \propto \exp[-\nu(R_\alpha - S)^2] \quad (R \leq R_c)$$

$$u_{L\alpha}^{(-)}(R_\alpha) - \varepsilon u_{L\alpha}^{(+)}(R_\alpha) \quad (R \geq R_c)$$

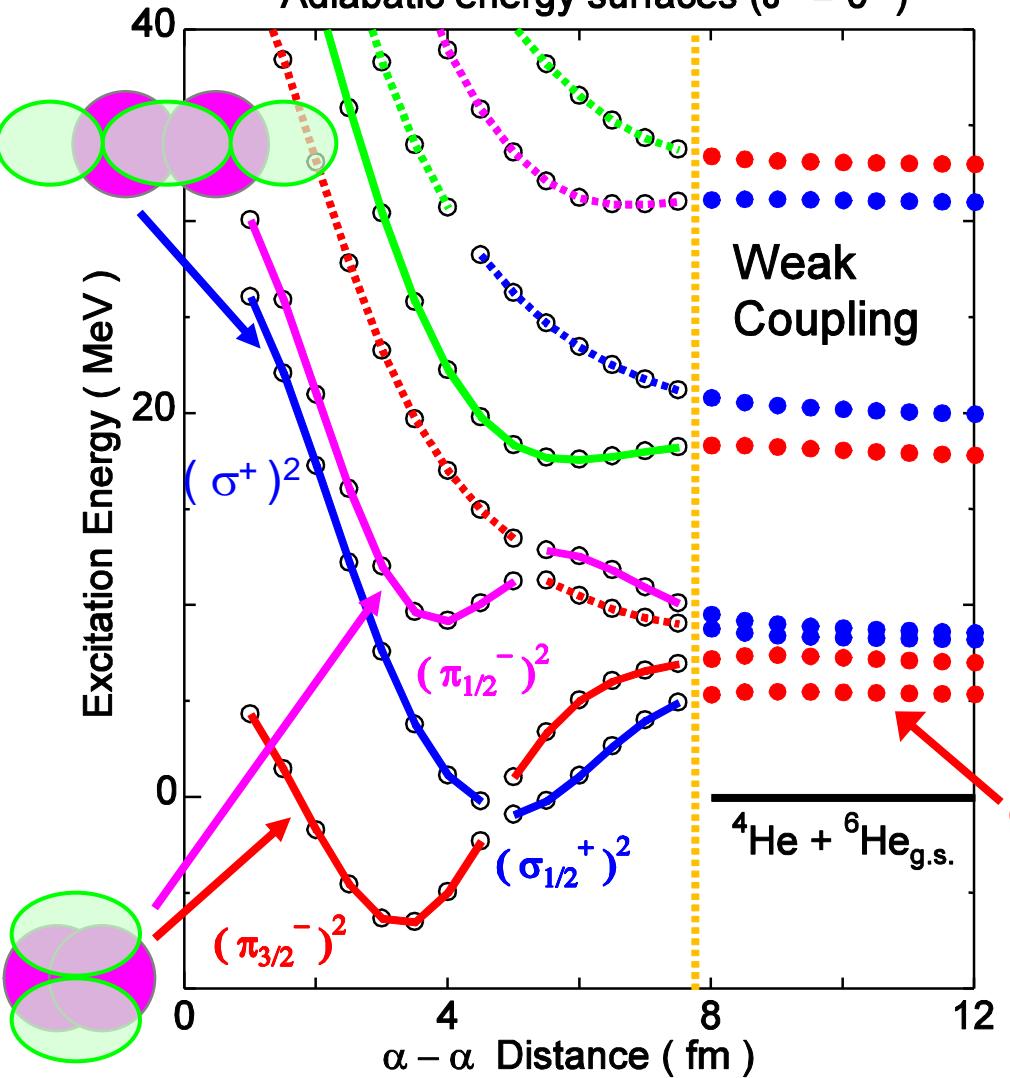
$$\Psi = \sum_{i,S} f(i, S) \Phi^{AD}(i, S)$$

$$(H - E)\Psi = 0$$

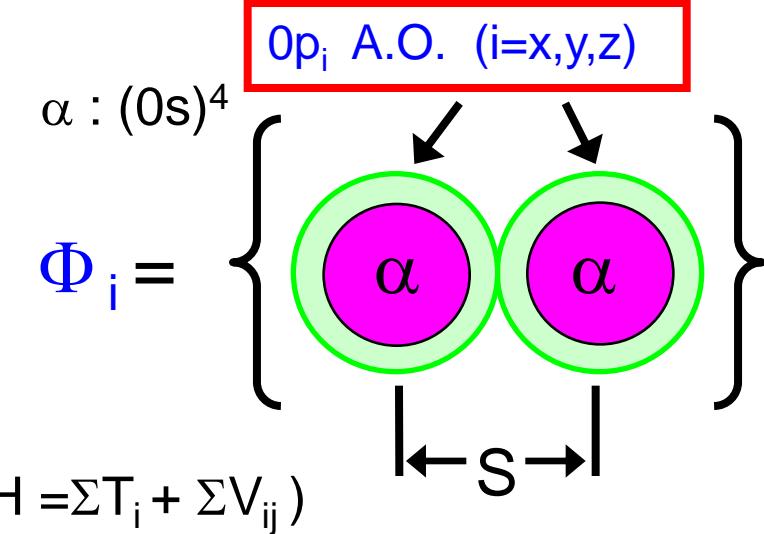
# Generalized Two-center cluster model (GTGM) : PLB588



Adiabatic energy surfaces ( $J^\pi = 0^+$ )



Basis : Atomic orbital (A.O.)



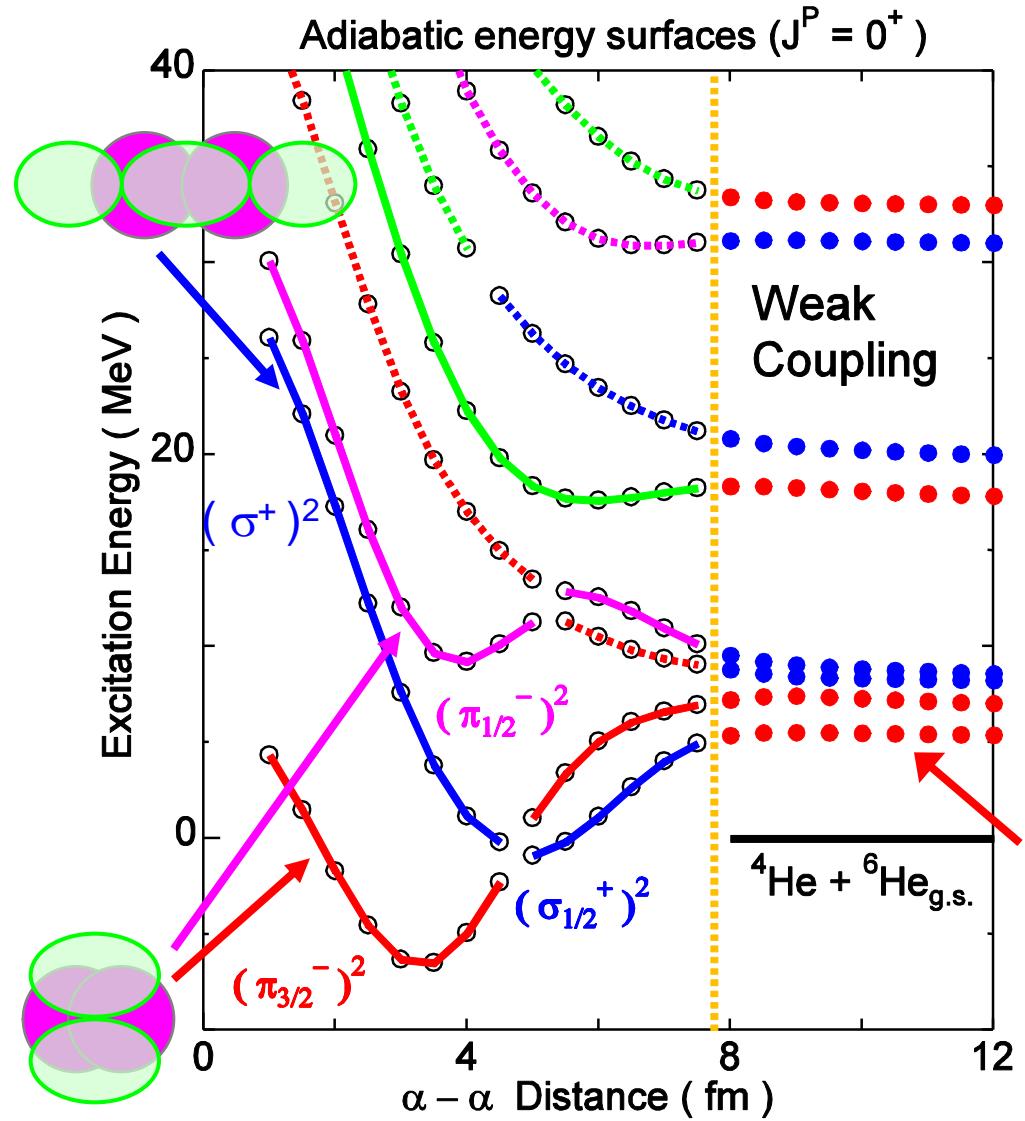
Total wave function

$$\Psi^{J\pi} = P^{J\pi} \sum C_i \Phi_i$$

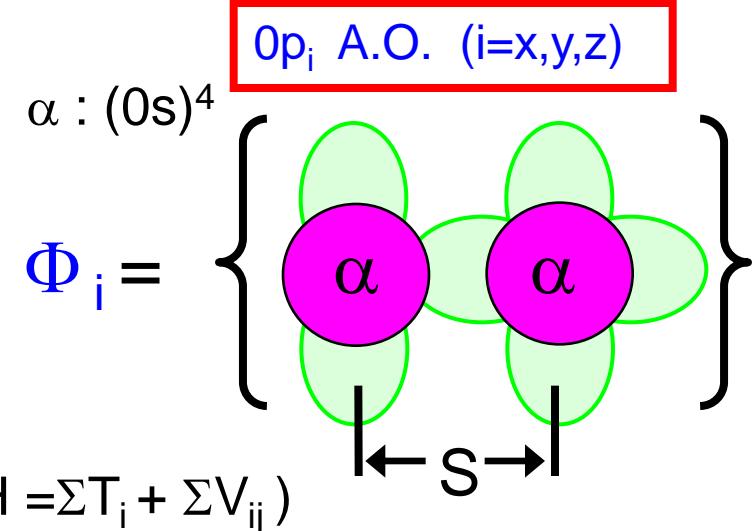
$J^\pi$  Proj. Anti-sym.

- Red Dots :  $[\alpha + {}^6\text{He}(1)]$  LJ
- Blue Dots :  $[{}^5\text{He}(l_1) + {}^5\text{He}(l_2)]$  LJ

# Generalized Two-center cluster model (GTGM) : PLB588



Basis : Atomic orbital (A.O.)



Total wave function

$$\Psi^{J\pi} = P^{J\pi} \sum C_i \Phi_i$$

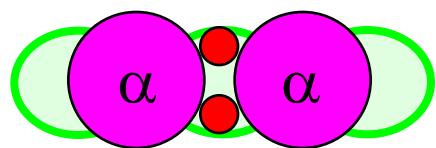
● Red Dots : [  $\alpha + ^6\text{He} (I)$  ] LJ

● Blue Dots : [  ${}^5\text{He}(I_1) + {}^5\text{He}(I_2)$  ] LJ

$J^\pi$  Proj. Anti-sym.

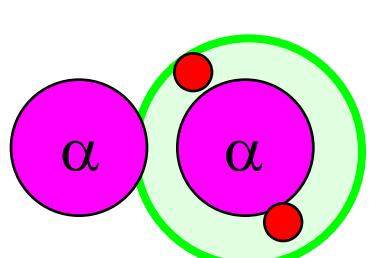
## Formulation

Linear Combination of  
Atomic Orbital (LCAO)



$$(\sigma^+)^2 = (p_z(L) - p_z(R))^2$$

$$= \left[ \begin{array}{c} \text{Diagram of } {}^6\text{He}(z) \\ \text{Two alpha particles with one red electron each, separated by a gap.} \end{array} \right] + \left[ \begin{array}{c} \text{Diagram of } \alpha + {}^6\text{He}(z)^2 \\ \text{One alpha particle and one } {}^6\text{He}(z) \text{ molecule} \end{array} \right] - 2 \left[ \begin{array}{c} \text{Diagram of } {}^5\text{He}(z) + {}^5\text{He}(z) \\ \text{Two } {}^5\text{He}(z) \text{ molecules} \end{array} \right]$$



$$\alpha + {}^6\text{He}(0^+)$$

$$= \left[ \begin{array}{c} \text{Diagram of } \alpha + {}^6\text{He}(x)^2 \\ \text{One alpha particle and one } {}^6\text{He}(x) \text{ molecule} \end{array} \right] + \left[ \begin{array}{c} \text{Diagram of } \alpha + {}^6\text{He}(y)^2 \\ \text{One alpha particle and one } {}^6\text{He}(y) \text{ molecule} \end{array} \right] + \left[ \begin{array}{c} \text{Diagram of } \alpha + {}^6\text{He}(Z)^2 \\ \text{One alpha particle and one } {}^6\text{He}(Z) \text{ molecule} \end{array} \right]$$