Studies on excited states of Be isotopes

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Contents

Introduction

1. Studies on nuclear structure

Model Space $\leftrightarrow$ Eff. Interaction **(Close connection)**

$\downarrow$

should depend on the subjects of studies

2. Studies on Be isotopes $(\alpha + \alpha + n + n + ...)$

· Low-lying states $\longrightarrow$ Molecular orbitals (π^-, σ^+)

· High-lying states $\longrightarrow$ Resonances (^{6}He, ^{8}He ??)

They should be studied in a unified way !!

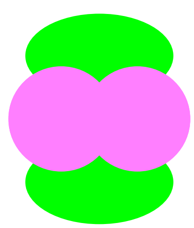
3. Appropriate model space

We should include high $\hbar\omega$ state around two α cores.

Small α–α distance

Molecular orbitals

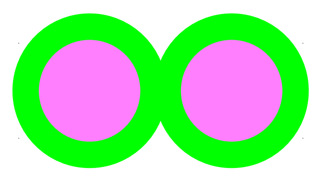
Low $\hbar\omega$



Large α–α distance

Valence bonding

High $\hbar\omega$



4. Present approach

Valence neutron's orbital $\rightarrow$ Simple LCAO (0p-shell)

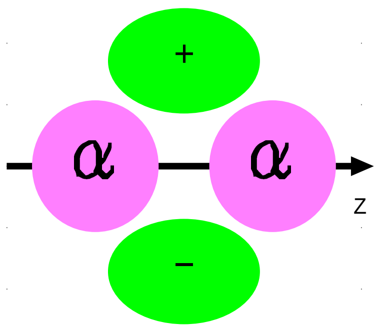
Full configuration of LCAO (0$\sim$2 $\hbar\omega$ excitation)

NN force $\rightarrow$ reproduce the threshold (Parameters)

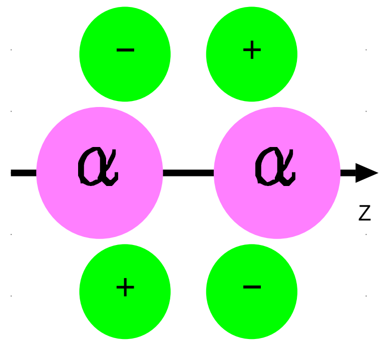
Molecular orbitals in LCAO

1. Linear Comb. of Atomic Orbitals (LCAO)

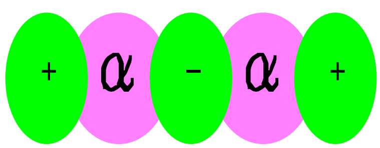
π^- ($0\hbar\omega$, 0p-shell)



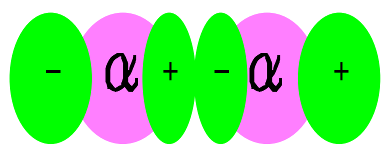
π^+ ($1\hbar\omega$, sd-shell)



σ^+ ($1\hbar\omega$, sd-shell)

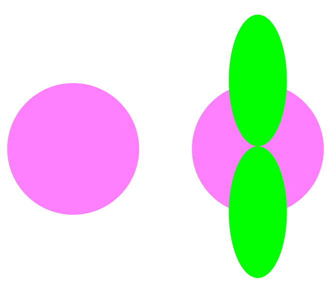


σ^- ($2\hbar\omega$, pf-shell)

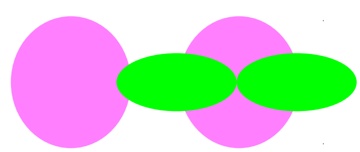


2. Projection to the atomic orbitals

$\pi^- + \pi^+ = 0\hbar\omega + 1\hbar\omega$



$\sigma^+ + \sigma^- = 1\hbar\omega + 2\hbar\omega$



3. Formation of ^{10}Be $= \alpha +$ ^{6}He(0_1^+)

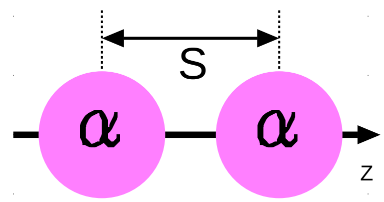
$+$ paity $\rightarrow 0,\ 2,\ 4\ \hbar\omega :\ (\pi^-)^2, (\pi^+)^2, (\sigma^+)^2, (\sigma^-)^2, \ldots$

$-$ paity $\rightarrow 1,\ 3\ \hbar\omega :\ (\pi^-\sigma^+), (\sigma^+\sigma^-), \ldots$

Generalized Two-center Cluster Model (GTCM)

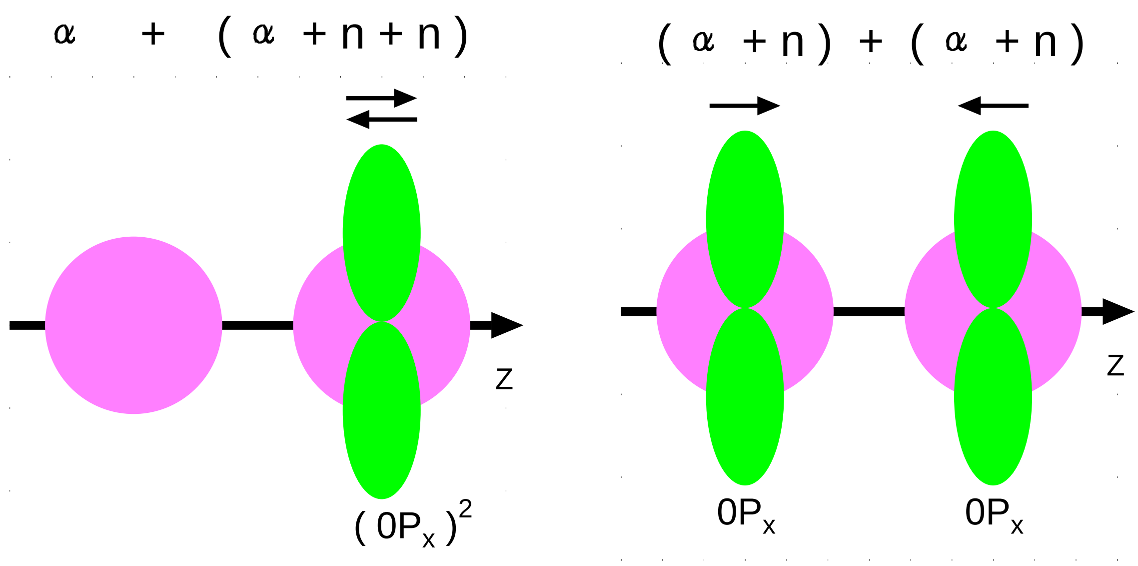
1. Construction of the basis functions

System : ^{10}Be=α+α+n+n $\quad$ α : $(0\mathrm{s})^4$



Neutrons are arranged around one of α cores with $0\mathrm{p}_x$, $0\mathrm{p}_y$, $0\mathrm{p}_z$

α + ^{6}**He Partition** $\qquad$ ^{5}**He** + ^{5}**He Partition**



$$\Phi^{J^\pi K}(S, n_1, n_2) = \mathcal{P}^\pi P^J_{MK} \mathcal{A}\{ [\varphi_L(\alpha) \varphi_R(\alpha) \phi(n_1, n_2)]_S \}$$

n_i : (Left or Right, $0\mathrm{p}_x$, $0\mathrm{p}_y$, $0\mathrm{p}_z$, $\uparrow$ or $\downarrow$), **b**=1.46 fm

2. Total wave function

$$\Psi^{J\pi} = \int dS \sum_{K,\beta} f(K, S, \beta)\, \Phi^{J^\pi K}(S, \beta) \qquad \beta = (n_1, n_2)$$

3. Full eigenvalue problem

$$\Psi^{J\pi} = \int dS \sum_{K,\beta} f(K,S,\beta)\, \Phi^{J\pi K}(S,\beta)$$

$$\equiv \int dS \;\chi^{J\pi}(S)$$

$$\chi^{J\pi}(S) \equiv \sum_{K,\beta} f(K,S,\beta)\, \Phi^{J\pi K}(S,\beta)$$

$$< \Phi^{JK'\pi}(S',\beta') \mid H - E \mid \int dS\, \chi^{J\pi}(S) \; >= 0$$

4. Adiabatic energy surfaces

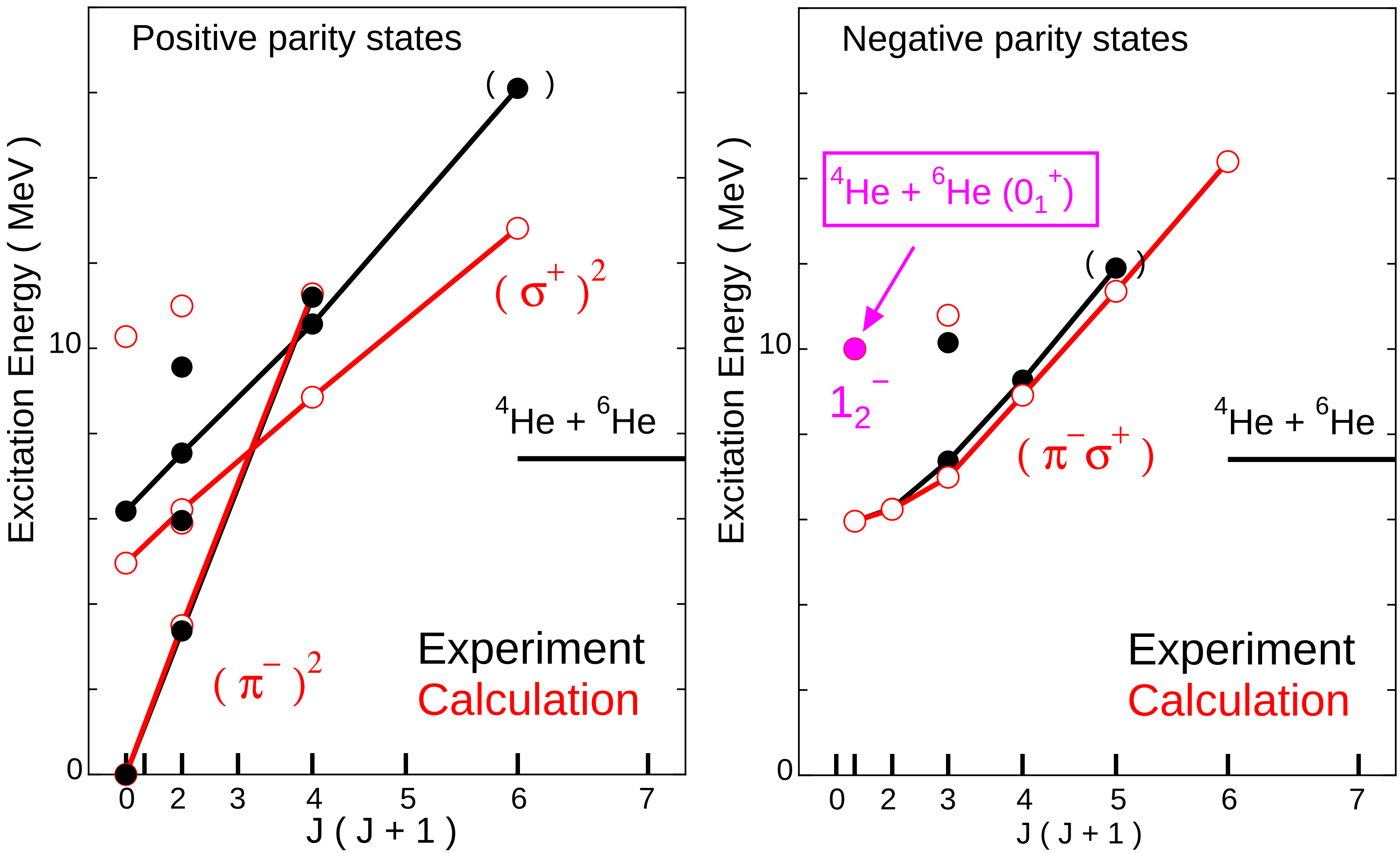
We can solve eigenvalue equations at a fixed distance S.

$$< \Phi^{JK'\pi}(S,\beta') \mid H - E(S) \mid \chi^{J\pi}(S) \; >= 0$$

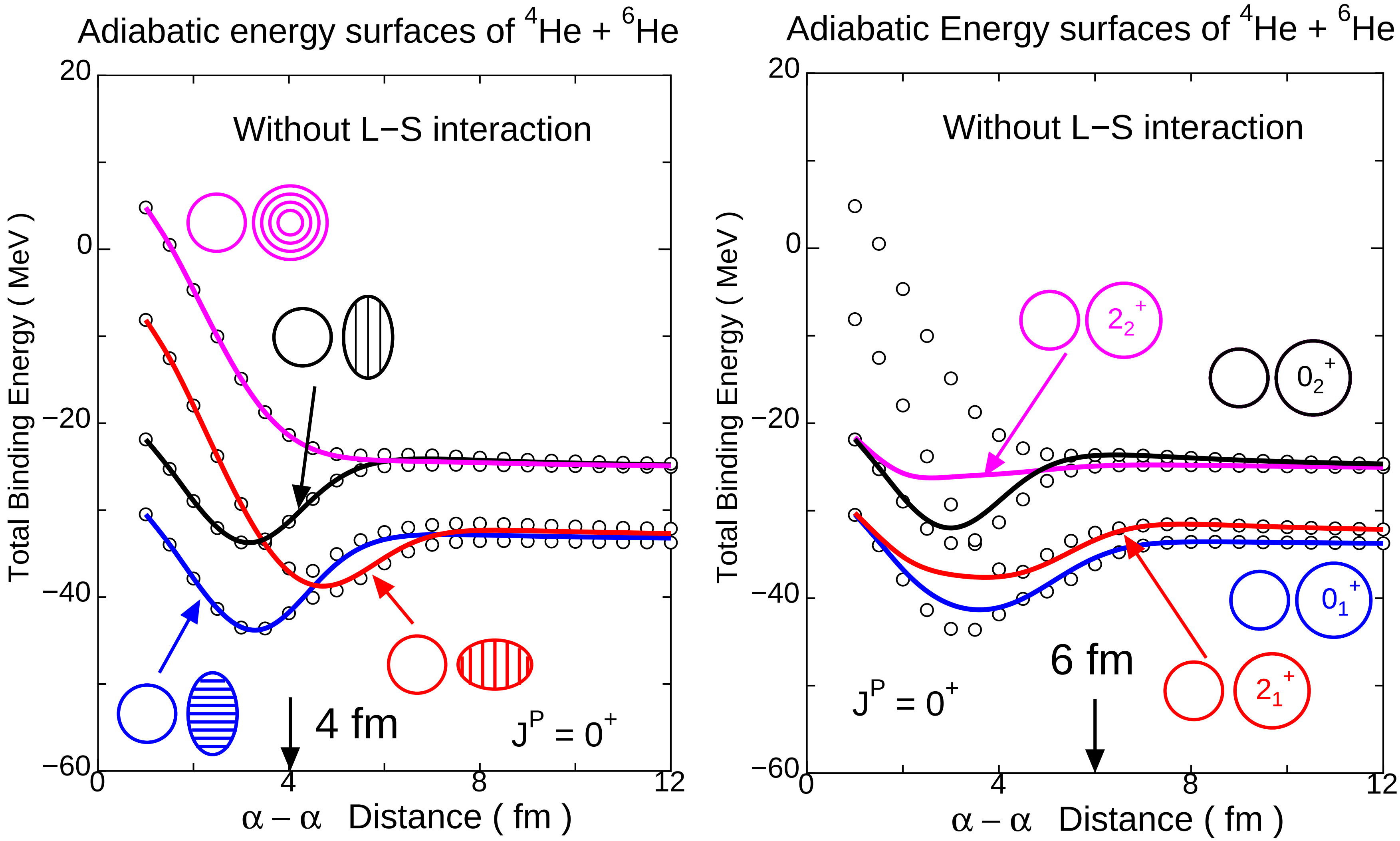
5. nucleon–nucleon interaction

- **Cent. : Volkov (2)** → M=0.643, B=−H=0.125
- **L–S : G3RS** → Rep. +3000, Att. −2000 (MeV)
- **Size b=1.46 fm**

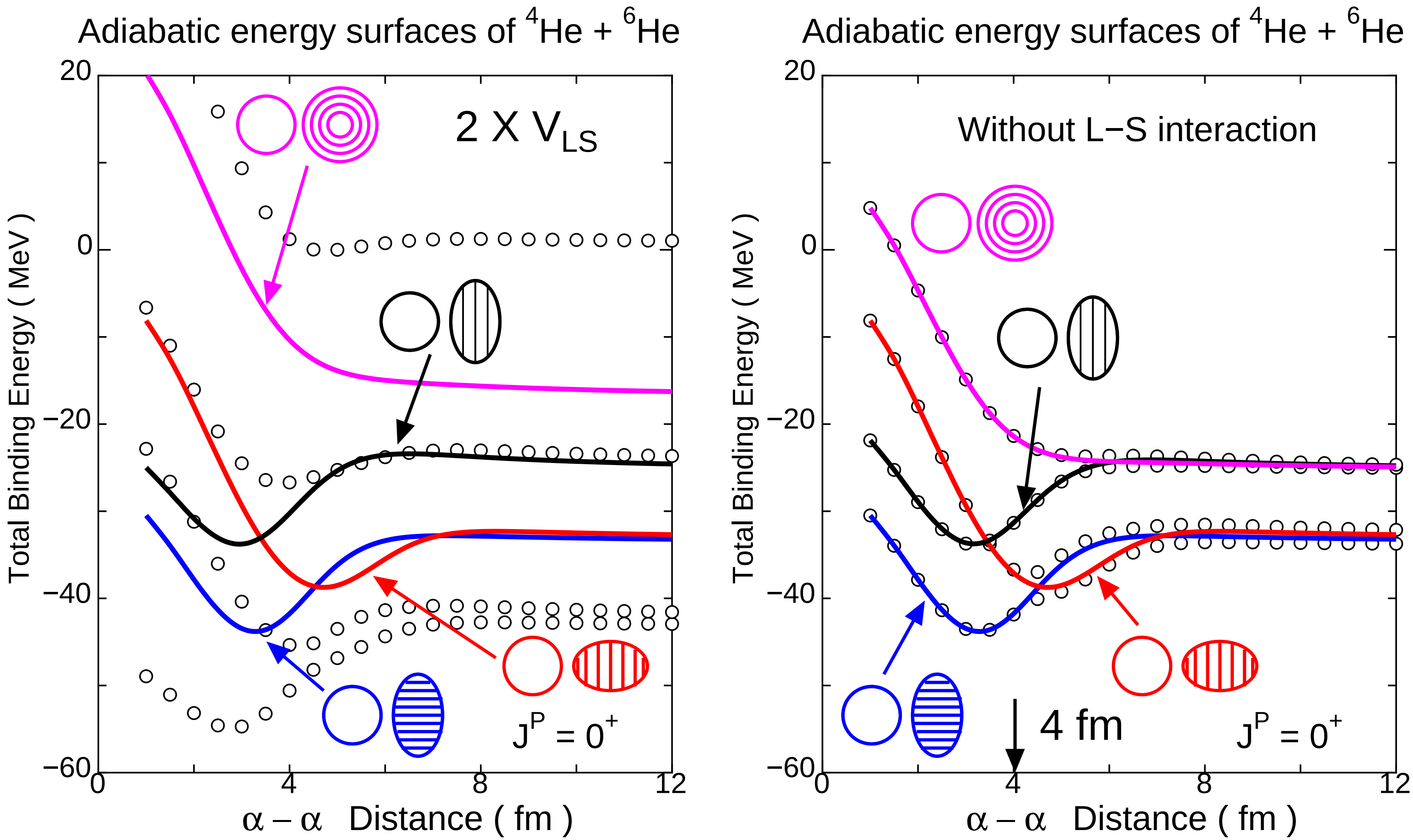
	Cal. (MeV)	Exp. (MeV)
E $_{th}$ (α+^{6}He)	7.41	7.41
^{6}He (2_1^+)	1.9	1.8
^{5}He L–S splitting	6.0	1.47



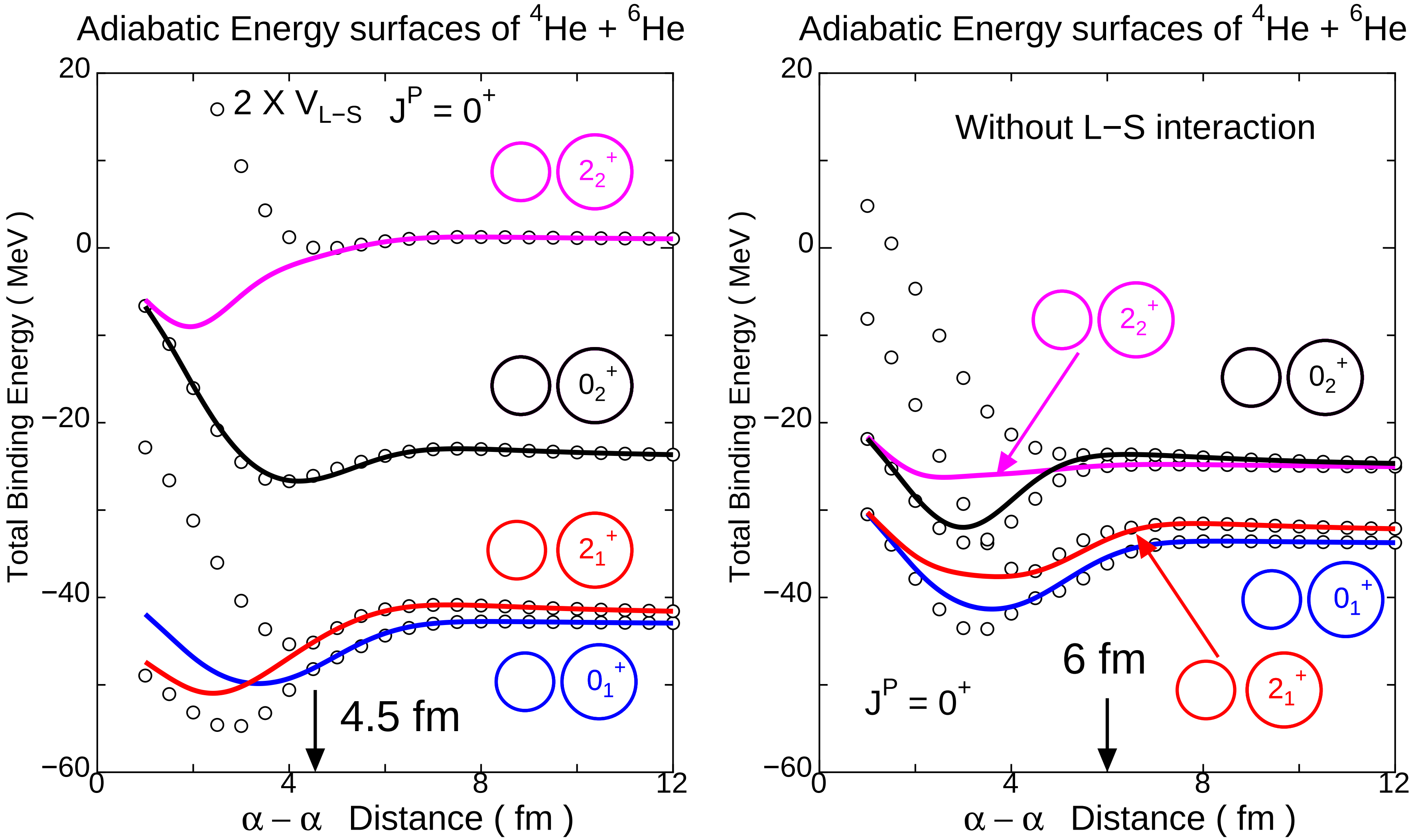
Positive parity states
Excitation Energy (MeV)
10
0
( )
(σ+)2
(π−)2
4He + 6He
Experiment
Calculation
0
2
3
4
5
6
7
J (J + 1)
Negative parity states
Excitation Energy (MeV)
10
0
4He + 6He (01+)
12−
( )
(π−σ+)
4He + 6He
Experiment
Calculation
0
2
3
4
5
6
7
J (J + 1)



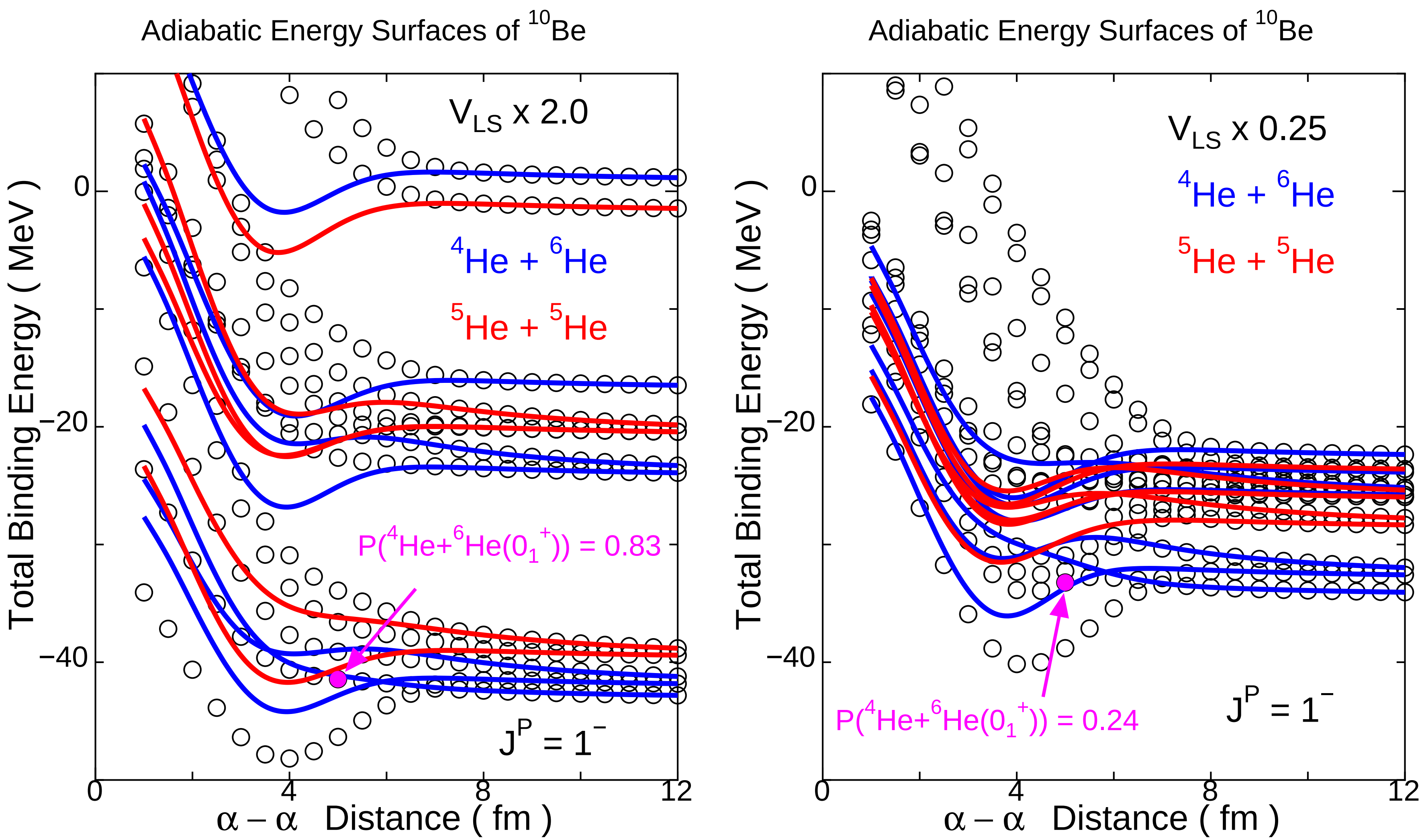
Adiabatic energy surfaces of 4He + 6He
Without L−S interaction
Total Binding Energy (MeV)
20
0
−20
−40
−60
0
4
8
12
4 fm
J^P = 0^+
α − α Distance (fm)
Adiabatic Energy surfaces of 4He + 6He
Without L−S interaction
Total Binding Energy (MeV)
2_2^+
0_2^+
0_1^+
2_1^+
6 fm
J^P = 0^+
α − α Distance (fm)



Adiabatic energy surfaces of ^{4}He + ^{6}He
2 X V_{LS}
$J^P = 0^+$
Total Binding Energy (MeV)
20
0
−20
−40
−60
0
4
8
12
α − α Distance (fm)
Adiabatic energy surfaces of ^{4}He + ^{6}He
Without L−S interaction
4 fm
$J^P = 0^+$
Total Binding Energy (MeV)
20
0
−20
−40
−60
0
4
8
12
α − α Distance (fm)



Adiabatic Energy surfaces of 4He + 6He
2 X VL−S JP = 0+
22+
02+
21+
01+
4.5 fm
Total Binding Energy (MeV)
α − α Distance (fm)
20
0
−20
−40
−60
0
4
8
12
Adiabatic Energy surfaces of 4He + 6He
Without L−S interaction
22+
02+
01+
21+
6 fm
JP = 0+
Total Binding Energy (MeV)
α − α Distance (fm)
20
0
−20
−40
−60
0
4
8
12



Adiabatic Energy Surfaces of 10Be
VLS x 2.0
4He + 6He
5He + 5He
P(4He+6He(01+)) = 0.83
JP = 1−
Total Binding Energy (MeV)
α − α Distance (fm)
0
−20
−40
0
4
8
12
Adiabatic Energy Surfaces of 10Be
VLS x 0.25
4He + 6He
5He + 5He
P(4He+6He(01+)) = 0.24
JP = 1−
Total Binding Energy (MeV)
α − α Distance (fm)

Observation of the α+^{6}He$_{g.s.}$ ($J^\pi = 1_2^-$)

E1 Coulomb Excitations (Breakup)

$^{10}\mathbf{Be}_{g.s.} \rightarrow {}^{10}\mathbf{Be}_{ex.} = |\,\alpha + {}^6\,\mathbf{He} > + \,|\, {}^5\mathbf{He} + {}^5\,\mathbf{He} >$

$^{10}\mathbf{Be}_{g.s.} \rightarrow \alpha$+^{6}**He : E1 transition is possible.**

$^{10}\mathbf{Be}_{g.s.} \rightarrow {}^5$**He+**^{5}**He : E1 transition is forbidden !!**

The transition ^{10}Be (g.s. $\rightarrow$ 1_2^-) will be enhanced in E1 Coulomb breakup !!

^{10}Be + Target inelastic scattering

^{12}C target : Nuclear dominance

^{208}Pb target : Coulomb dominance

$\rightarrow$ **^{10}Be(g.s. $\rightarrow$ 1_2^-) will be enhanced !!**

e. g. $^{12}\mathrm{Be}_{g.s.} \longrightarrow {}^{12}\mathrm{Be}\ (1^-)$ by Iwasaki *et al.*

Systematics in Be isotopes

^{x}Be	Occupation	J$^\pi$	Cluster	Probe
^{10}Be	$(\pi^-_{3/2}\pi^+_{3/2})$	1^-	^{4}He + ^{6}He	Coulomb
^{12}Be	$(\pi^-_{3/2})^2(\pi^+_{3/2})^2$	0^+	^{6}He + ^{6}He	Nuclear
^{14}Be	$(\pi^-_{3/2})^2(\pi^+_{3/2})^2\ (\sigma^+_{1/2}\sigma^-_{1/2})$	1^-	^{6}He + ^{8}He	Coulomb

Summary

We applied GTCM to ^{10}Be and discussed the effect of the L–S interaction for the weak-coupling formation of α + ^{6}He.

Conclusion

1. Model space

   The high $\hbar\omega$ states : (0p) $\sim$ (1p 0f) shell

   0$\sim$2$\hbar\omega$ excitation in a single particle state

2. L–S interaction

   Break the geometrical configuration

   Enhance the weak-coupling configuration

3. Observation of ^{6}He or ^{8}He cluster states

   Coulomb breakup $\rightarrow$ α+^{6}He, ^{6}He+^{8}He

   Nuclear breakup $\rightarrow$ ^{6}He + ^{6}He

Future plans

1. Application of Complex Scaling Method

Identification of resonance poles and their width

2. Transition density of ^{x}Be

Coupled channels of ^{x}Be + Target