Studies of light neutron-excess systems from bounds to continuum

— Unified studies of Be structure and $^{x}He+^{y}He$ reactions —

Makoto Ito

Department of Pure and Applied Physics, Kansai University

I. Introduction: Duality in nuclei and variety of excited state

II. Present subject on Be isotopes and framework

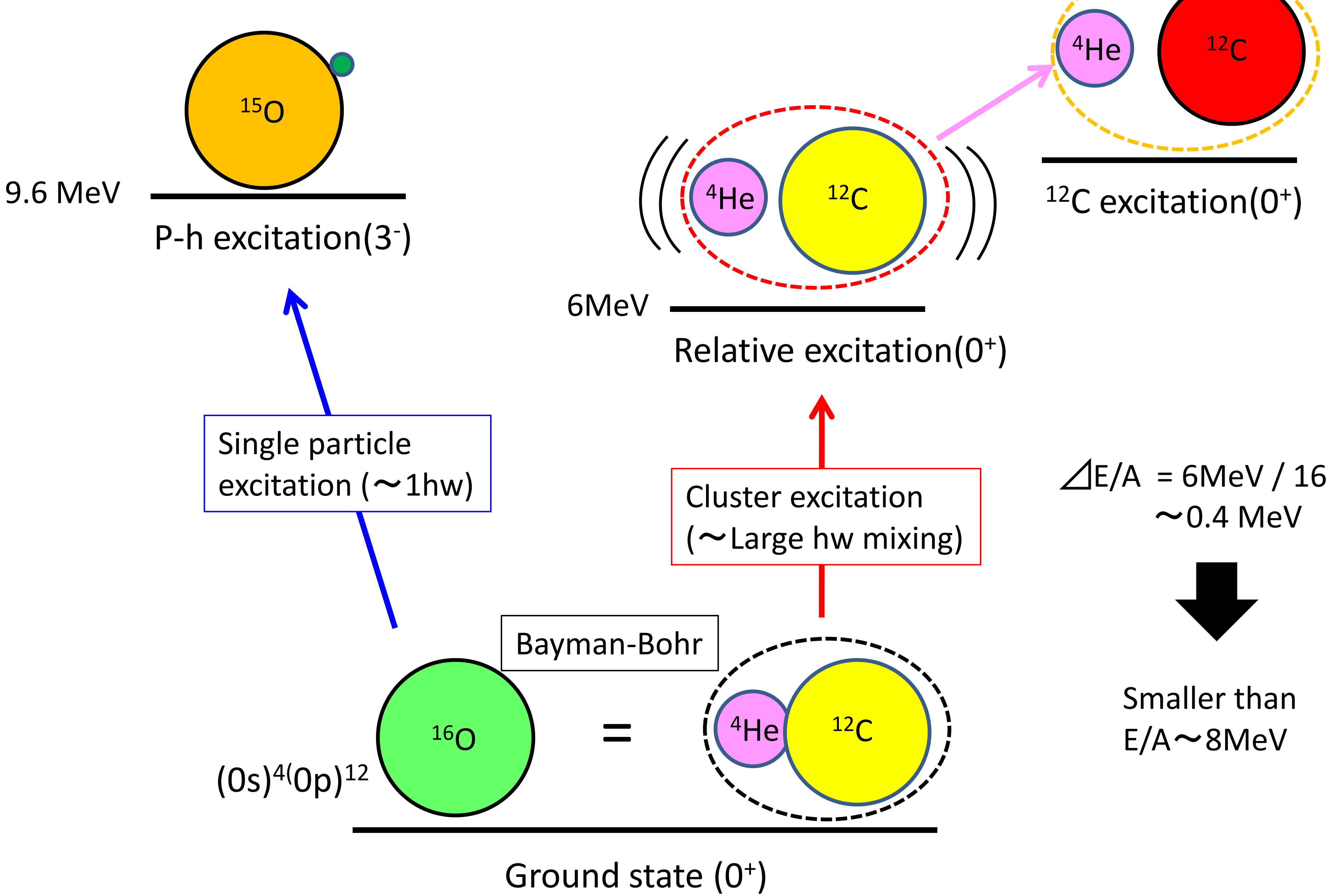
III. Application to the structure problem of ^{12}Be and Be isotopes

IV. Enhancement phenomena in neutron transfer reaction

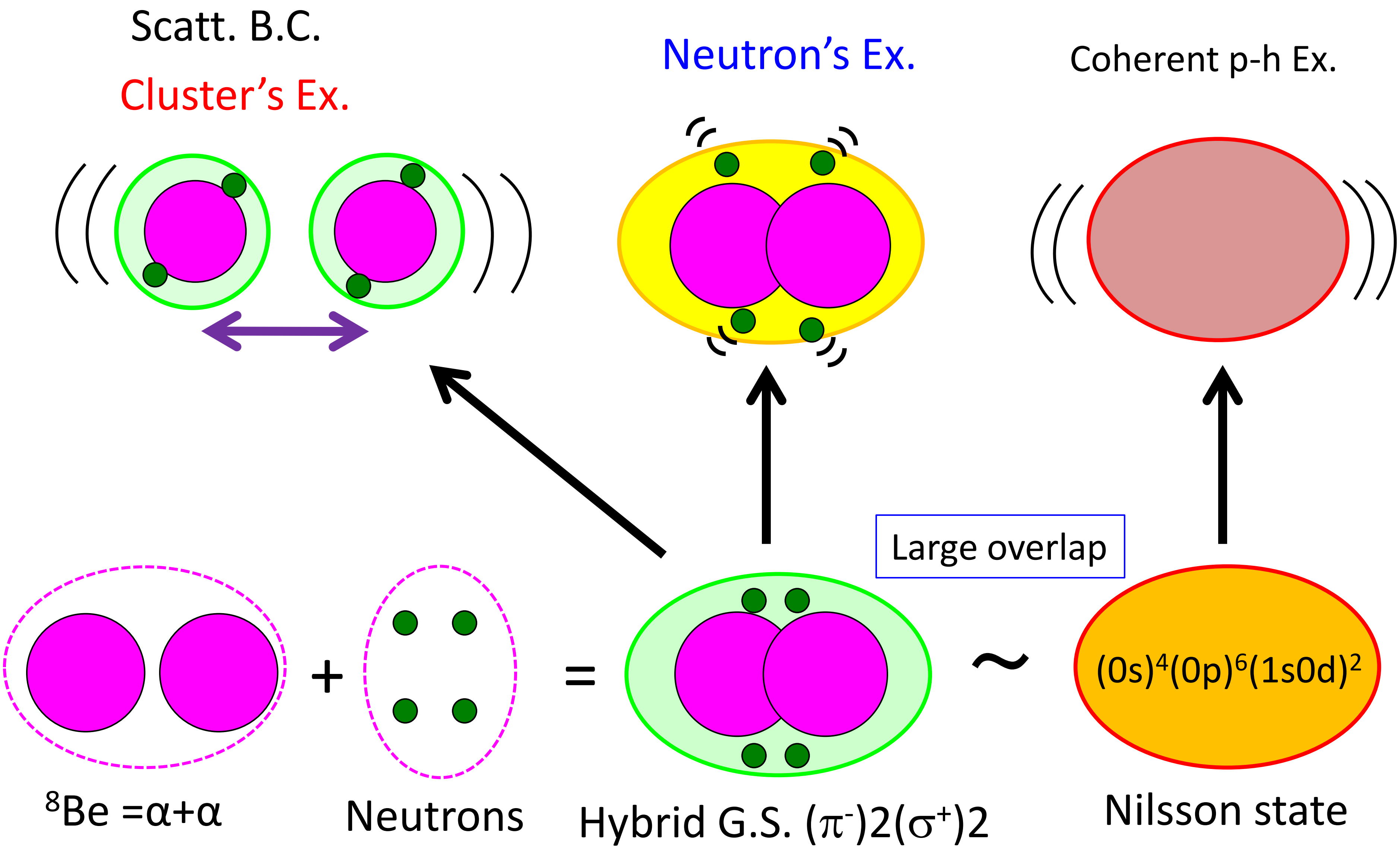
V. Summary and future studies

Supported by Prof. K. Ikeda (RIKEN)

^{16}O: Typical example of Duality: Shell model and Clusters



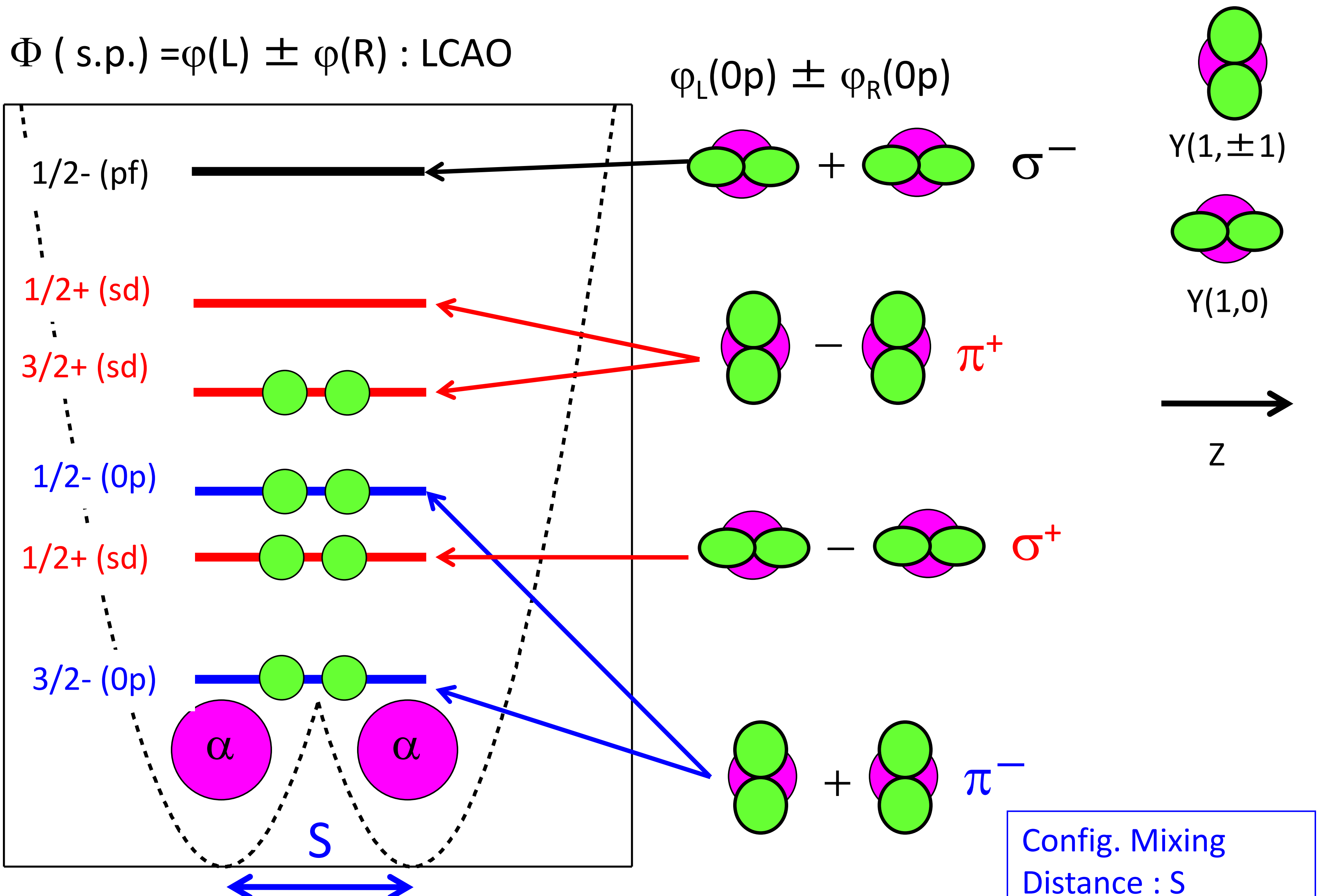
Present subject: Interest on Be isotopes (Example of ^{12}Be)



We can expect variety in the excitation modes of cluster and excess-neutrons.

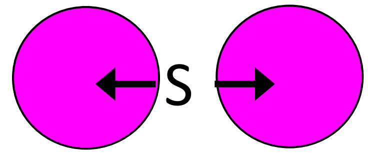
Formulation (I) : Single particle motion in two centers

Φ (s.p.) $=\varphi(L) \pm \varphi(R)$: LCAO



Config. Mixing
Distance : S

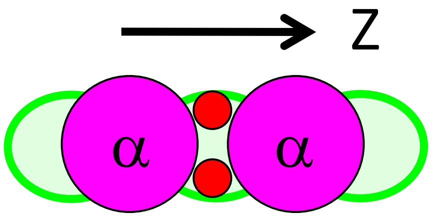
Formulation



Linear Combination of Atomic Orbital (LCAO)

NN int. Volkov No.2 +G3RS

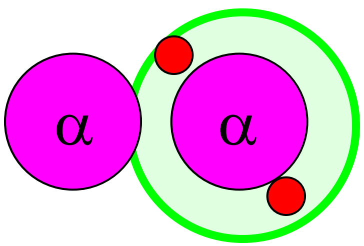
Central LS



$$(\sigma^{+})^2 = \left(P_z(L) - P_z(R) \right)^2$$

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

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



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

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

$^{12}Be(4N)$, $^{14}Be(6N)$, $^{16}Be(8N)$

Total wave function

$$\Psi = \sum_{\beta,S} \underline{C(\beta,S)}\, P_m(a) \cdot P_n(b) \qquad (m,n)=x,y,z \qquad (a,b) = L,R$$

Variational PRM

What is adiabatic energy surfaces ?

S : Distance PRM

α : Basis number

1. Full solutions

Atomic orbit basis

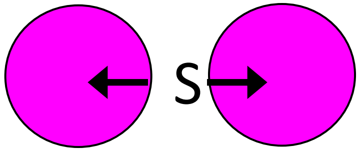
$$(H-E)\Psi_E = 0\,, \quad \Psi_E = \int dS \sum_{\alpha} C_{\alpha}^{E}(S)\, \boxed{\varphi_{\alpha}(S)}$$

2. Adiabatic solutions

Atomic orbit basis

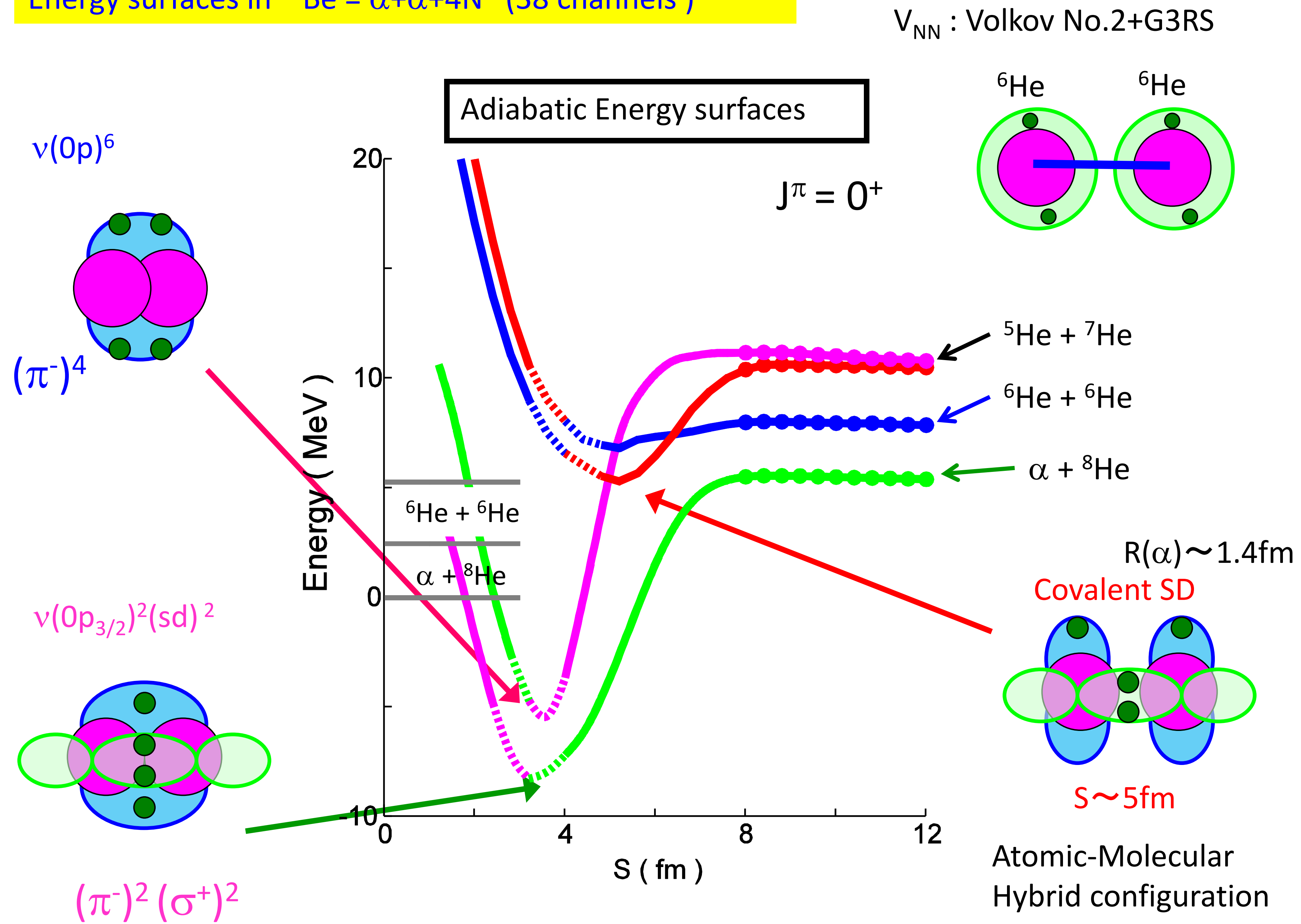
$$(H-E)\underline{\Phi_E^{adi}(S)} = 0\,, \quad \underline{\Phi_E^{adi}(S)} = \sum_{\alpha} D_{\alpha}^{E}(S)\, \boxed{\varphi_{\alpha}(S)}$$

$\underline{\Phi_E^{adi}(S)}$: Adiabatic state

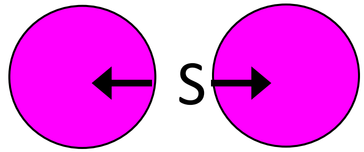


We can observe a smooth change from the covalent MO to the asymptotic channels as a function of the S parameter.

Energy surfaces in $^{12}Be = \alpha+\alpha+4N$ (38 channels)

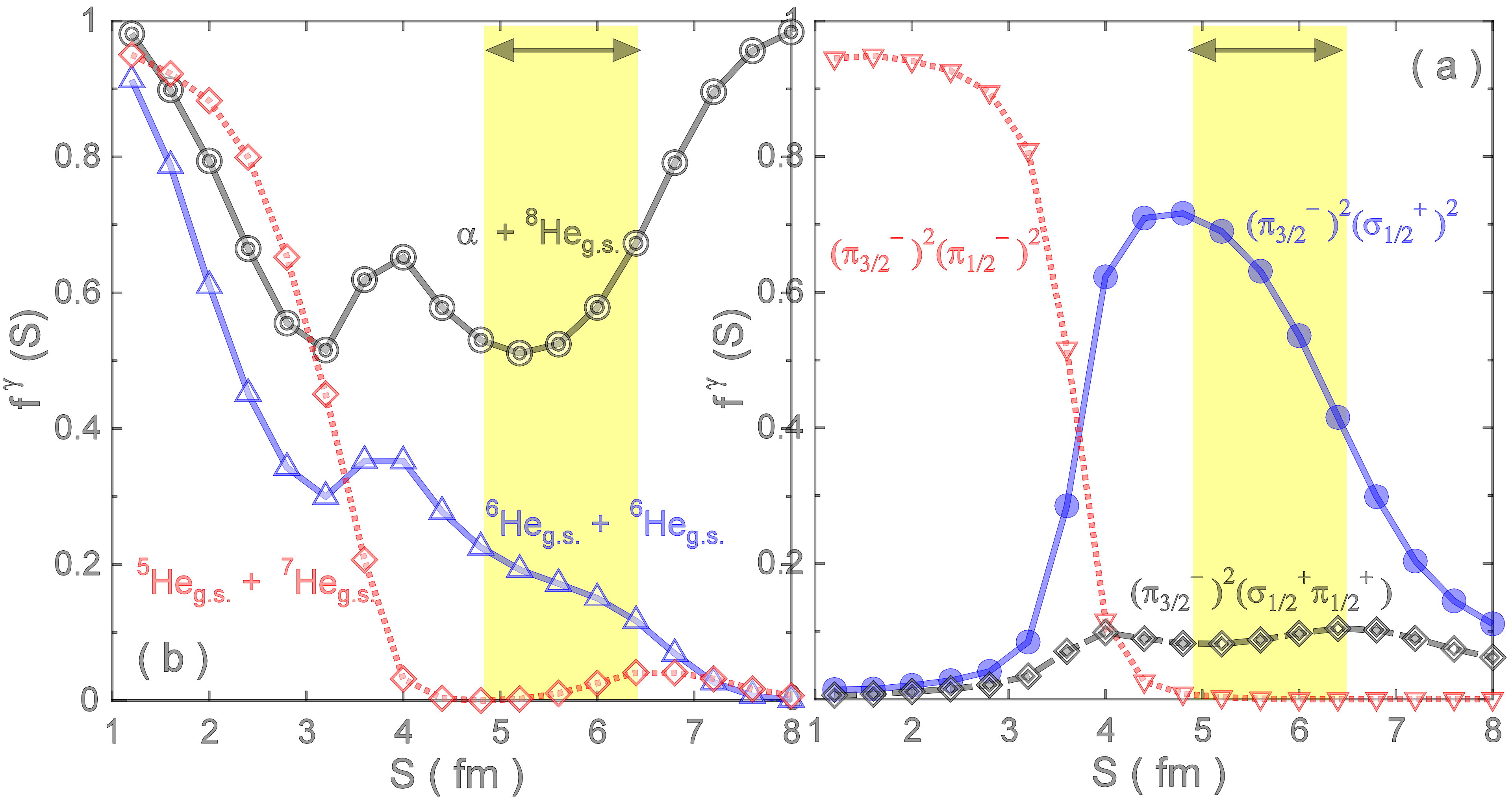


Structure of 1^{st} AES

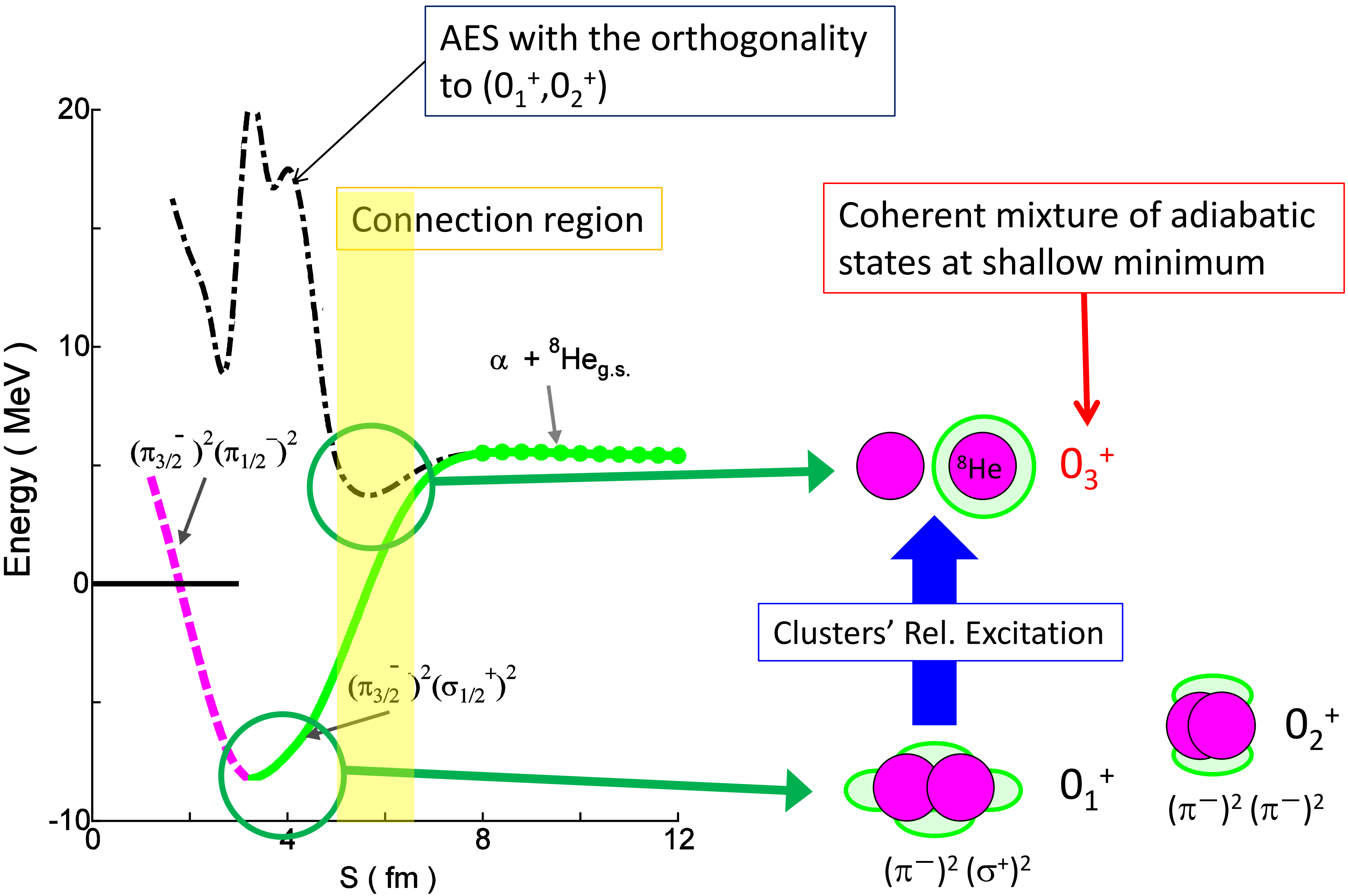


S=5〜6.5 fm: The adiabatic state has an intermediate character of MO and He-He clusters.

$$f(S) = \left|\left\langle Cluster \,|\, \Phi_E^{adi}(S) \right\rangle\right|^2 \qquad f(S) = \left|\left\langle Mol.Orb. \,|\, \Phi_E^{adi}(S) \right\rangle\right|^2$$

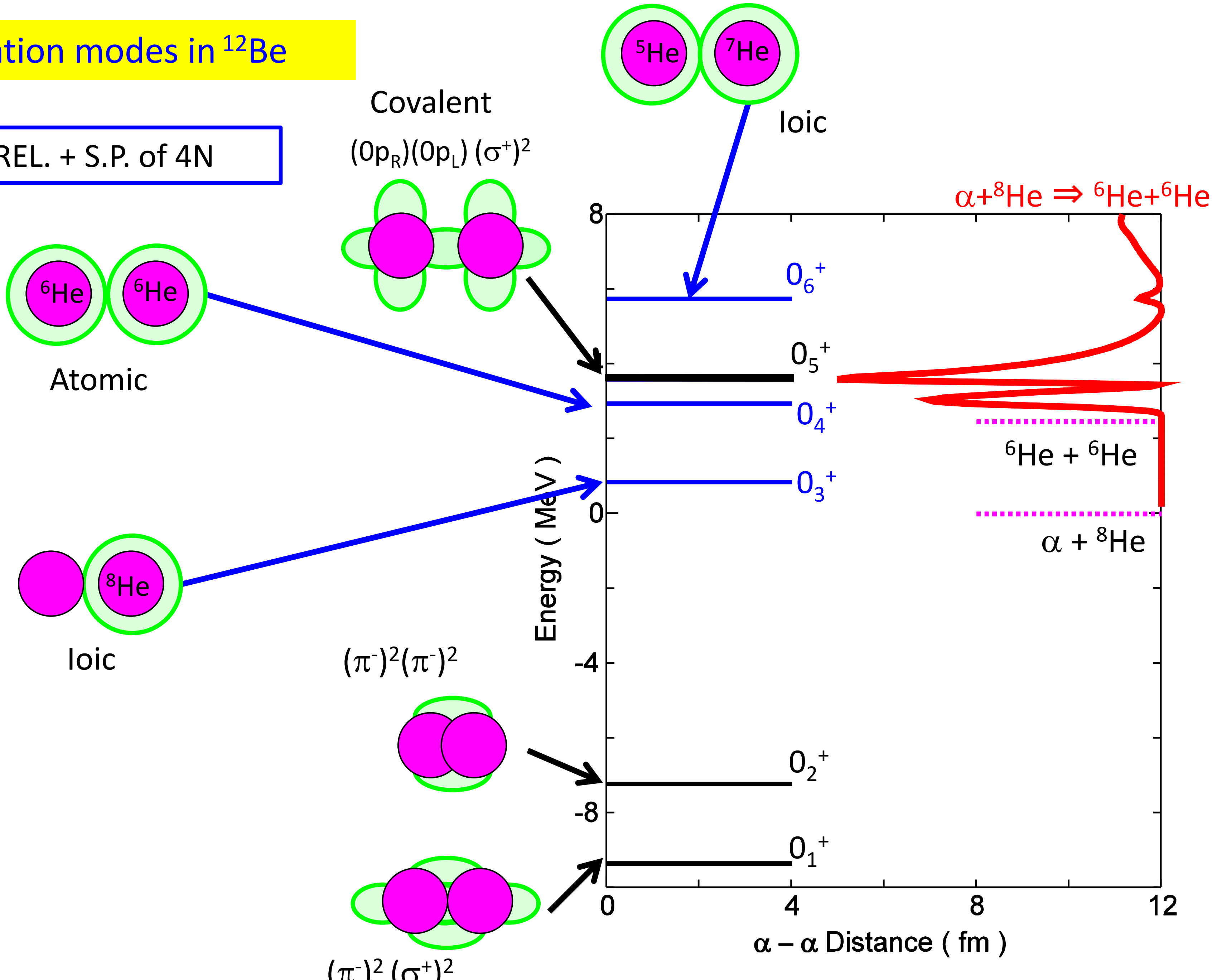


Cluster formation due to the orthgonality effect

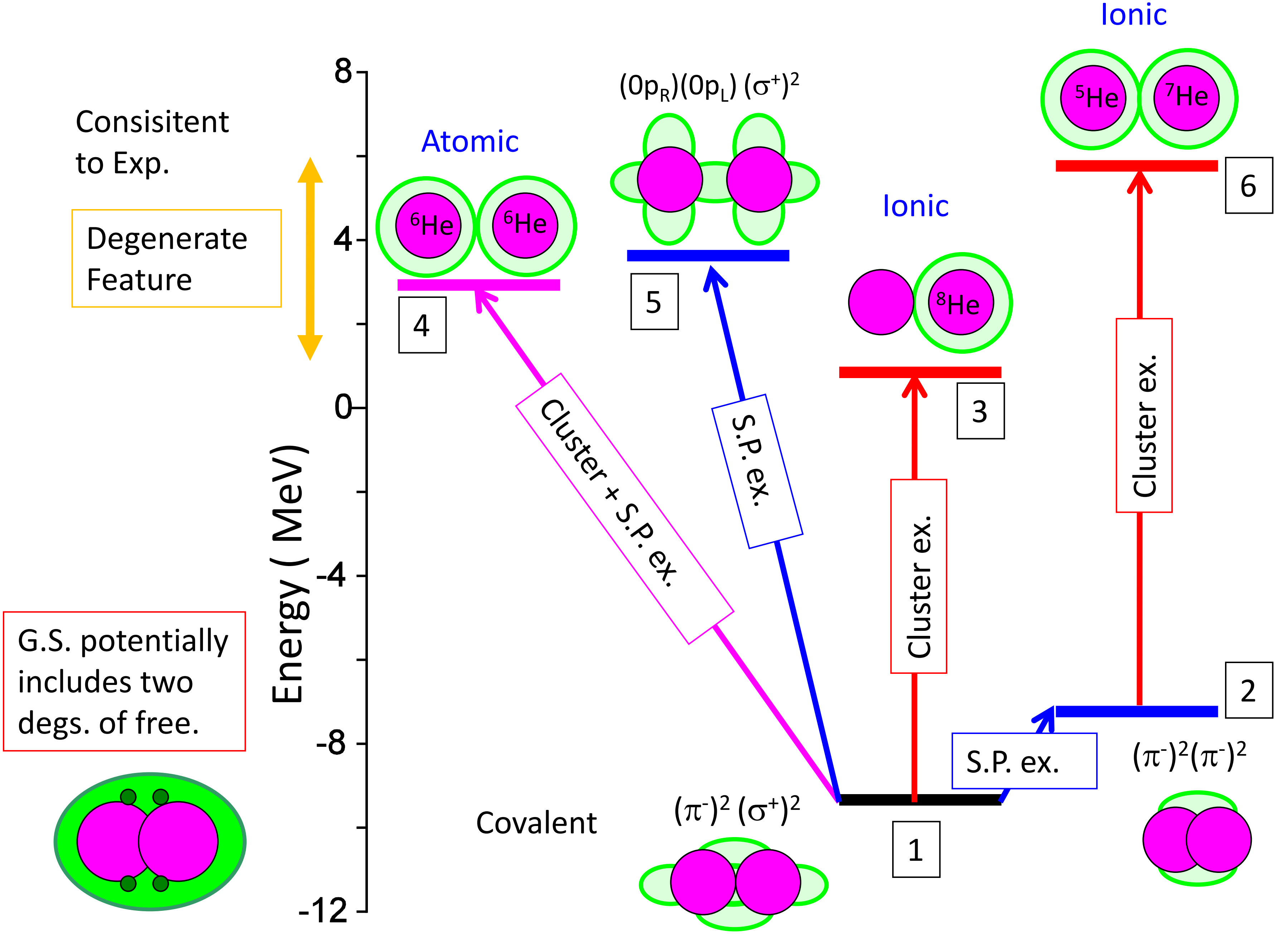


Excitation modes in ^{12}Be

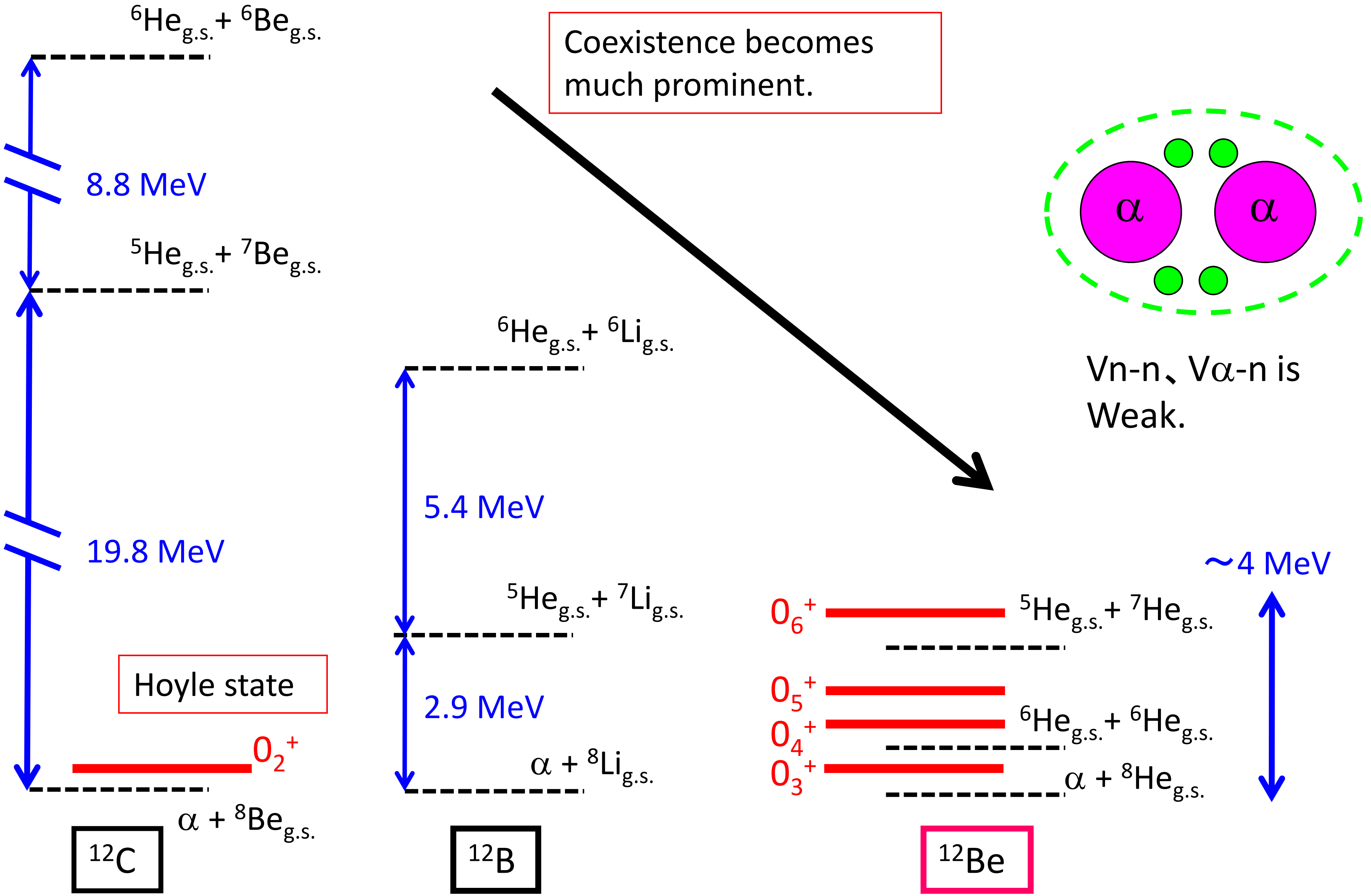
α-α REL. + S.P. of 4N



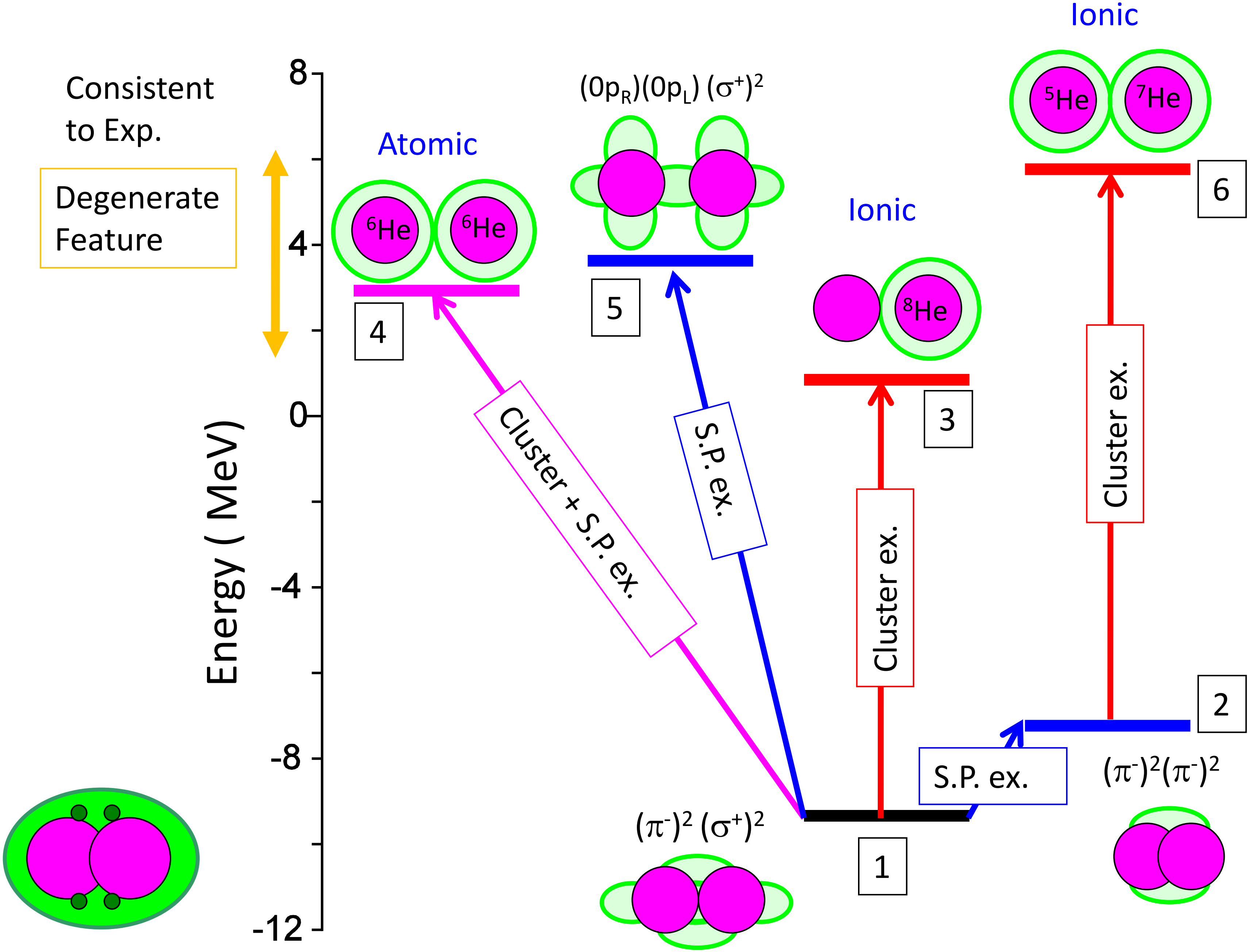
Femto-Molecules : $^{12}Be=\alpha+\alpha+4N$ $J^{\pi}=0^{+}$



Coexistence phenomenon in A=12 systems (Threshold rule)



Femto-Molecules : $^{12}Be=\alpha+\alpha+4N\ J^{\pi}=0^{+}$



Monopole strength of ^{12}Be：Ratio to S.P. strength

Simple shell model is difficult to explain M(IS) strength below E～20 MeV !

$$M(IS) = \left\langle 0_f^+ \left| \sum_{i=1}^{12} r_i^2 \right| 0_1^+ \right\rangle$$

$$M^{\mathrm{s.p.}} = \langle 1p, b | r^2 | 0p, b \rangle = 2b^2 \sqrt{\frac{5}{8}}.$$

T. Yamada et al., PTP.120, 1139 (2008)

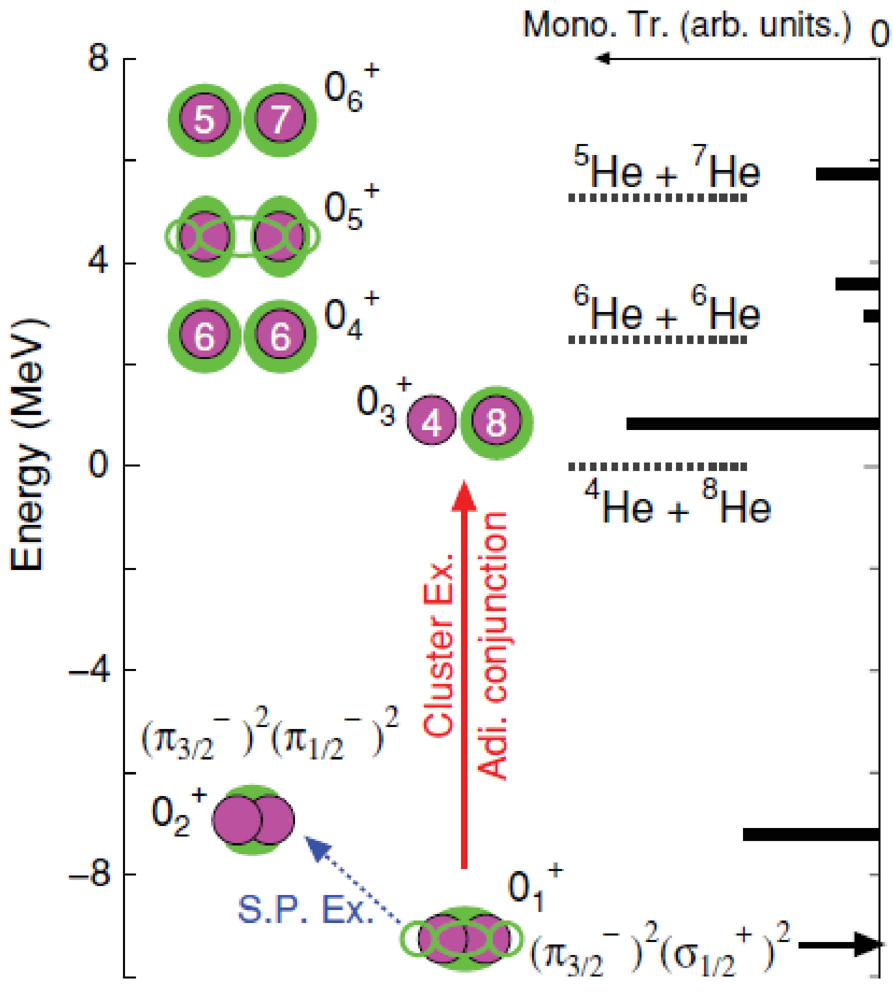
State	Ex. Energy (MeV)	$\lvert M(IS)/M^{s.p.} \rvert$
0_2^+	2.12	2.59
0_3^+	10.19	3.53
0_4^+	12.29	0.92
0_5^+	12.94	1.48
0_6^+	15.09	1.76

All the excited states have a comparable to or a few times larger strength in comparison to the S.P. strength.

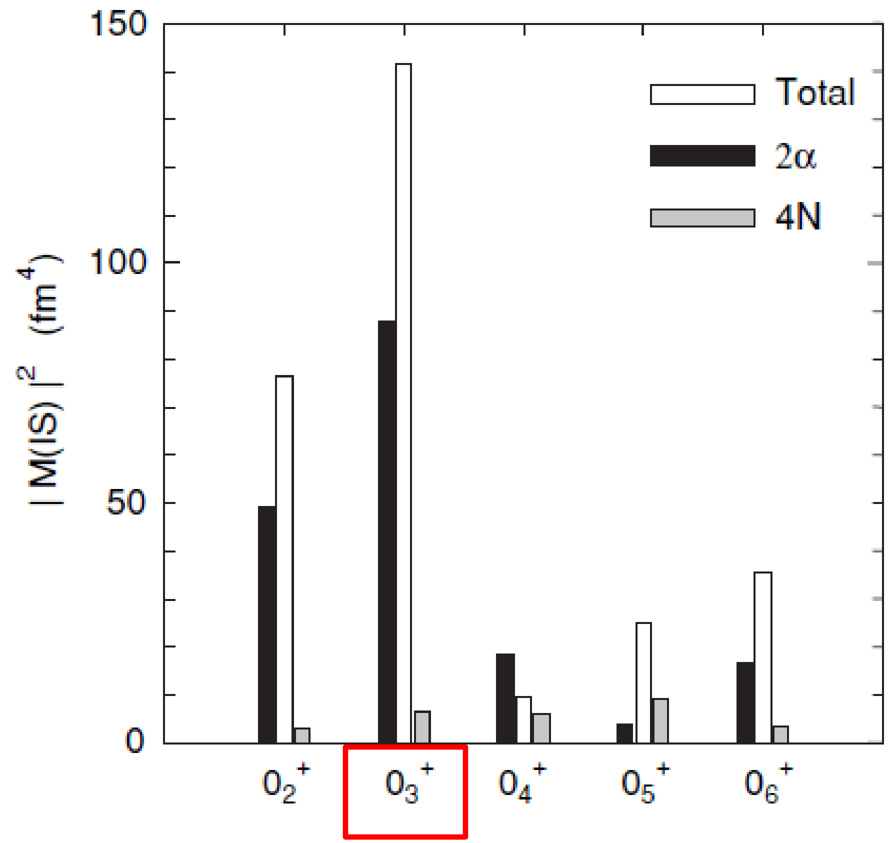
^{12}Be : Monopole transition

$$M(IS) = \left\langle 0_f^+ \left| \sum_{i=1}^{12} r_i^2 \right| 0_1^+ \right\rangle$$

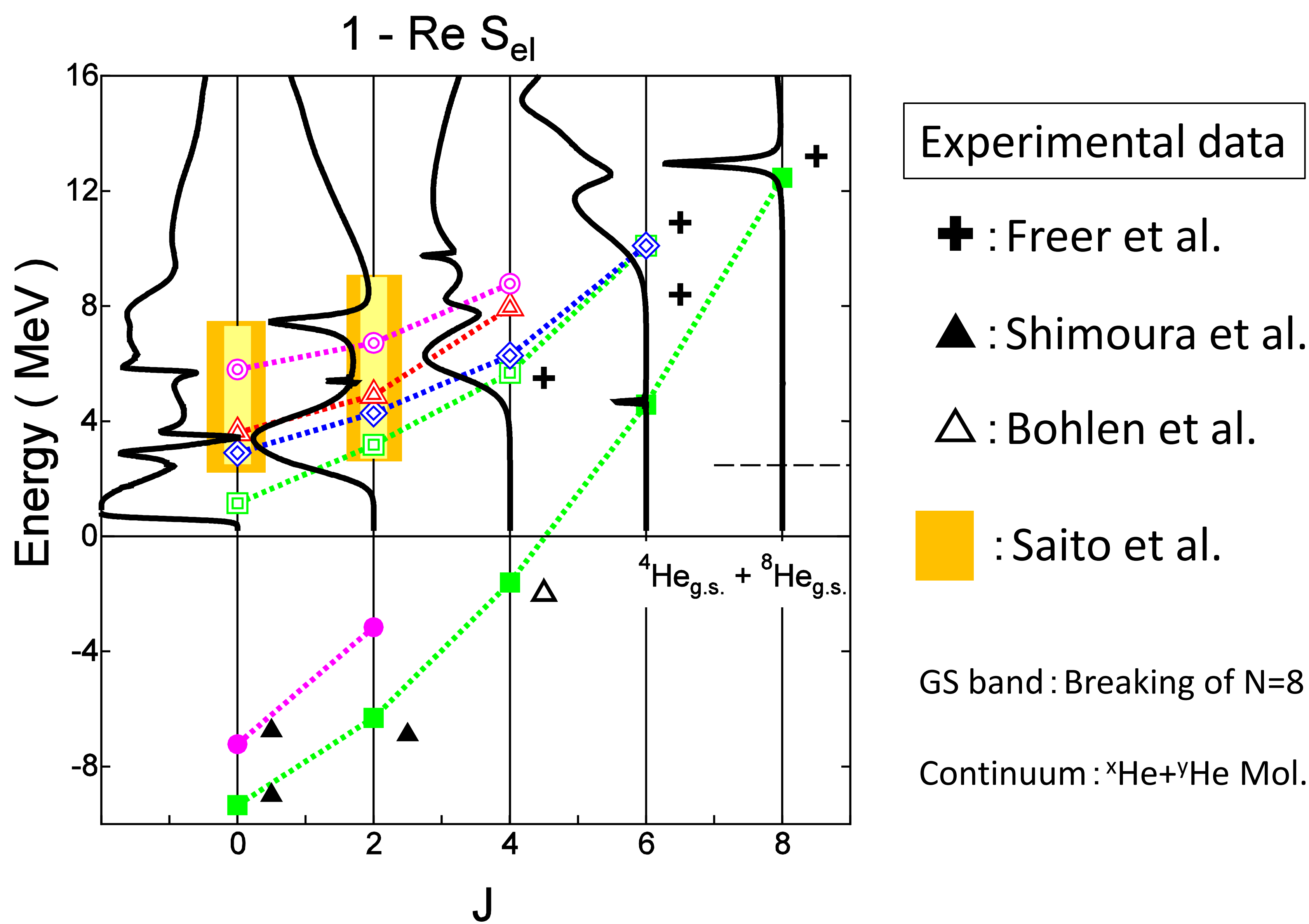
Monopole distribution



Contribution form α－α part



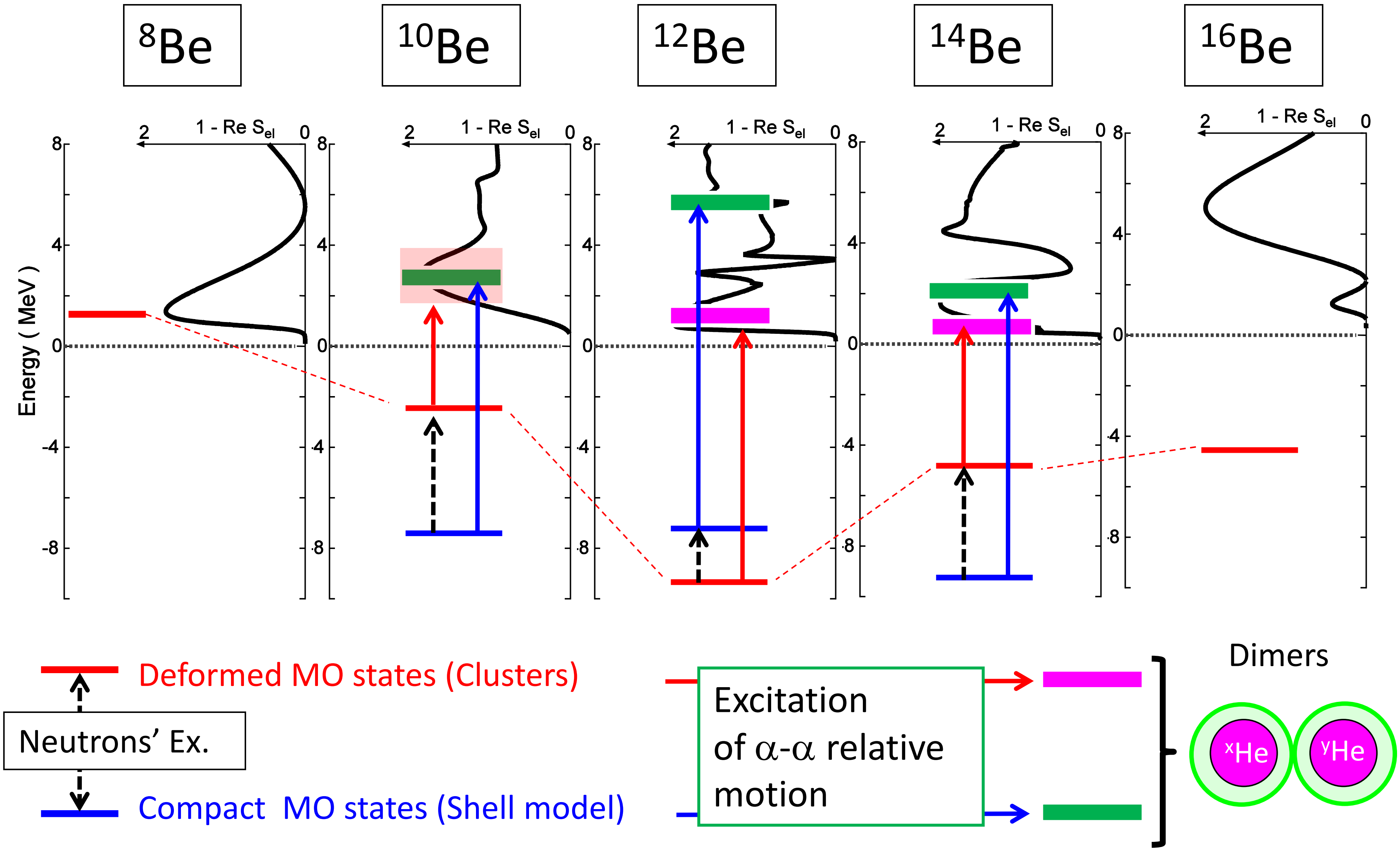
Rotational Bands : $^{12}Be=\alpha+\alpha+4N$



GS band : Breaking of N=8

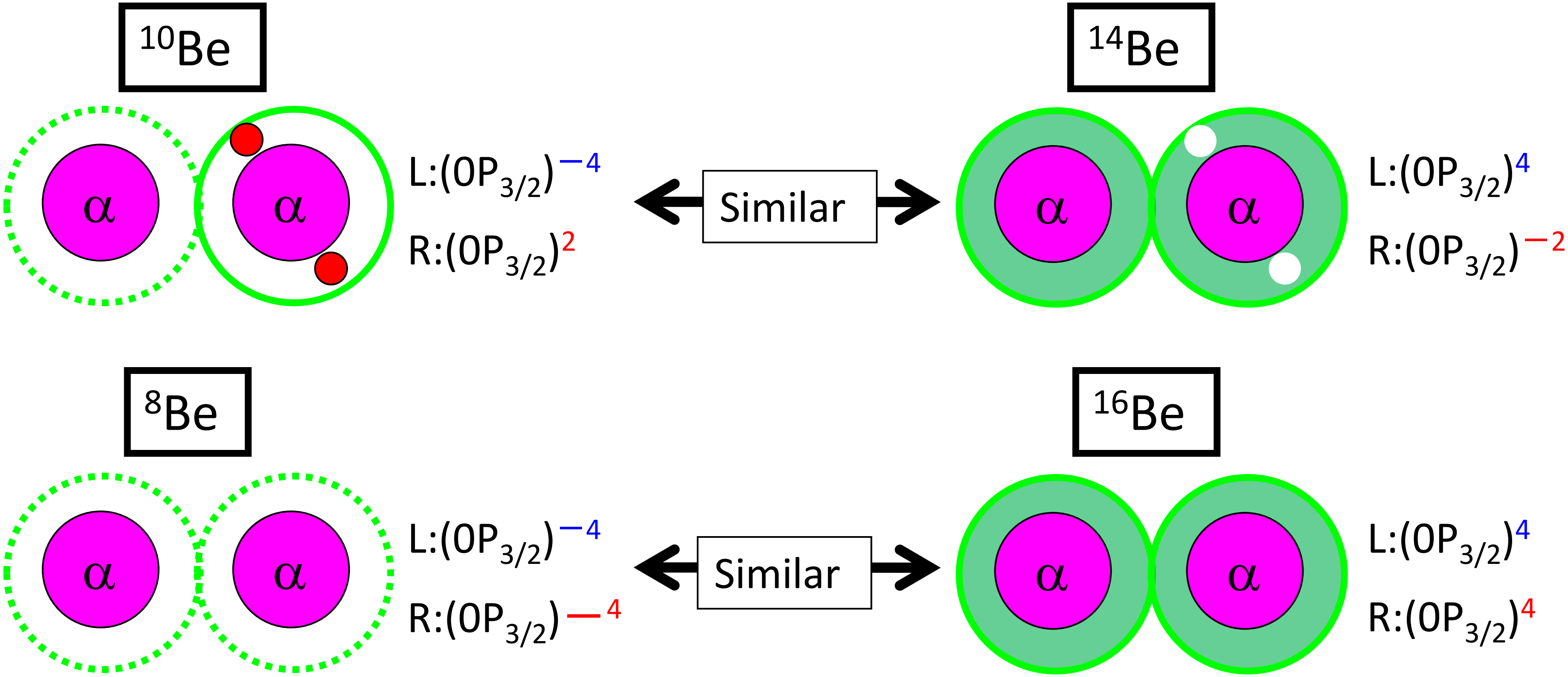
Continuum : $^{x}He+^{y}He$ Mol. Res.

Be isotopes from bounds to continuum : $J^{\pi} = 0^{+}$



Two degrees of cluster + neutrons prominently appears in Be isotopes.

Systematics based on the Cluster Picture



We are now analyzing wave functions.

Special feature in ^{12}Be

^{12}Be=^{6}He+^{6}He, α+^{8}He is a self conjugate when atomic p-h are exchanged.

⇒ This is a special nucleus in even Be isotopes

Cluster effects in reactions

1. Molecular Resonances (MRs) are typical examples : $^{12}C+^{12}C$, $^{16}O+^{16}O$, $^{12}C+^{16}O$

   ⇒ Collective excitation of individual nuclei is essential.

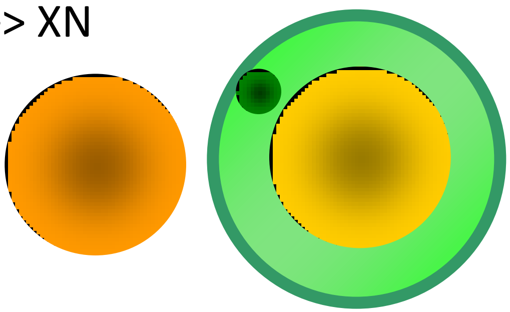
An additional neutron ↓

2. MR system + one valence neutron : $^{12}C+^{13}C$, $^{16}O+^{17}O$, etc…

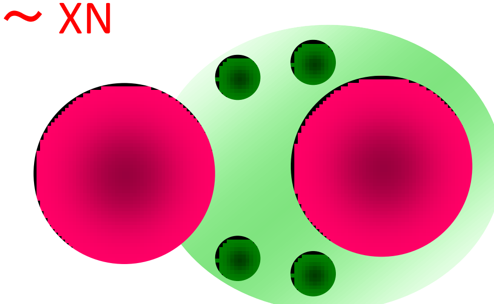
   Transfer process is extensively investigated ⇒ NO clear resonances !!

Transfer effect in neutron-rich systems

Previous studies ($^{12}C+^{13}C$ etc)	Neutrons' drip-line case
A (Cores) >> XN	A (Cores) ∼ XN
N∼Z	N >> Z



Val. N : tight binding



Val. N : weak binding

Transfers of a valence neutron
→ No sharp resonances

Transfer of "active" neutrons
→ Sharp resonances are generated ?

Coupling to open channels in continuum

Closed states method : Prof. Kamimura, Prog. Part. Nucl. Phys. 51 (2003)

Open channels — Compound states (Closed)

$$\Psi^{(+)} = \sum_{\beta} \varphi_{\beta} \chi^{(+)}_{\beta,\alpha} + \sum_{\nu} b_{\nu} \Omega^{K=0}_{\nu}$$

Scattering B.C.

Bound state approximation
with Atomic Orbital Basis

$$(H - E_{\nu}) \Omega^{K=0}_{\nu} = 0$$

400～500 S.D. with J^{π} projection

$$\chi^{(+)}_{\beta,\alpha} \xrightarrow[R_{\beta}=\infty]{} u^{(-)}_{L_{\beta}} \delta_{\beta,\alpha} - S_{\beta,\alpha} u^{(+)}_{L_{\beta}}$$

Rearrangement channels : α + $^{8}He_{g.s.}$、 $^{6}He_{g.s.}$ + $^{6}He_{g.s.}$、 $^{5}He_{g.s.}$ + $^{7}He_{g.s.}$

Future perspectives : Combination of MF models, AMD and scattering

Open channels   Compound states (Closed)

$$\Psi_c^{(+)} = \sum_\beta \mathrm{A}\left\{\varphi_\beta \chi_{\beta,c}^{(+)}\right\} + \sum_\nu b_\nu \Omega_\nu^{K=0}$$

$$(H-E)\Psi^{(+)} = 0$$

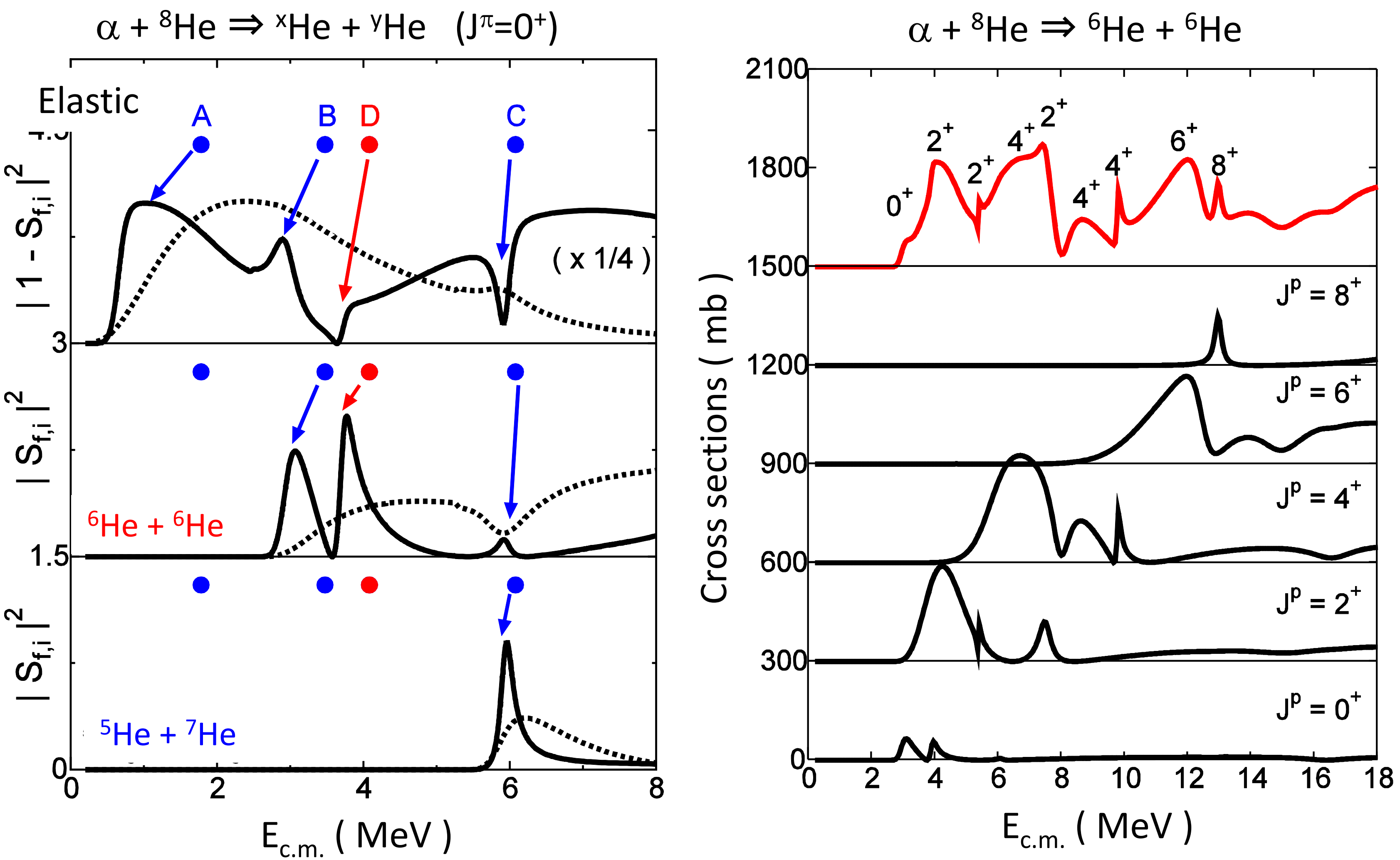
$$\left\langle \Omega_\nu^{K=0} \left| H \right| \Omega_{\nu'}^{K=0} \right\rangle = \varepsilon_\nu \delta_{\nu,\nu'}$$

$$\chi_{\beta c}^{(+)}(R_\gamma) = \sum_{i=0}^{n} C_{\beta i}^{(c)} u_{\beta i}(R_\beta)$$

$$b_\nu = \frac{-1}{\varepsilon_\nu - E}\left\langle \Omega_\nu^{K=0} \left| (H-E) \right| \sum_\beta \mathrm{A}\left\{\varphi_\beta \chi_{\beta,c}^{(+)}\right\} \right\rangle$$

$$= \frac{-1}{\varepsilon_\nu - E}\sum_{\beta,i} C_{\beta i}^{(c)} \left\langle \Omega_\nu^{K=0} \left| (H-E) \right| \mathrm{A}\left\{\varphi_\beta u_{\beta,i}(R_\beta)\omega(x_G)\right\} \right\rangle$$

Cross sections of neutron transfers



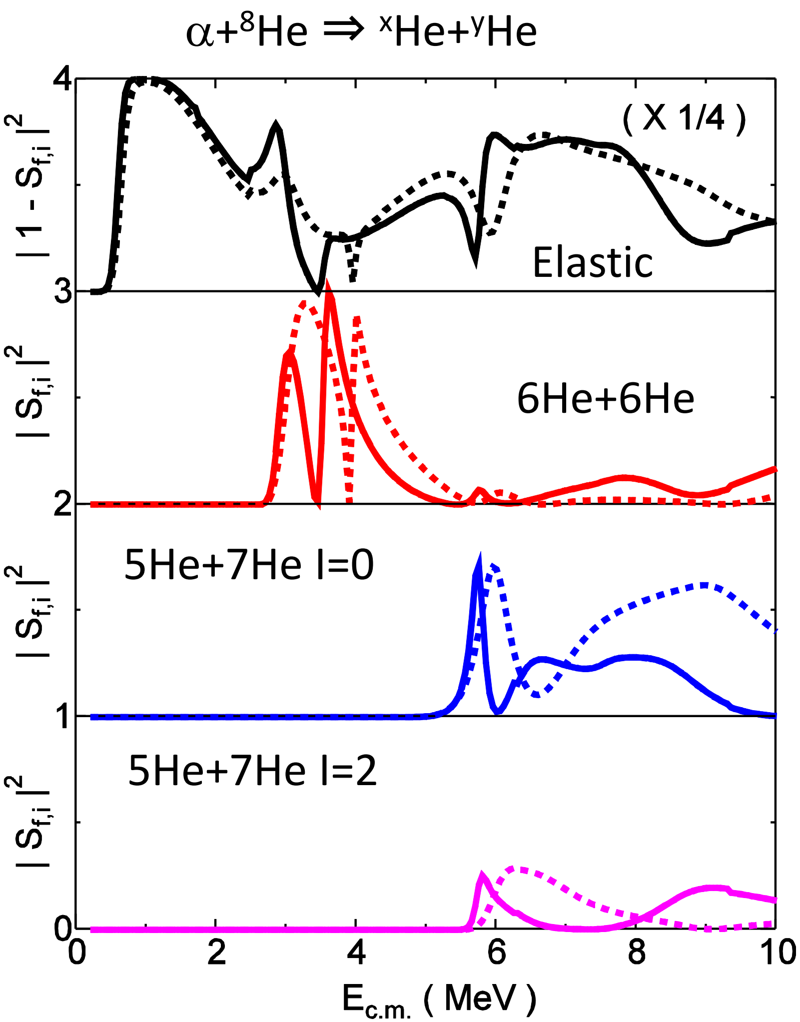
Dotted curves : Three open channels only

Solid curves: Open + closed chanels

This is a prediction for recent experiments at GANIL.

Effects of the transfer coupling : Minimum coupling

Solid : Full calculation



Dotted curves

$\alpha + {}^8He_{g.s.}$

$\alpha + {}^8He(2_1^+)$

${}^5He(3/2^-) + {}^7He(3/2_1^-)$

${}^5He(3/2^-) + {}^7He(1/2_1^-)$

${}^5He(3/2^-) + {}^7He(5/2_1^-)$

${}^5He(1/2^-) + {}^7He(3/2_1^-)$

${}^6He_{g.s.} + {}^6He_{g.s.}$

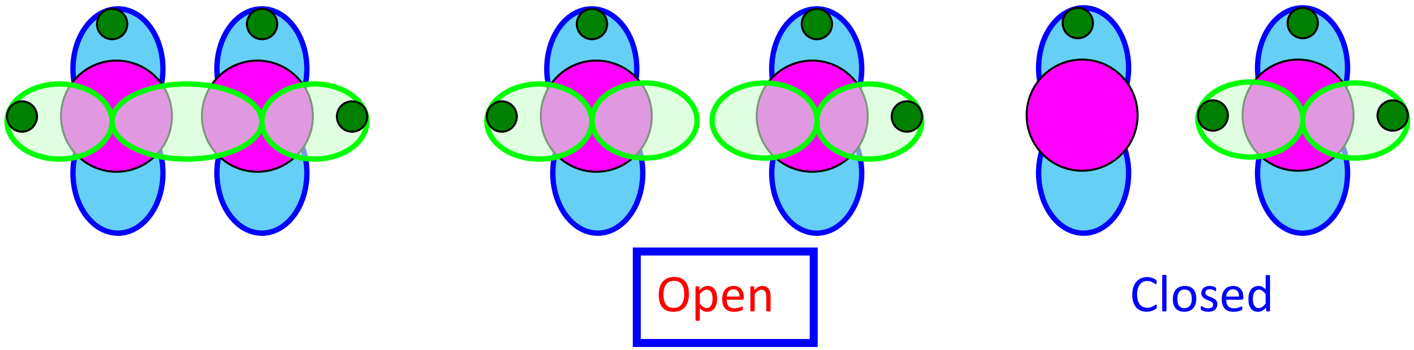
${}^6He_{g.s.} + {}^6He(2_1^+)$

${}^6He(2_1^+) + {}^6He(2_1^+)$

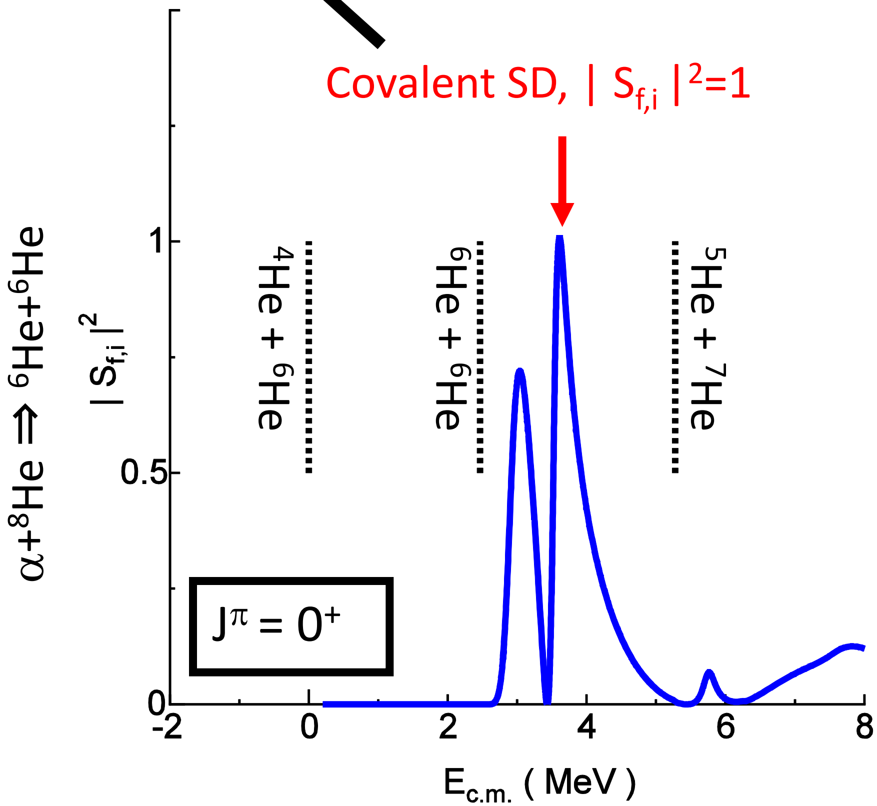
Sharp resonant structures are generated by Transfer Coupling → New aspects !!

Enhancement of the two neutron transfer

$$\left|\Phi(Cov.SD)\right\rangle = \left|\chi(^{6}He+^{6}He)\right\rangle + \left|\varphi(^{5}He+^{7}He)\right\rangle$$



Strong decay into $^{6}He+^{6}He$



S-matrix reaches almost unity.

$$\left|S\left(^{6}He+^{6}He \leftarrow \alpha+^{8}He\right)\right|^{2} \approx 1$$

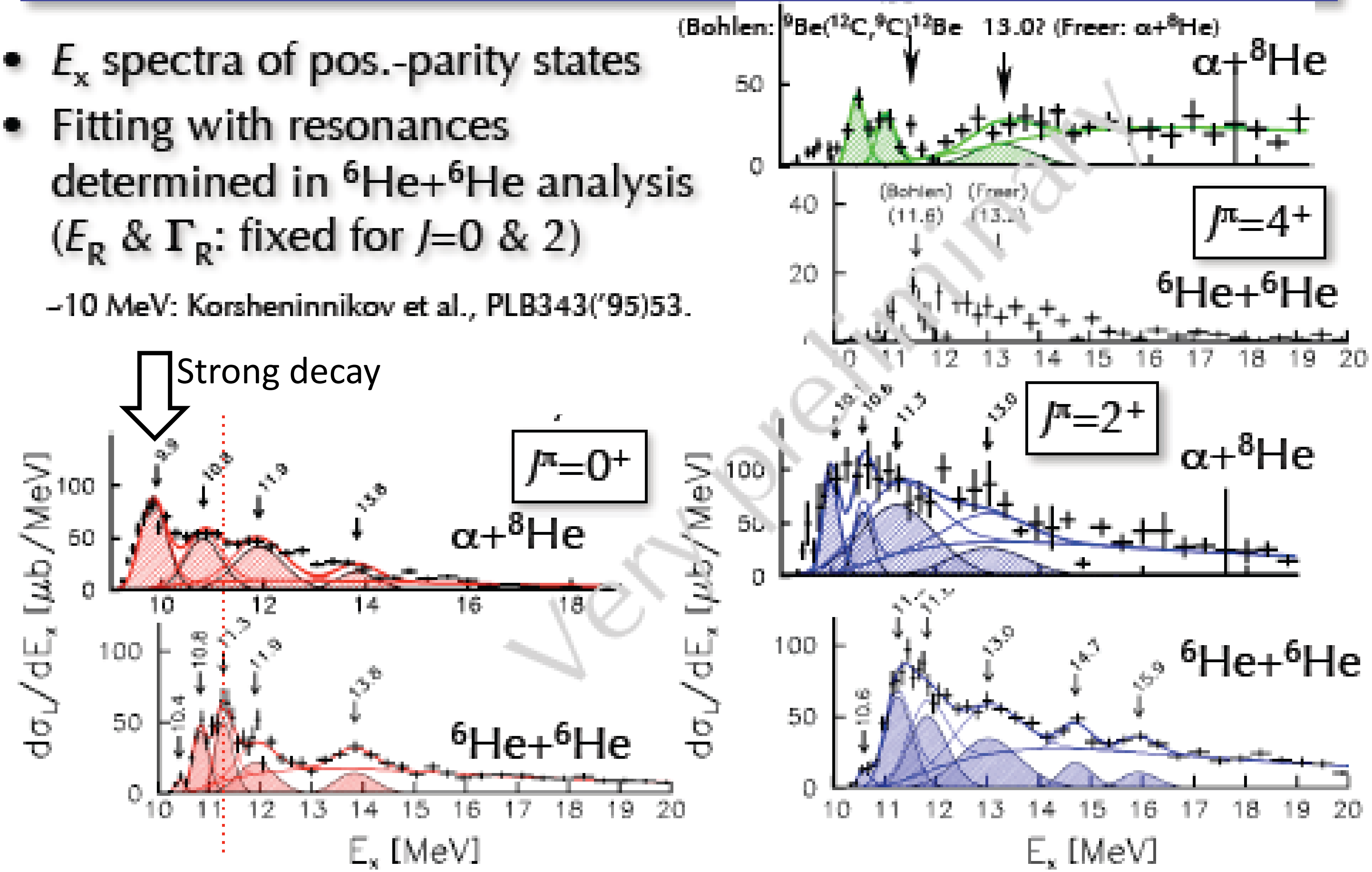
Large part of the flux flows to $^{6}He+^{6}He$.

Consistent to Exp. of ^{12}Be breakup
By S. Shimoura et al.

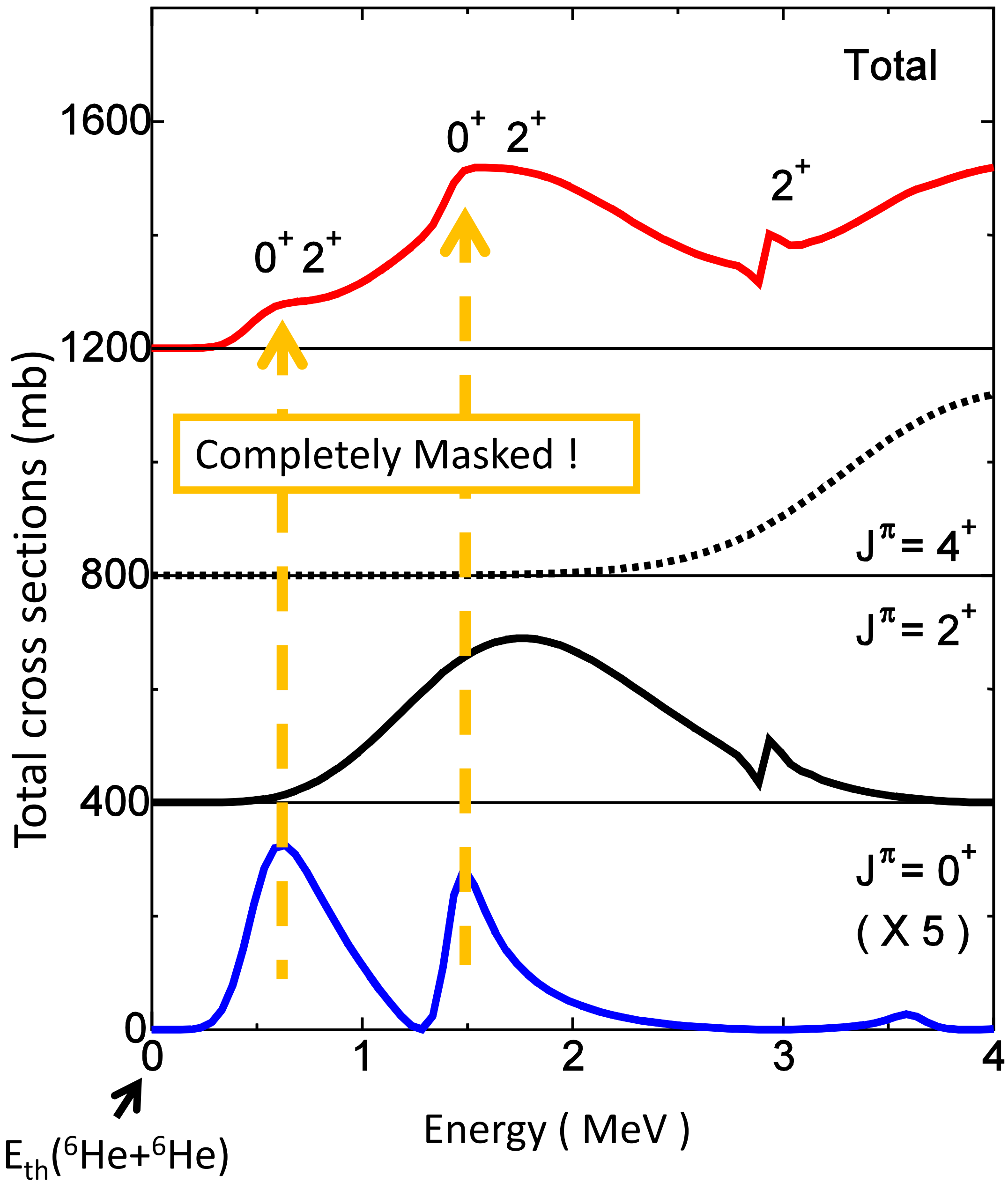
E_x spectra of ^{12}Be(α,α')^{4}He^{8}He (positive parities)

- E_x spectra of pos.-parity states
- Fitting with resonances determined in ^{6}He+^{6}He analysis (E_R & Γ_R: fixed for J=0 & 2)

–10 MeV: Korsheninnikov et al., PLB343('95)53.



Extraction of the $J^{\pi}=0^{+}$ strength in $\alpha+{}^{8}He \Rightarrow {}^{6}He+{}^{6}He$



Precise measurements of scattering will be available !

$$\sigma(E) = \frac{\pi}{k^2} \sum_{J=even} (2J+1) \left| S^{J}_{f,i}(E) \right|^2$$

The $J^{\pi}=0^{+}$ strength is quite small .

(Due to a factor of 2J+1)

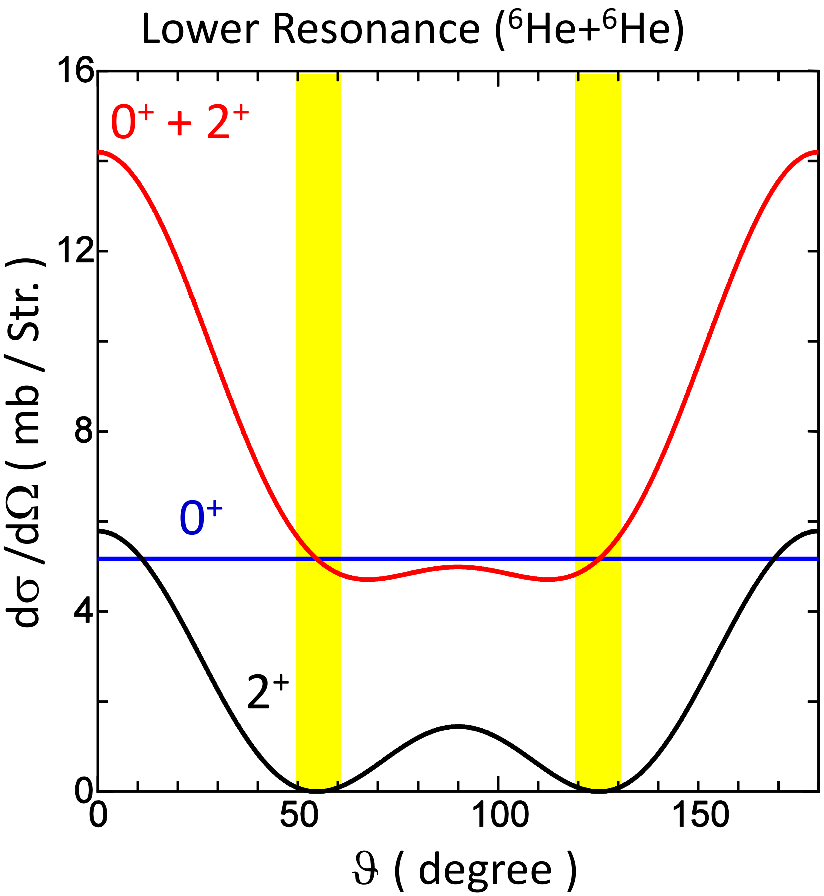
$J^{\pi}=2^{+}$ strength is dominant.

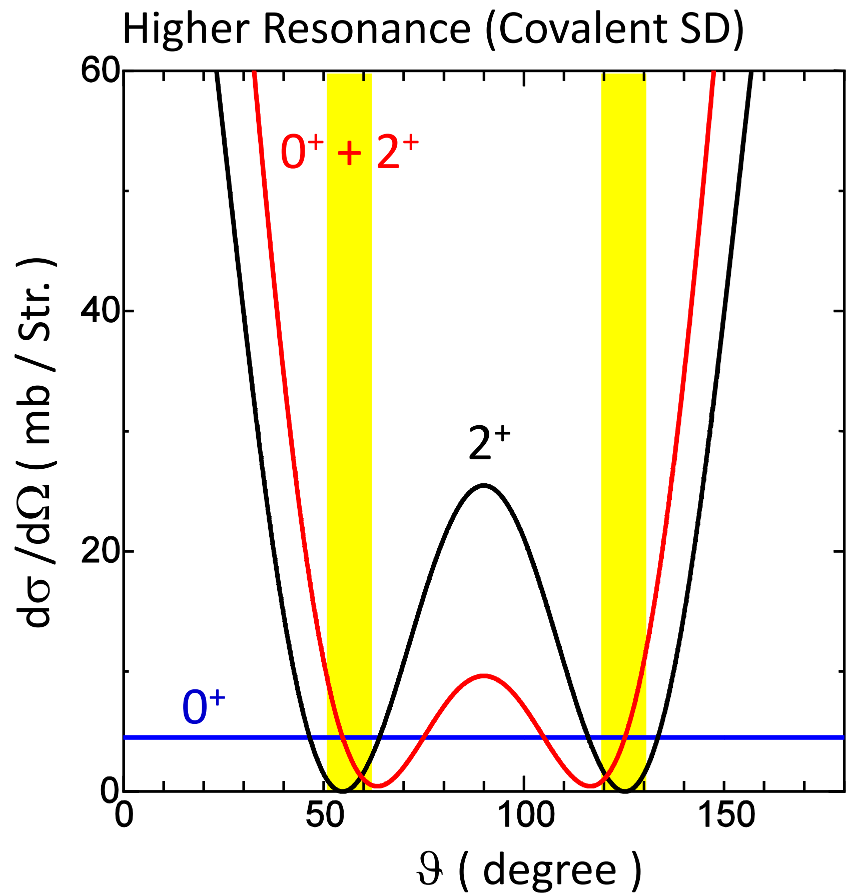
(4^{+} strength is negligible.)

We should extract the 0^{+} contribution from the total strength.

Angular distributions for the resonances of $\alpha+{}^{8}He \Rightarrow {}^{6}He+{}^{6}He$

$$\frac{d\sigma}{d\Omega} = \frac{1}{4k^2}\left|\sum_{J=0,2}(2J+1)\,S_{f,i}(J,E)\,P_J(\cos\vartheta)\right|^2$$ For Spinless channels



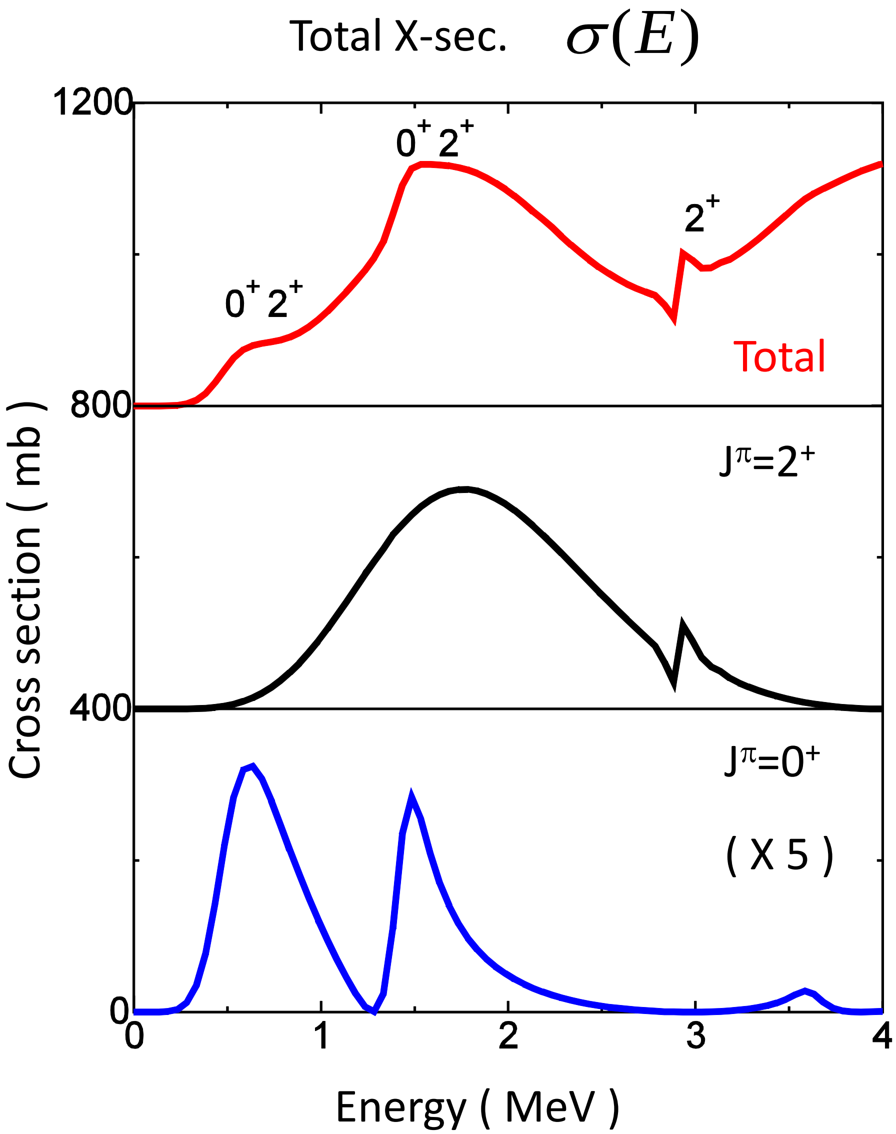


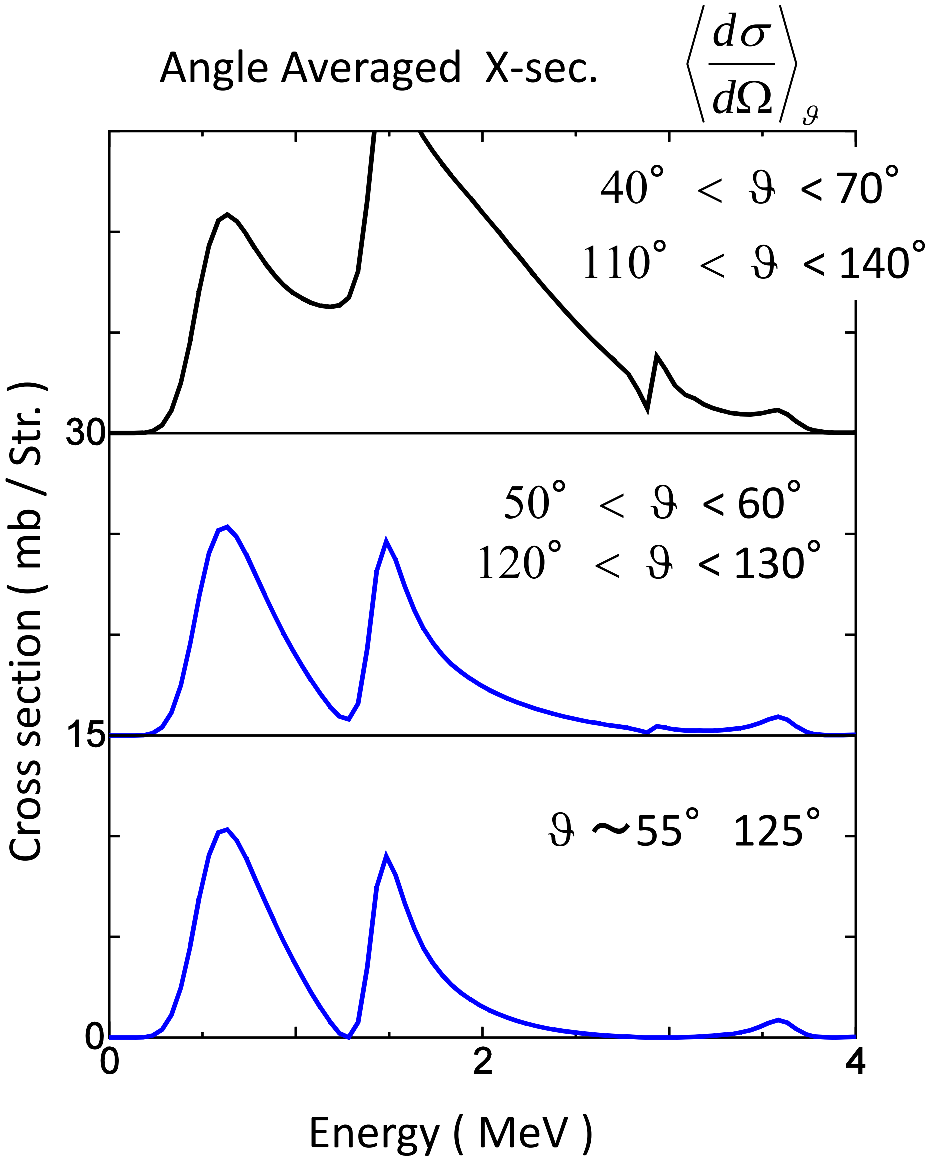
Gate of angular range :

1. $\vartheta \sim$ 55 and 125 (degree) $\Rightarrow$ P(J=2)=0

2. $50 < \vartheta < 60$, $120 < \vartheta < 130$ (degree)

Gating of angular distribution of $\alpha+{}^{8}He \Rightarrow {}^{6}He+{}^{6}He$





The angle averaged cross section nicely reproduces the 0+ contribution !!

Present studies

PRL100 (08), PRC78(R) (08), PR Focus 22(08), PRC83(11), PRC84(11)

Systematic studies of Be isotopes from bounds to continuum

Results of the studies

1. Nuclear structure of ^{12}Be and Be isotopes
   - ⇒ Due to the hybrid configuration, there appears a wide variety in the excited states
   - ⇒ Clusters' and neutrons' degrees of freedom coexist in a ground state
2. Transfer reaction in α+^{8}He slow scattering
   - ⇒ Resonance enhancements are generated in the neutron transfer process.
   - ⇒ Decay scheme has a close connection to the intrinsic structure

To obtain an essential picture of nuclei, it is very important to investigate structure changes over a wide energy, including the scattering states.

Feature studies

Duality will appear systematically in other light neutron excess system.

Systematic study⇒ O=α+^{12}C+XN、Ne=α+^{16}O+XN

Cluster Limit in Shell model wave function

$u_n(x)$: Harmonic Oscillator in 1 dim.

$$u_0(x) = \left(\frac{2\nu}{\pi}\right)^{1/4} e^{-\nu x^2}$$

$$u_0(x-S) = \sum_{n=0}^{\infty} C(n)\ u_n(x)$$

$$\left|C(n)\right|^2 = \left(\nu S^2\right)^n \frac{1}{n!} e^{-\nu S^2}$$

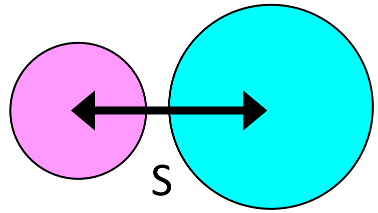
Poisson Distribution

$$\langle n \rangle = \nu S^2 \qquad \Delta n = \sqrt{\nu S^2}$$

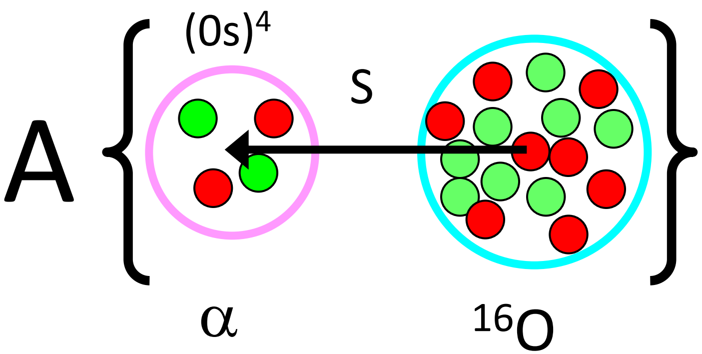
S⇒∞ (Development of cluster) ⇒ Mixing of higher quanta

Cluster limit of ^{20}Ne=α+^{16}O

Limit of S → Large in the α+^{16}O system



Strong configuration mixing measured from a center of ^{16}O



S ∼ 5.1 fm (Contact distance)

ν ∼ 0.24 fm^{-2} (Standard value)

Quanta for single nucleon: n

$$\langle n \rangle = \nu S^2 \approx 6 \qquad \Delta n = \sqrt{\langle n \rangle} \approx 2.4$$

Quanta for 4 nucleons (α-particle): N

$$\langle N \rangle = 4\langle n \rangle \approx 24$$

$$\Delta N = \sqrt{4\langle n \rangle} \approx 5$$

→ If S∼7 fm, N∼50 !

Aalpha particle is loosely coupled !

c.f. : No core shell model (N<10) for A < 16

Original Fermi-surface becomes meaningless.

数値計算の本質的に新しい点

二中心系の構造・散乱問題について大規模チャンネル結合GCM計算を行った。

^{12}Beから得られた新しい描像

1. 励起状態は基底状態が内包する自由度の活性化により形成される。

⇒核の基底状態は、αクラスターと一粒子運動の自由度の共存が
本質的な構造(核のGlobal featuresを捉えることが重要)

2. He二体クラスターは強い縮退性を持って現れる (Loose clusters)。

⇒ 中性子過剰核は弱相互作用系であるため、中性子の再配置が容易におこる。
弱相互作用系の特徴が励起準位に現れる。

反応面 ⇒ 正面衝突の核子移行反応に顕著な共鳴現象

実験観測の議論

散乱粒子について検出器の配置を考慮する必要性を指摘した

単極遷移に対する興味

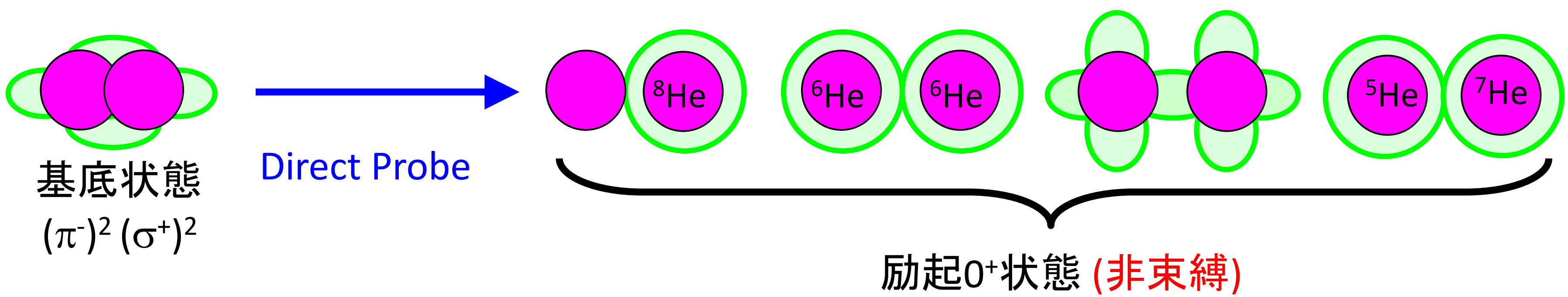
N～Z核での先行研究 : T. Yamada et al., PTP120

クラスター構造の発達 ⇒ 単極遷移の増大をもたらす (より詳細な条件は?)

例えば、どの様な種類のクラスター構造が発達すれば増大するのか?

12Beの結果

^{12}Be = $\alpha + \alpha$ + 4N系における基底状態から高励起状態への構造転移



どれが一番増えるのか?

今回の報告内容

単極遷移の増大の条件を断熱エネルギー曲線の構造と結び付けて議論する

↑

GTCM法 : 共有結合から漸近クラスターへの変化を断熱エネルギー上で追跡可能

What is adiabatic energy surfaces ?

S : 距離PRM
α : 基底の番号

1. Full solutions

原子軌道基底

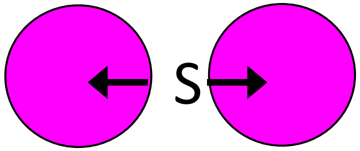
$$(H-E)\Psi_E = 0\,, \qquad \Psi_E = \int dS \sum_{\alpha} C_{\alpha}^{E}(S)\,\boxed{\varphi_{\alpha}(S)}$$

2. Adiabatic solutions

原子軌道基底

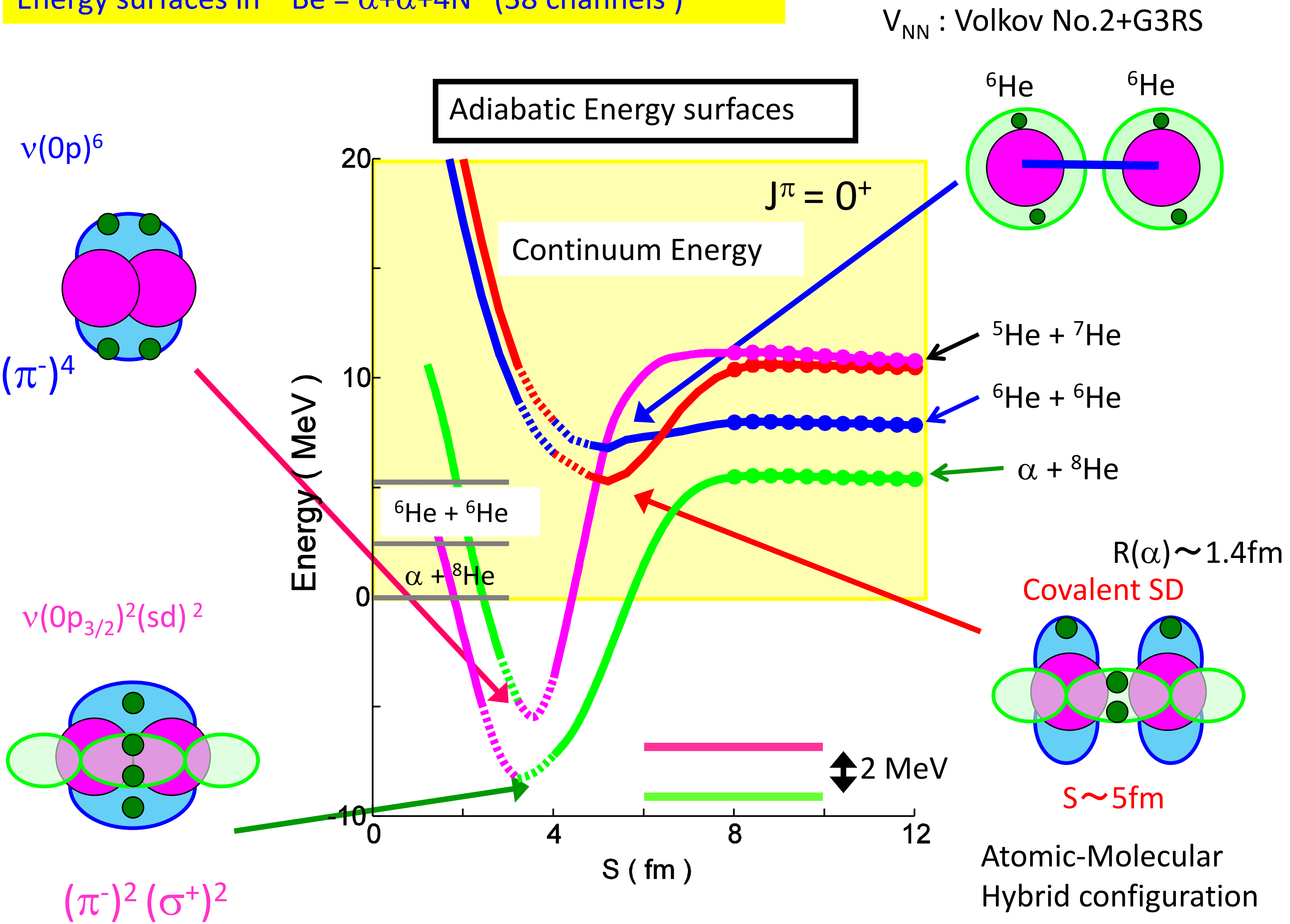
$$(H-E)\underline{\Phi_E^{adi}(S)} = 0\,, \qquad \underline{\Phi_E^{adi}(S)} = \sum_{\alpha} D_{\alpha}^{E}(S)\,\boxed{\varphi_{\alpha}(S)}$$

$\underline{\Phi_E^{adi}(S)}$: 断熱状態

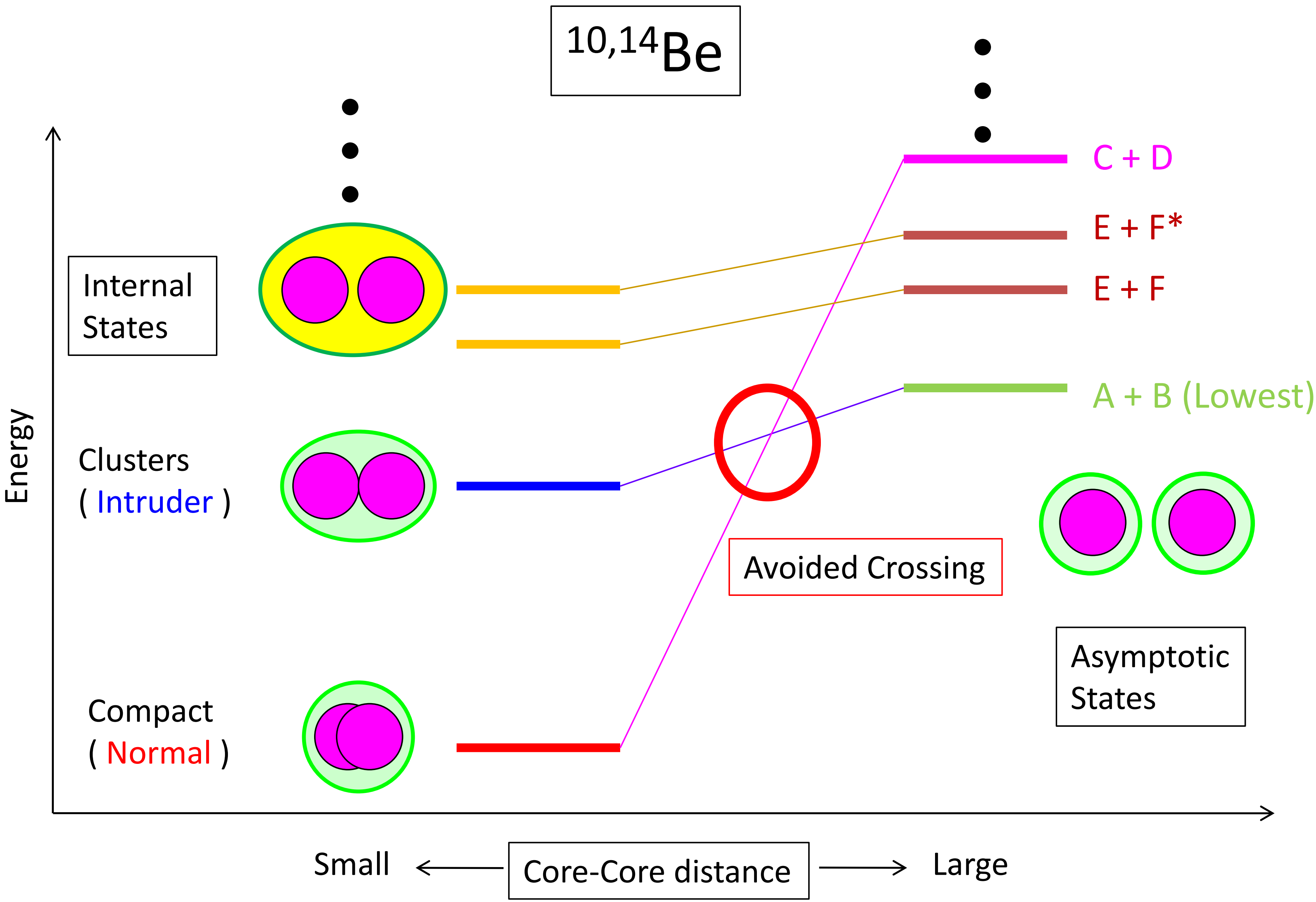


距離PRM(S)の変化に応じて、分子軌道と漸近クラスター(チャンネル状態)の変化を追跡可能

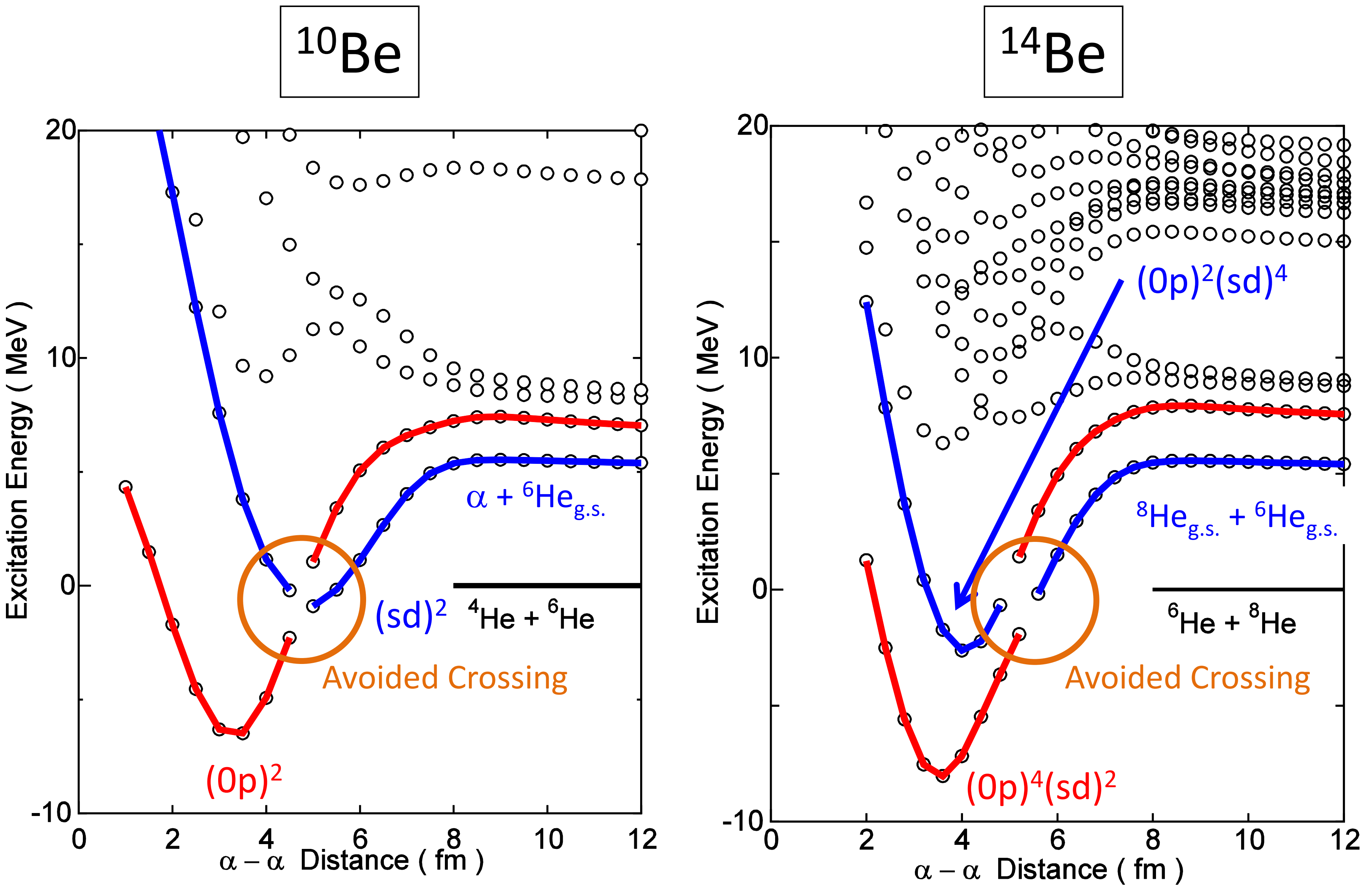
Energy surfaces in $^{12}Be = \alpha+\alpha+4N$ (38 channels)



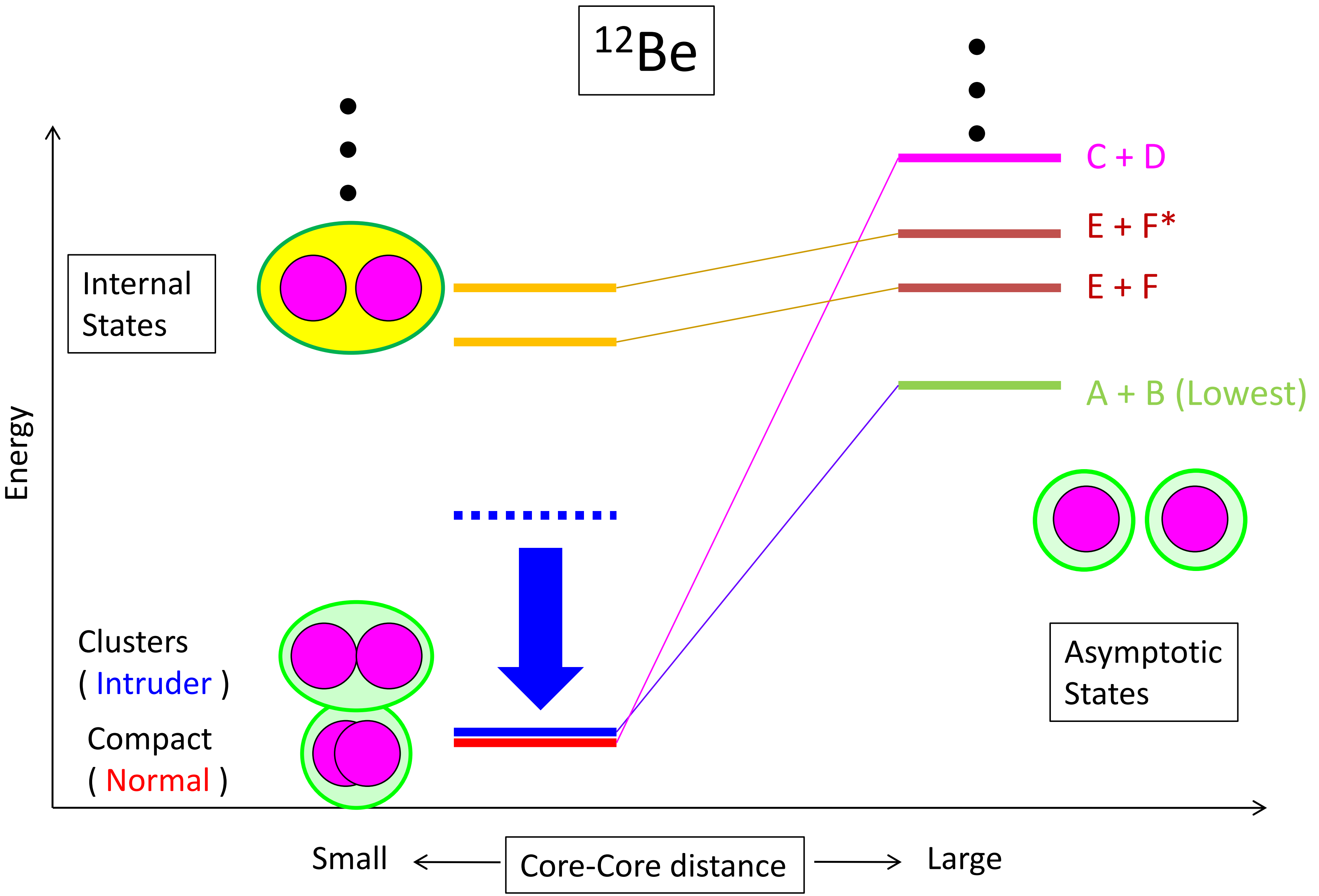
Global behaviors of Level Crossings in Be isotopes



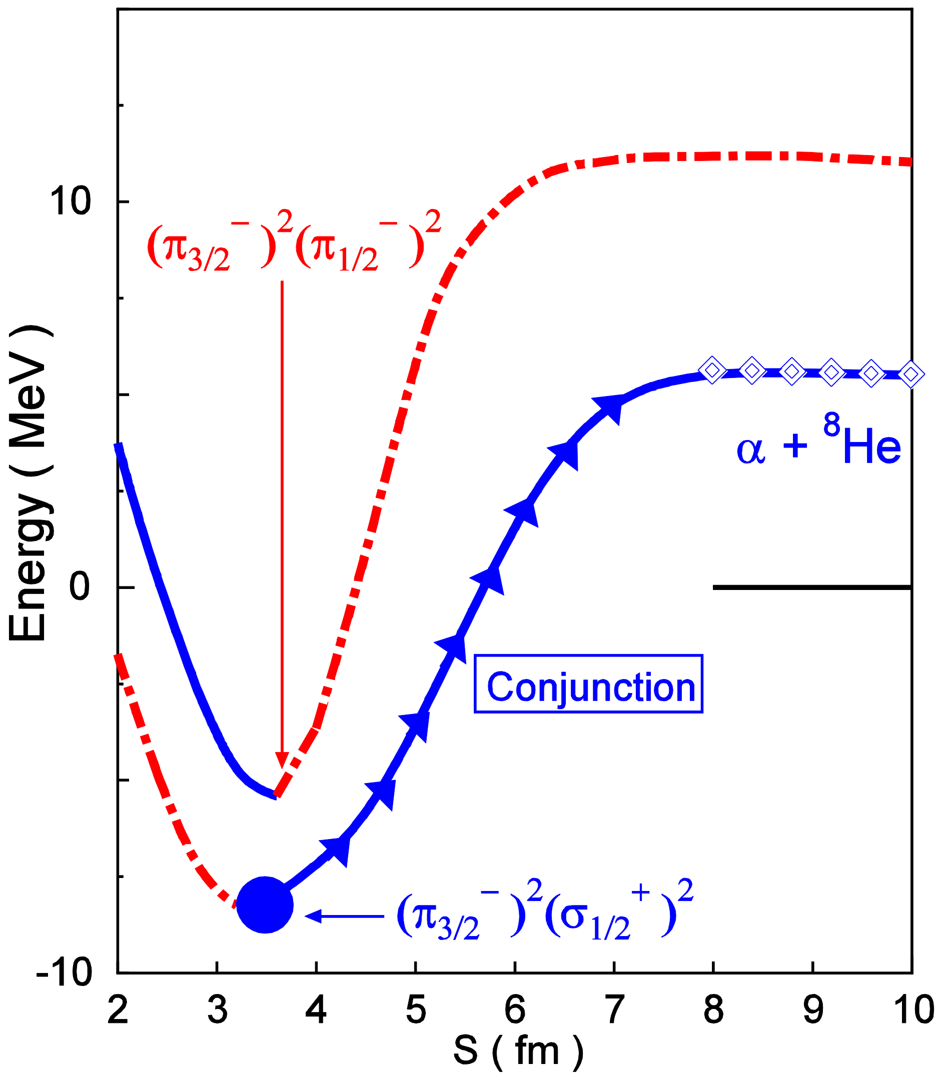
Level Crossings in $^{12,14}Be=\alpha+\alpha+XN$ (X=2,6)



Global behaviors of Level Crossings in Be isotopes



断熱連結(adiabatic conjunction)



1. 内側～Minimum

$(\pi_{3/2}^{-})^2\ (\pi_{1/2}^{-})^2$ ⟺ $(\pi_{3/2}^{-})^2\ (\sigma_{1/2}^{+})^2$

分子軌道間のLevel crossing

2. Minimum ～ 漸近領域

$(\pi_{3/2}^{-})^2\ (\sigma_{1/2}^{+})^2$ ⟺ $\alpha + {}^8He$

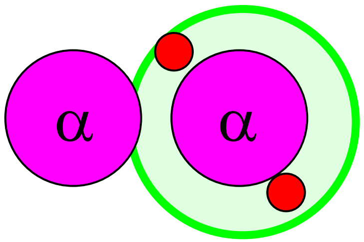
分子軌道から漸近チャンネルへの滑らかな変化

⇓

断熱連結(adiabatic conjunction)

Refinement of calculation

1. これまでのやり方



[α+^{6}He(l^{+})] K=0

K=0の基底 　　K=0の基底

$0^{+} \rightarrow P_x(R) \cdot P_x(R) + P_y(R) \cdot P_y(R) + P_z(R) \cdot P_z(R)$

$2^{+} \rightarrow P_x(R) \cdot P_x(R) + P_y(R) \cdot P_y(R) - 2P_z(R) \cdot P_z(R)$

(lK)を手で組んで(解析的に)K射影を行っていた。⇒ 価核子の数が増えると面倒!!

2. 新しいやり方

J_zの演算子を数値的に対角化することにより、K射影を行う。

$$J_z\,\Phi(K) = K\,\Phi(K) \qquad \Phi(K) = \sum_{\alpha} C_{\alpha}\,\varphi(\alpha)$$

$$J_z = \sum_{i=1}^{A} j_z(i)$$

原子軌道の基底

価核子の数に関係なく
機械的に計算可能!!

但し解析射影の場合より
余分なK状態が若干できる。

Improvement of the projection procedures

Jz Diagonalization

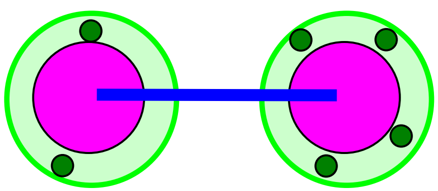
$$\langle K' | OP^{J\pi} | K \rangle$$

1. Constructions of the K-projected basis

Projection of the K quantum number ⇒ Diagonalization of $\hat{J}_z$ in body-fixed frame
Generation of |J π K> basis

2. Construction of the asymptotic channels

Channel wave functions (反応での基底)



^{6}He(I_1) ^{8}He(I_2)

$$\begin{cases} \vec{I}_1 + \vec{I}_2 = \vec{I} \\ \vec{L} + \vec{I} = \vec{J} \end{cases}$$

Diagonalization of total Hamilton at an asymptotic region (large distance)

↓

Construction of channel wfs

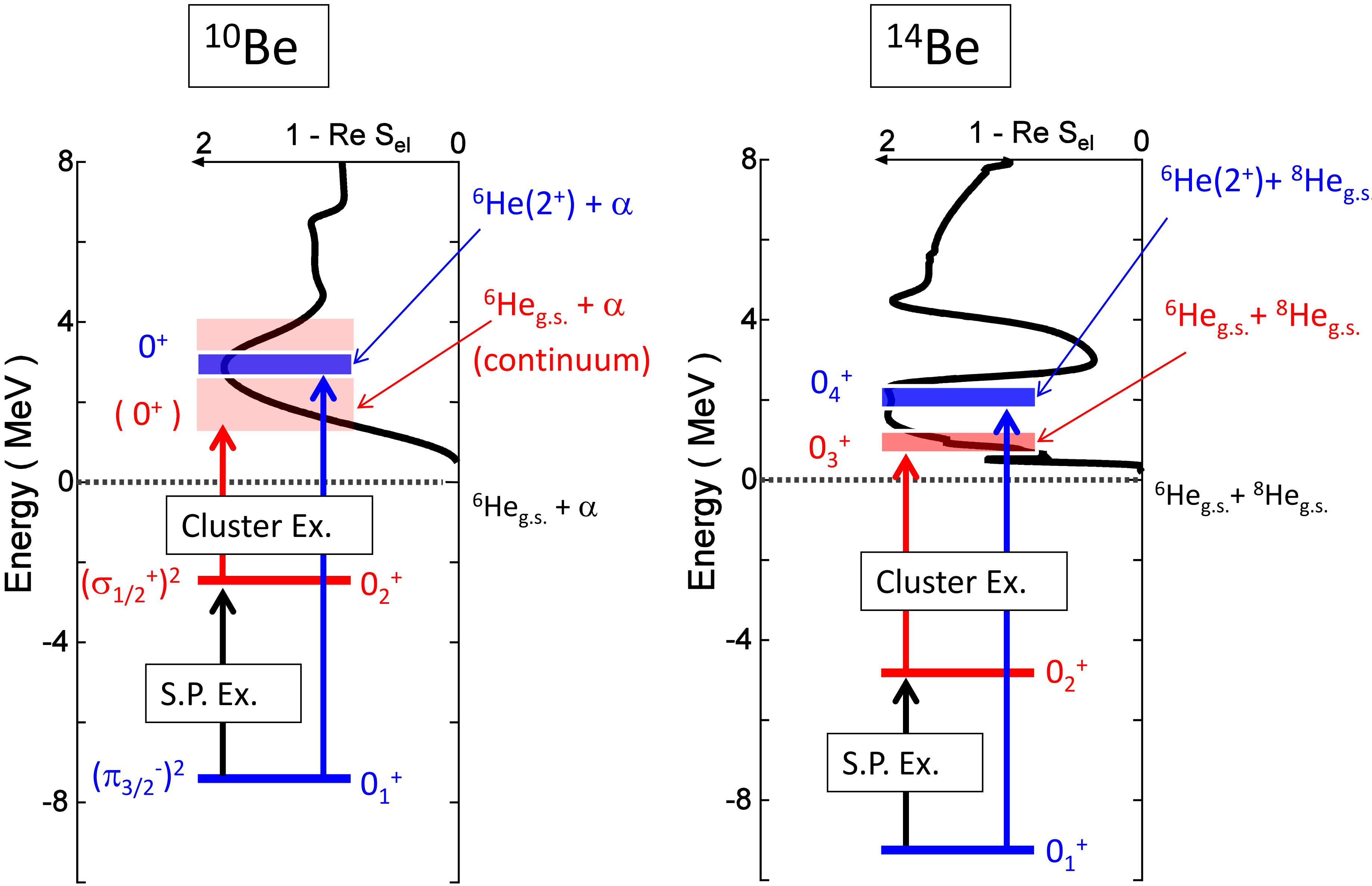
$$\langle K' | HP^{J\pi} | K \rangle_{S \to large}$$

Generation of |(I_1 I_2)I L J π>

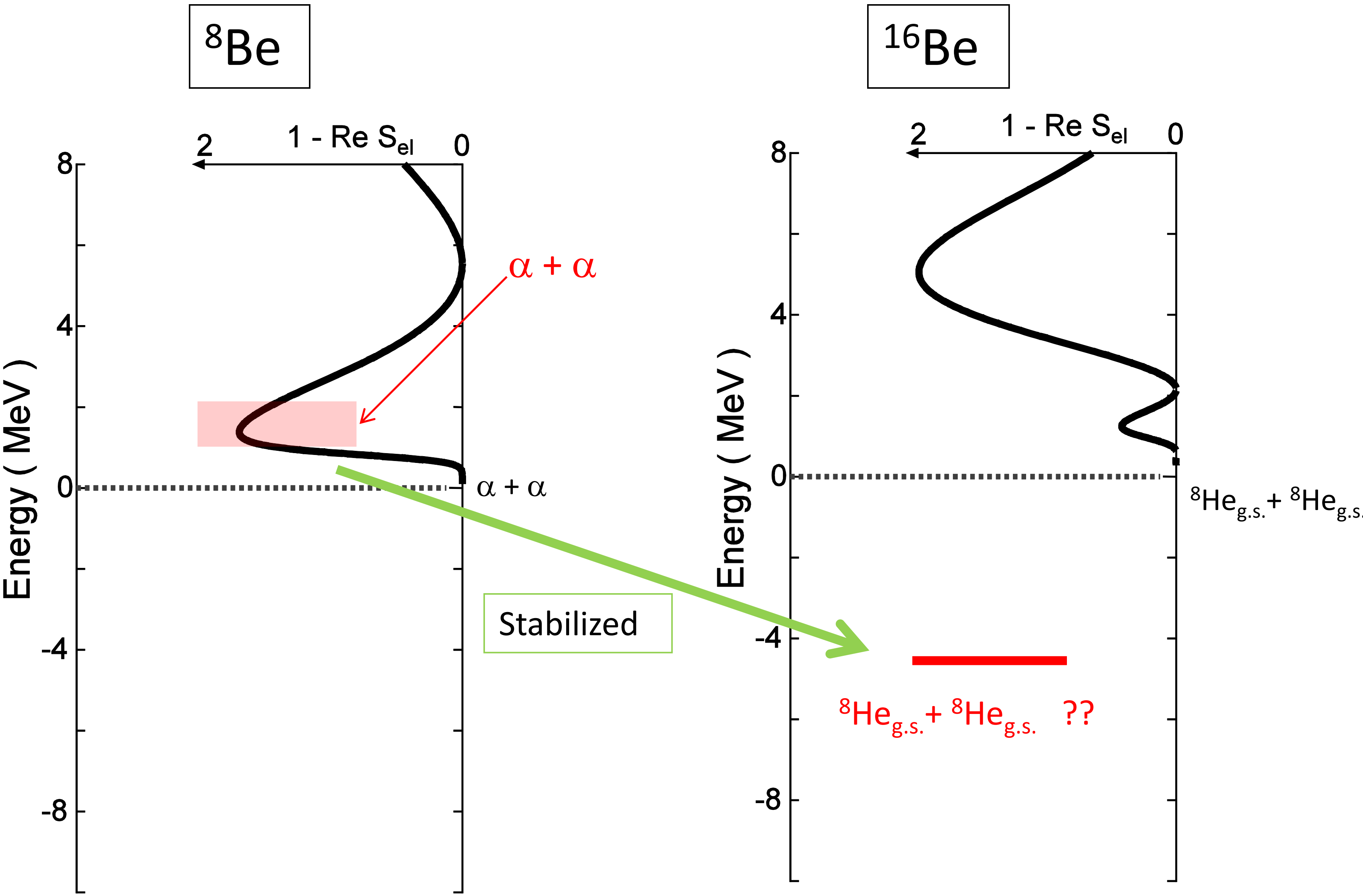
We need NOT to handle spins of excess neutrons .

→ 一般の二中心系の構造･反応計算が機械的に可能である

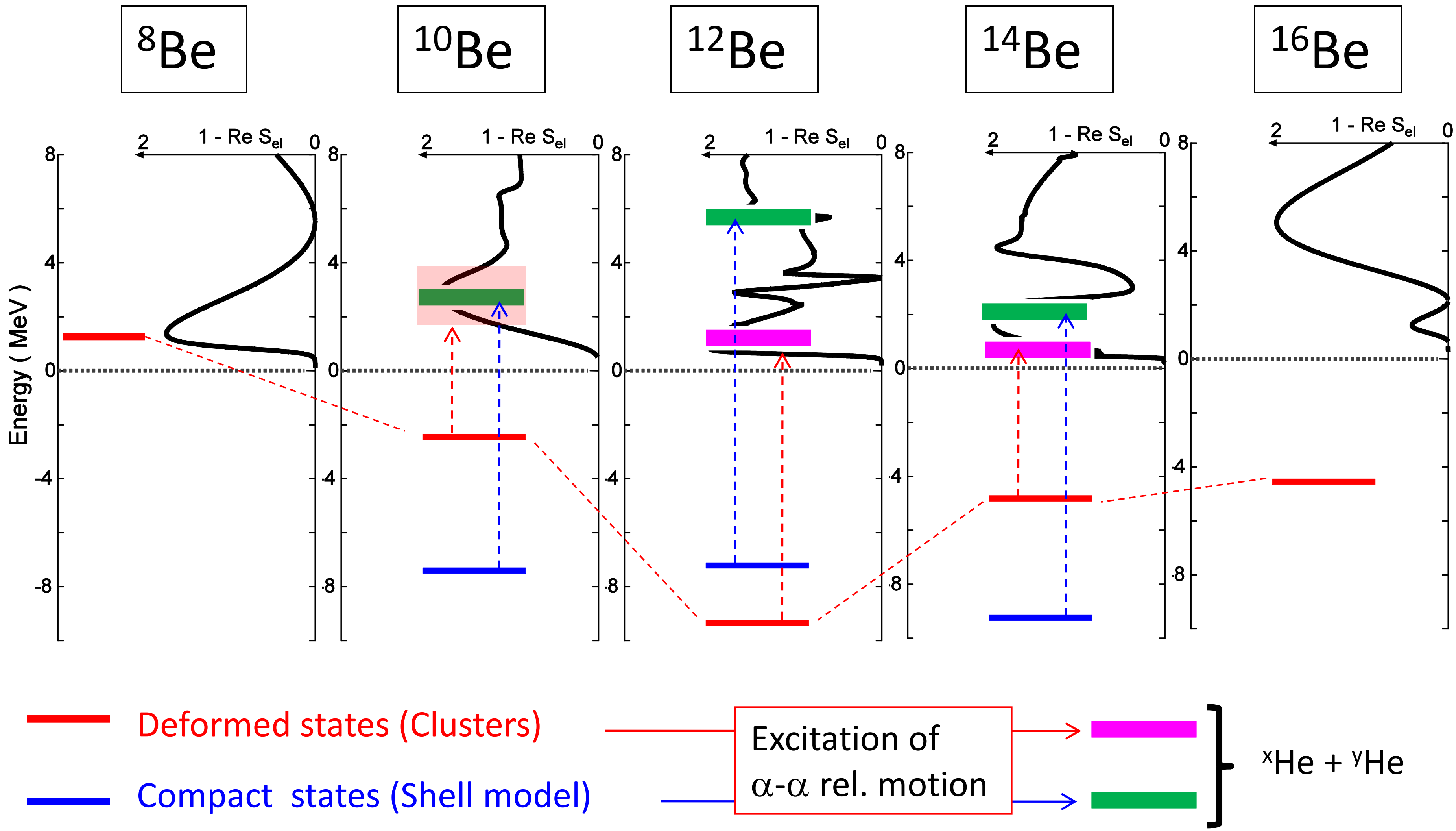
^{10}Be vs ^{14}Be : $J^{\pi} = 0^+$



^{8}Be vs ^{16}Be : $J^{\pi} = 0^{+}$



Be isotopes from bounds to continuums : $J^{\pi} = 0^{+}$



Deformed states (Clusters)

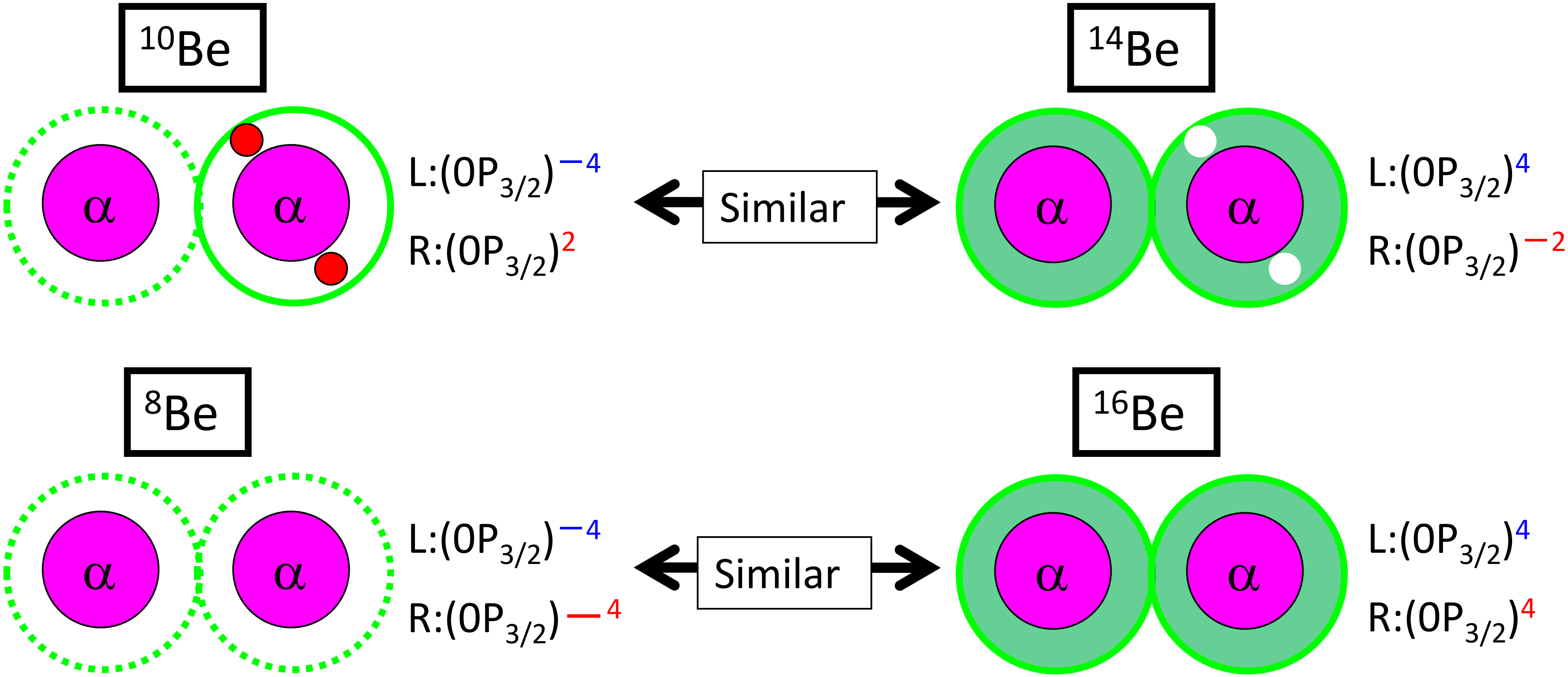
Compact states (Shell model)

Excitation of α-α rel. motion

^{x}He + ^{y}He

All the cluster states are expected to have a large monopole strength.

Systematics based on the Cluster Picture



We are now analyzing wave functions.

Special feature in ^{12}Be

$^{12}Be = {}^{6}He + {}^{6}He$, $\alpha + {}^{8}He$ is a self conjugate when atomic p-h are exchanged.

⇒ This is a special nucleus in even Be isotopes

これまでの分析

1. 偶Be同位体の広い構造転移 ⇒ 基底状態の見直し、縮退した弱クラスター
2. 核子移行反応断面積 ⇒ 散乱角度選択の導入
3. モノポール遷移の増大機構⇒ 断熱連結

研究の戦略

1. 低励起～高励起状態の構造転移と縮退現象
2. 低速反応による高励起状態の実験測定条件
3. モノポール励起の増大現象

→ 不変性と個別性を探る！

Feature subjects

1. 計算の素直な拡張 ⇒ $^{14}C = \alpha + ^{10}Be$、Freer の散乱実験との比較
2. SD shell への拡張 ⇒ $O = \alpha + ^{12}C + XN$、$Ne = \alpha + ^{16}O + XN$
3. 三中心系への拡張 (池田さん、山田さんとの共同研究)

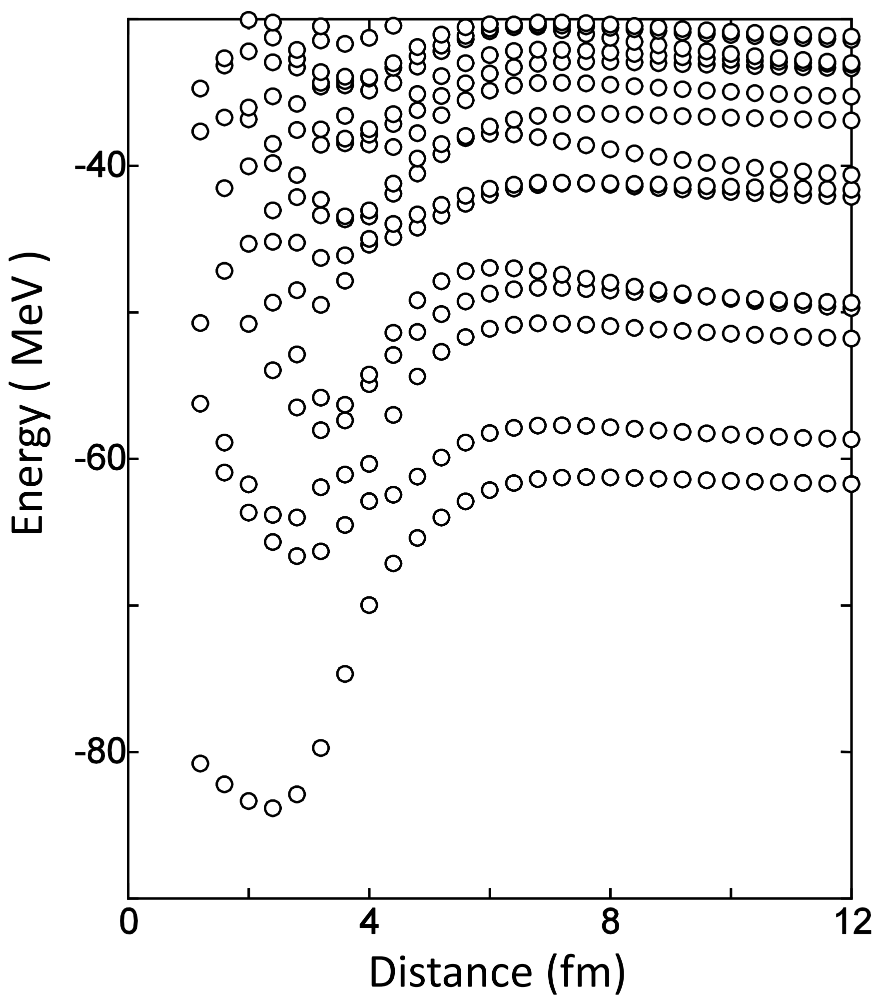
Recent Application to α+^{10}Be = ^{14}C

(Recent Scattering exp. By Freer et al.)

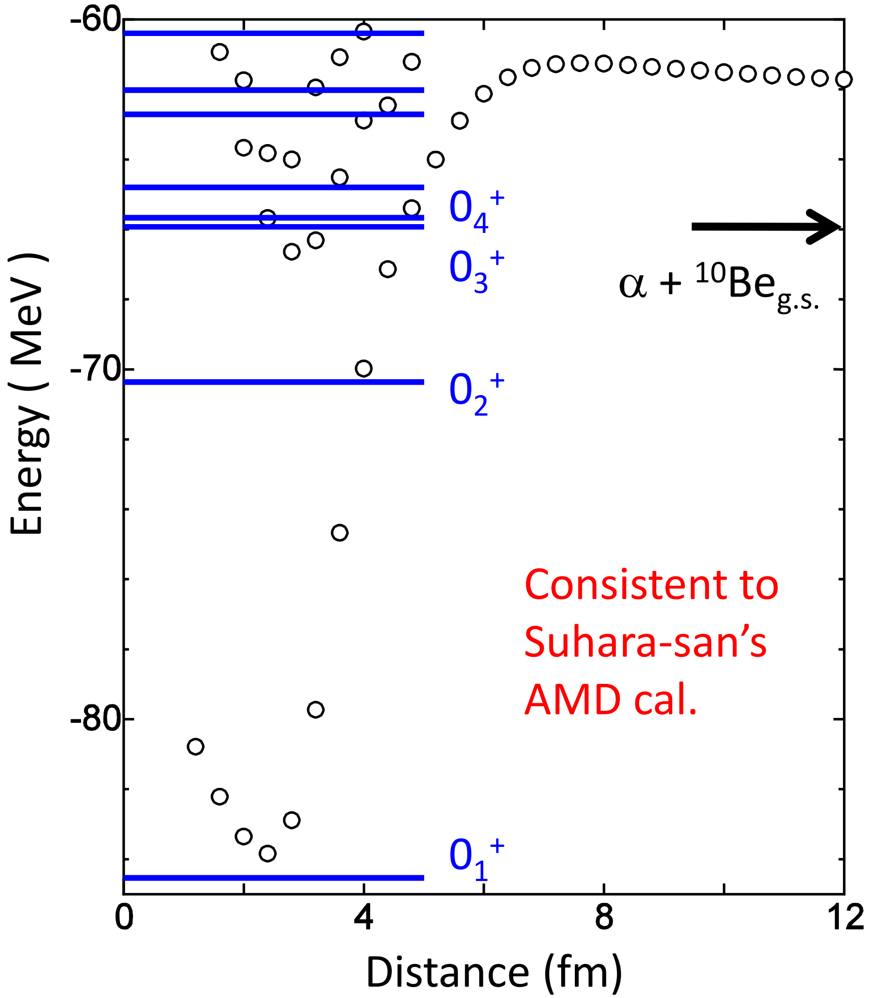
Calculation: Coupled channels of α+^{10}Be (0pshell)

(Parameters are same as Be isotopes)

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



Energy spectra ($J^{\pi} = 0^{+}$)



How to construct intrinsic states based on AMD

1. Basis construction by imaginary time evolutions

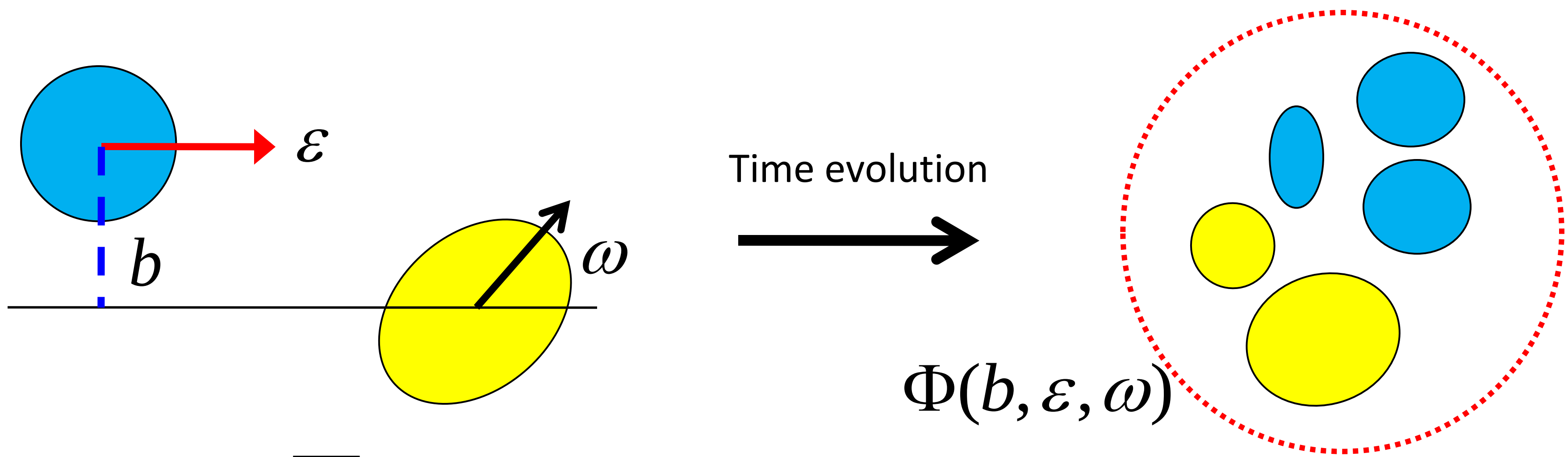
   Constraint Cooling + GCM (Generation of collective states)

$$\Omega_\nu = \sum_\beta C_\beta^{(\nu)} \Phi(\beta)$$

β : Collective Coordinates

2. Basis construction by real time evolutions

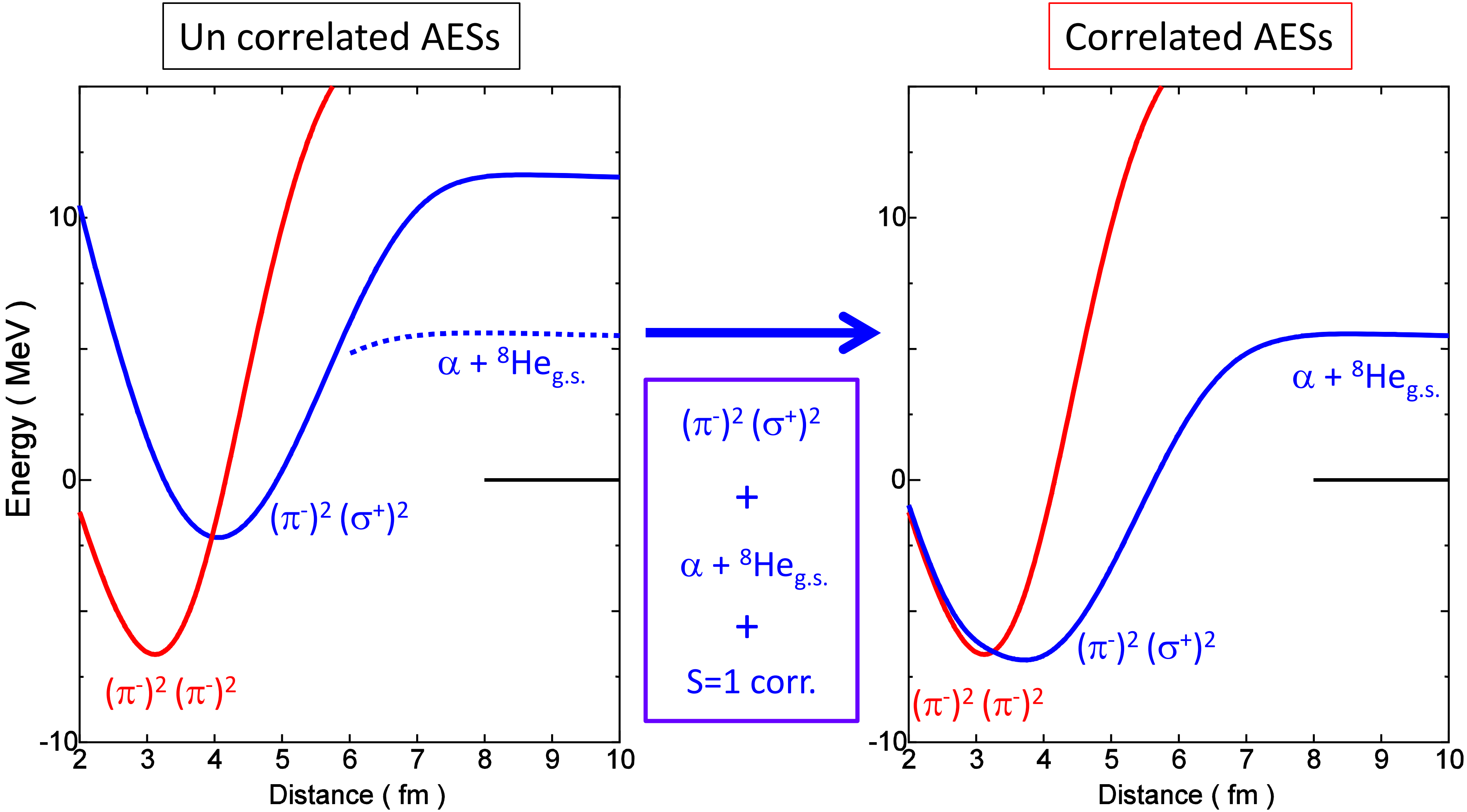
   Sampling of collision events (Cluster correlations during scattering ??)



$$\Omega_\nu = \sum_{b,\varepsilon,\omega} C_{b,\varepsilon,\omega}^{(\nu)} \Phi(b,\varepsilon,\omega)$$

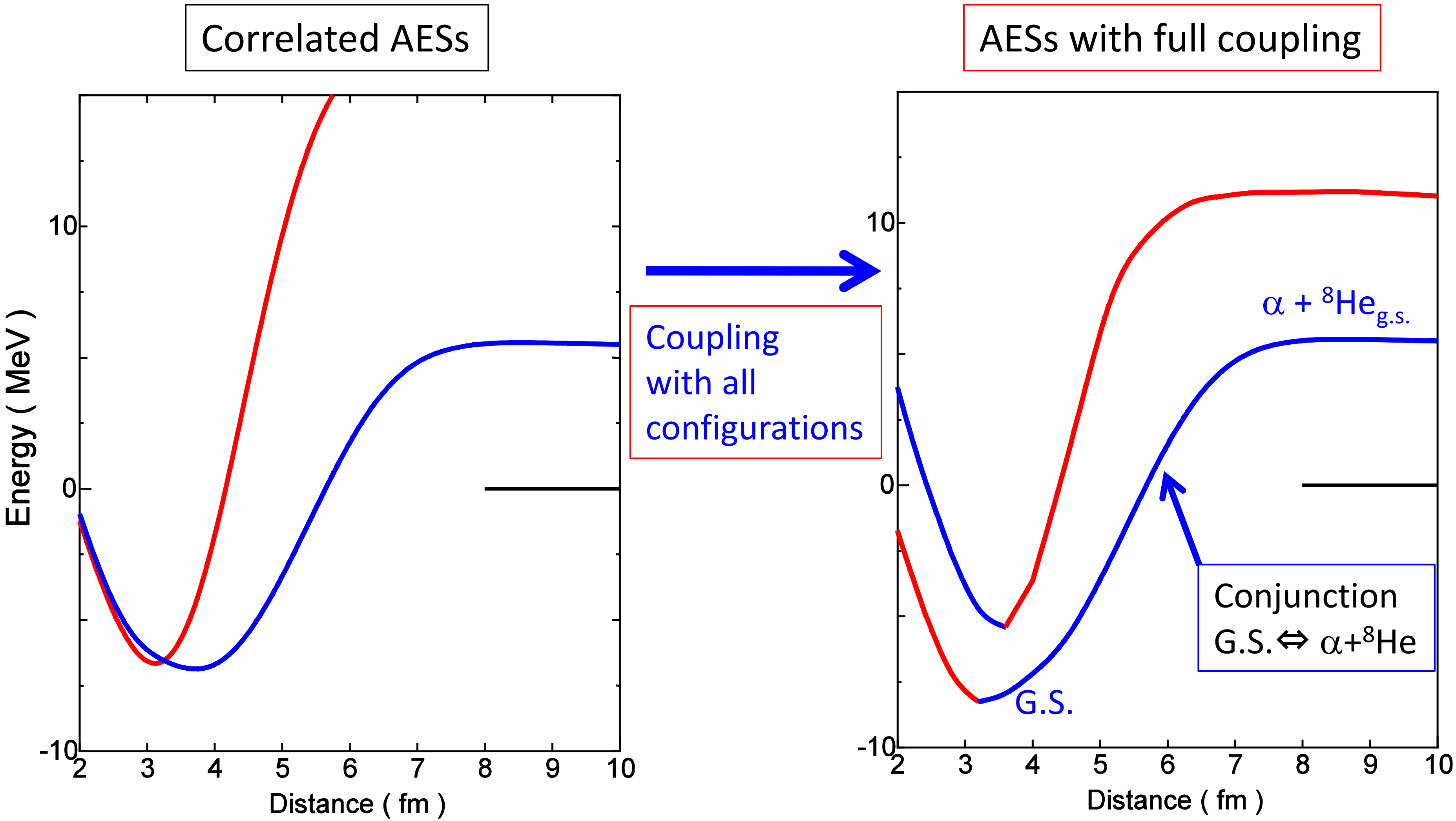
Stop at
Interacting region

Level Crossing in ^{12}Be (1)



Two AESs are almost degenerated due to correlations ⇒ Crossing occurs at inner region !

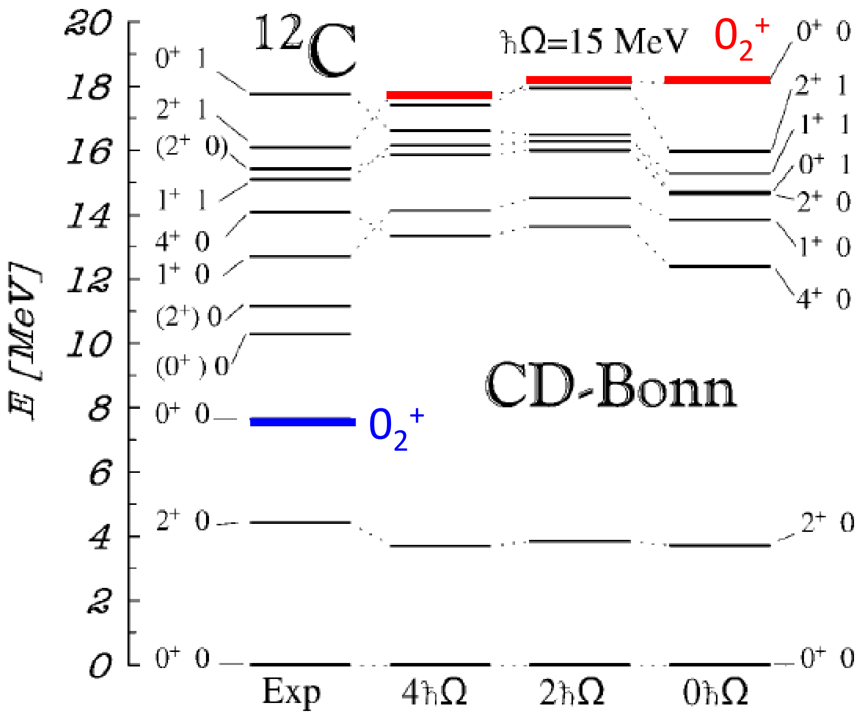
Level Crossing in ^{12}Be (2)



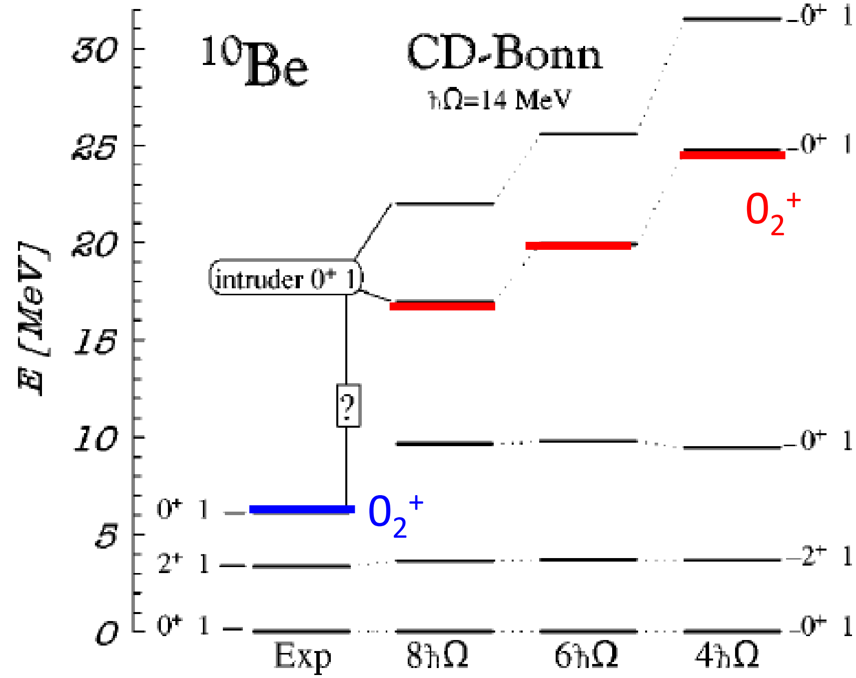
Lowest minimum smoothly connected to α+$^{8}He_{g.s.}$ ⇒ Formation of adiabatic conjunction

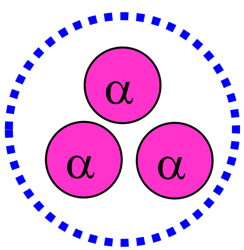
Results of No core shell model

Navratil et al., PRL84 (00)



Caurier et al., PRC66 (02)



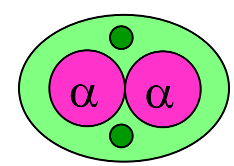


0_2^+

N～60 for α-α rel. motion

By T. Yamada et al.

(σ^+)^2



Recent progress of GFMC : $^{12}C(0_2^+)$, Ex ～ 12±8MeV , Linear-chain -like density

Singnificance of the present work

A. Present situation of the ab-initio calculations with realistic NN forces

1. ab-initio calculations can mainly reproduce the yrast states in (well known) light systems.

2. Application to the reaction problem is performed (e.g. ^{4}He+n, A<6).

K. M. Nolett et al., PRL99 (07)

However, these calculations are difficult to describe intruder states, in which the cluster degree of freedoms strongly activate.

(Predictive powers for unknown state is weak…)

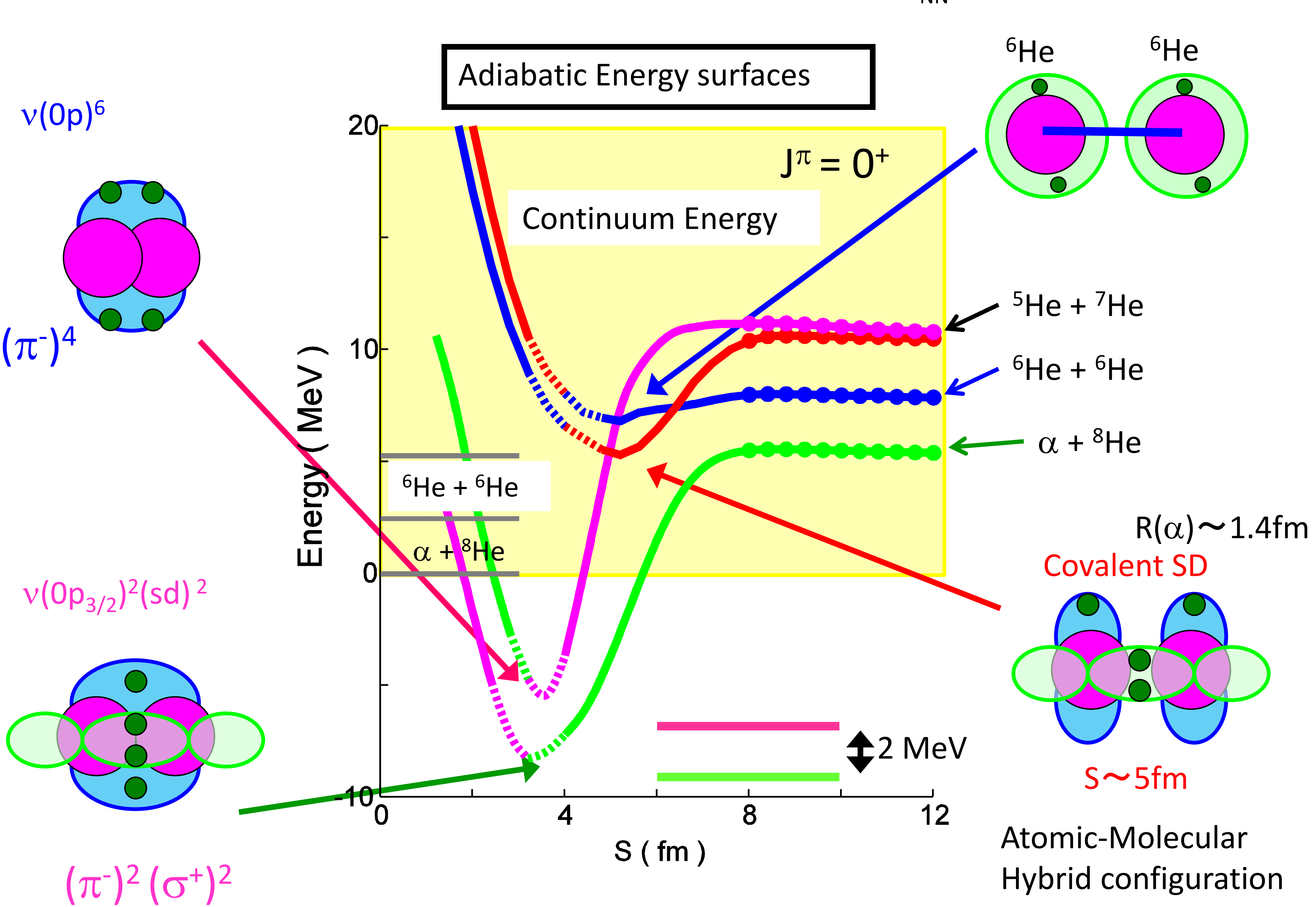
B. Approaches based on the cluster model with effective NN forces

It is important to search for new cluster-phenomena in unknown systems by employing cluster model approaches.

↓

Neutron Excess Systems

Energy surfaces in $^{12}Be = \alpha+\alpha+4N$ (38 channels)

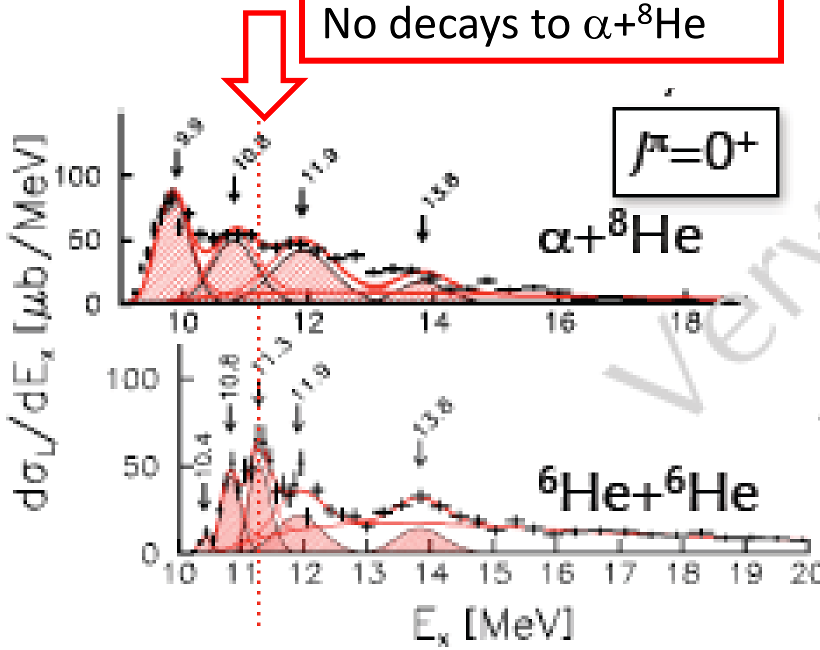


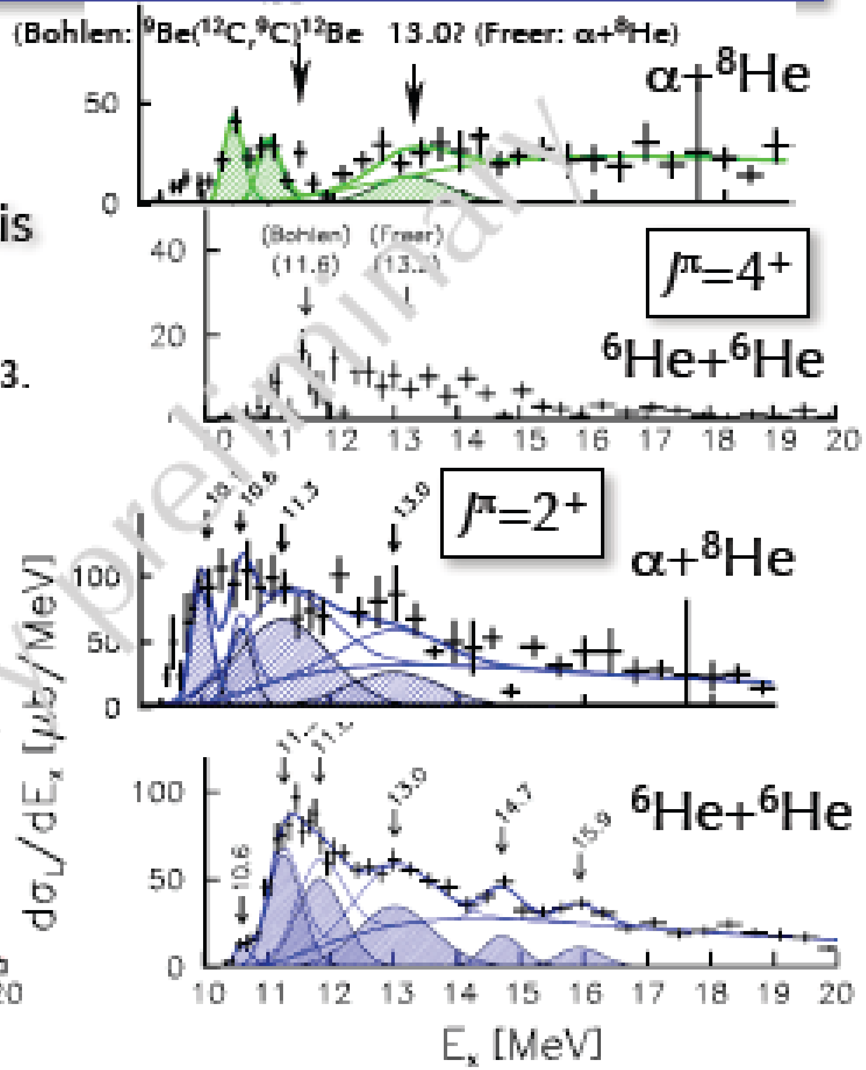
E_x spectra of $^{12}Be(\alpha,\alpha')^4He^8He$ (positive parities)

- E_x spectra of pos.-parity states
- Fitting with resonances determined in $^6He+^6He$ analysis (E_R & Γ_R: fixed for J=0 & 2)

~10 MeV: Korsheninnikov et al., PLB343('95)53.

No decays to $\alpha+^8He$





Present studies

1. 偶Be同位体の束縛領域から非束縛領域に渡る構造転移、反応現象
 ⇒ 多様な構造が発現する。基底状態の描像を見直すべき?

2. Adiabatic conjunctionによるモノポール遷移の増大現象 ⇒ 普遍的ではないか?
 (基底状態につながるクラスター状態は必ず一つは存在する)

Developments of calculation method

K射影、二重射影(Channel wf)を対角化により機械的に構築する方法を開発
(角運動量代数を全く使わなくてよい)

⇒ 一般の二中心系の計算が機械的に可能になった(幅広い適用性が期待できる)

Feature subjects

1. 計算の素直な拡張 ⇒ $^{14}C = \alpha + ^{10}Be$、Freer の散乱実験との比較

2. SD shell への拡張 ⇒ $O=\alpha+^{12}C+XN$、$Ne=\alpha+^{16}O+XN$
 普遍性と個別性 : hybrid structures of clusters + excess neutrons in O and Ne

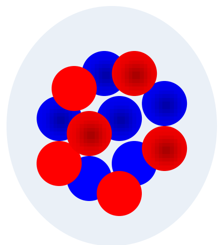
3. 三中心系への拡張 (池田さん、山田さんとの共同研究)

数値計算による励起量子数Nの評価

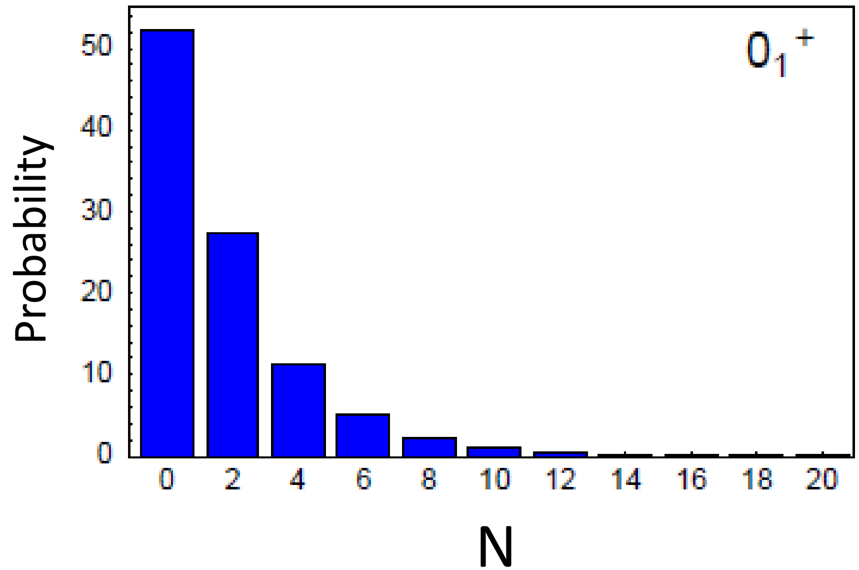
T. Neff et al., (2008)

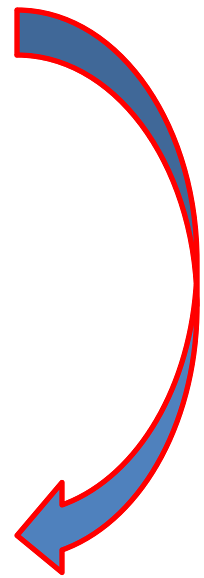
3α模型で計算

^{12}Cの場合 (N=Z=6)

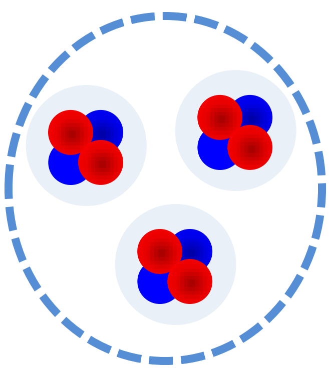


基底状態

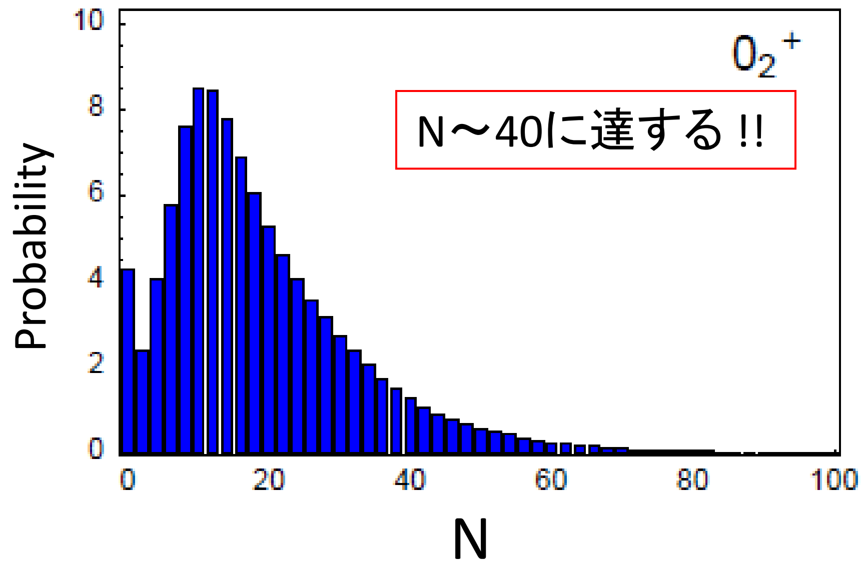




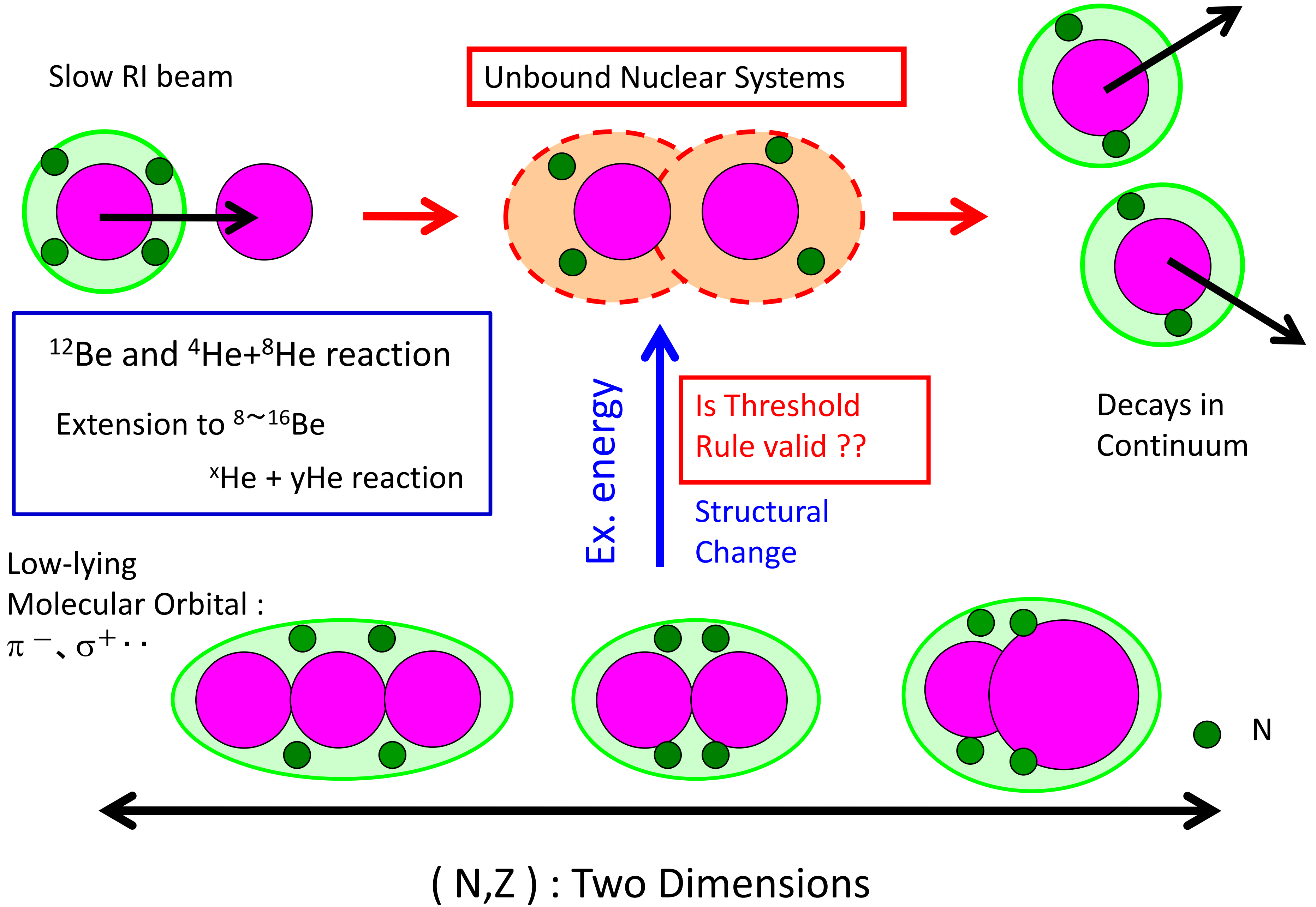
ΔE/A = 7.6/12
～0.6 MeV



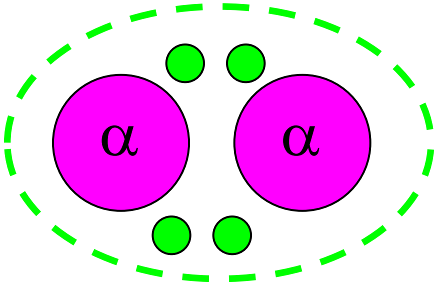
励起0^+状態



Studies on Exotic Nuclear Systems in (E_x,N, Z,J) Space



Computational conditions of ^{12}Be

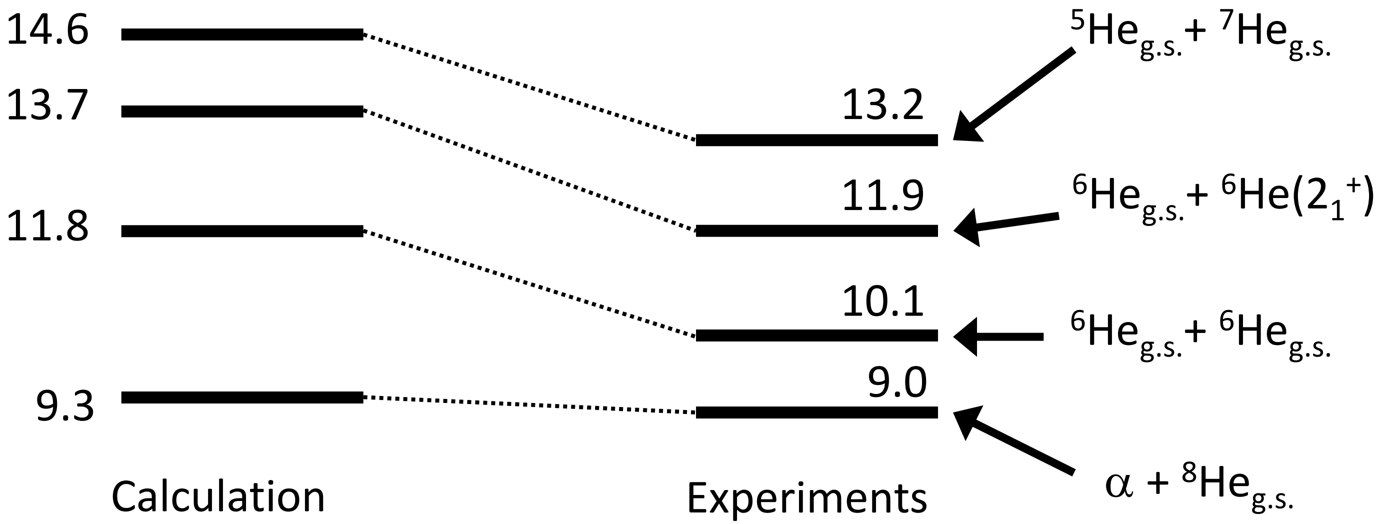


1. Parameters in NN interaction

NN int. : Volkov No.2 (Central) + G3RS (LS-int.)

⇒Fixed at ^{10}Be (NO modification for Be isotopes)

Cluster threshold



2. Model space

All the 0p-shell Atomic orbitals ($K^\pi=0^+$) ⇒ About 800 Slater determinant with J^π projection

(S=2～8.8 fm、ΔS=0.4 fm、SD=40)

最近の分析内容

この一年は主に論文作成に必要な分析を進めていた(最近順次投稿中)

1. 断熱曲線の構造分析と単極励起の増大現象

   M. Ito, PRC83, 044319 (2011)

2. $\alpha+{}^{8}He \Rightarrow {}^{6}He+{}^{6}He$反応機構と共鳴観測の実験条件の考察

   M. Ito, D. Suzuki, PRC84, 014608 (2011)

3. ${}^{12}Be$におけるN=8魔法数の破れとクラスター相関

   M. Ito, N. Itagaki, K. Ikeda, Submitted to PRC (2011)

4. 高励起${}^{12}Be$におけるLoose clusters形成機構

   M. Ito, To be submitted to PRC (2011)

本研究の意義

A. 現実的核力に基づいた第一原理計算による研究

主に軽い安定核(既知核)の イラスト状態の構造の記述に成功 している
(構造はA～12、反応はA～5程度まで)

- クラスターの自由度が活性化する状態や現象は取り扱いが困難
- 中性子過剰核などの未知な系の計算はより困難

⇒ 未知核のクラスター現象の研究は不可能に近い

(例) GFMC : $^{12}C(0_2^+)$, Ex ～ 12±8MeV , Linear-chain -like density

B. 有効核力に基づいたクラスター模型による構造・反応研究

- クラスター模型 : クラスターの離散集合を自然に取り扱える
- 平均場 ⇔ クラスターに渡る大きな構造転移 + 散乱境界条件

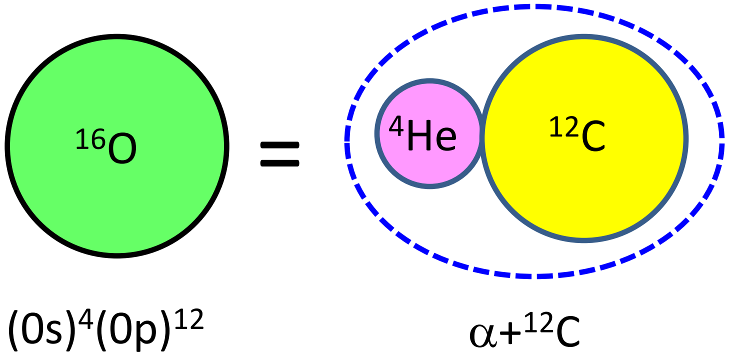
⇒原子核の構造転移に関して包括的様相をつかむことが可能

⇩

中性子過剰系の未知なクラスター現象を探索する

Introduction

Duality in light nuclei : Coexistence of Shell model and Cluster states



Bayman-Bohr Theorem: T. Yamada et al.

⇩

Excitations of individual degrees of freedom are possible.

Studies of global behaviors over a wide energy range are very important !!

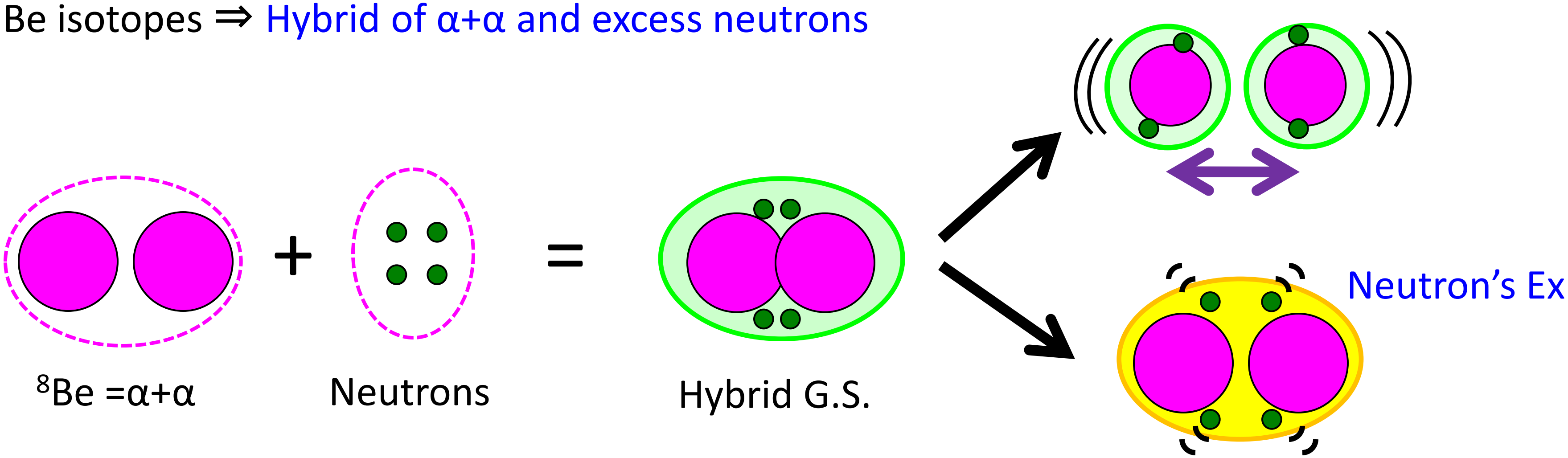
Present subject

We demonstrate the prominent duality appearing in Be isotopes

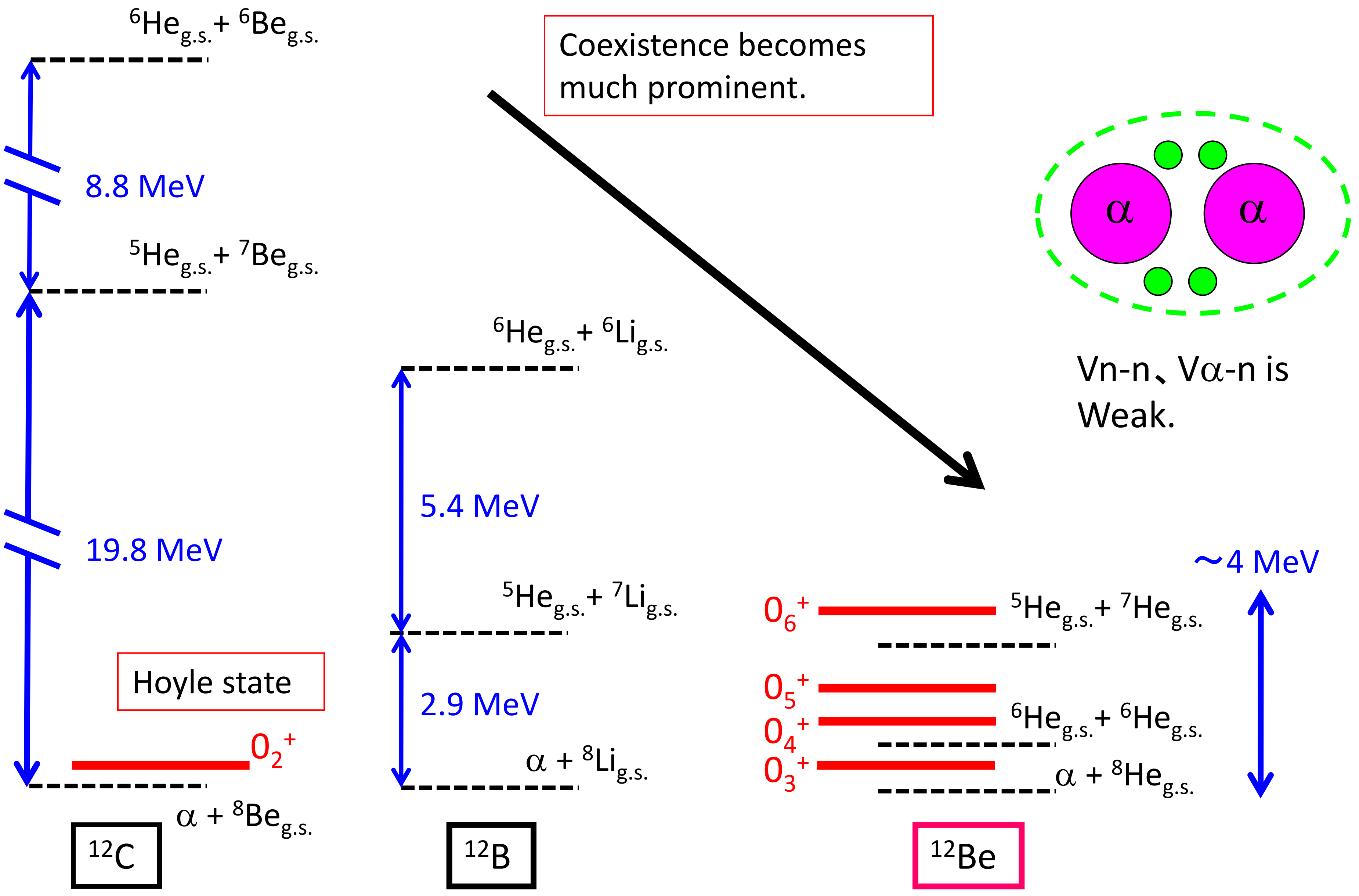
Be isotopes ⇒ Hybrid of α+α and excess neutrons

Scatt. B.C.

Cluster's Ex.

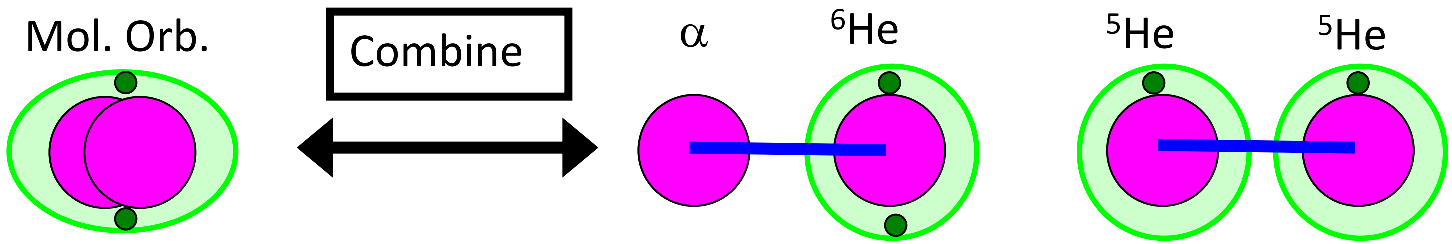


Coexistence phenomenon in A=12 systems (Threshold rule)

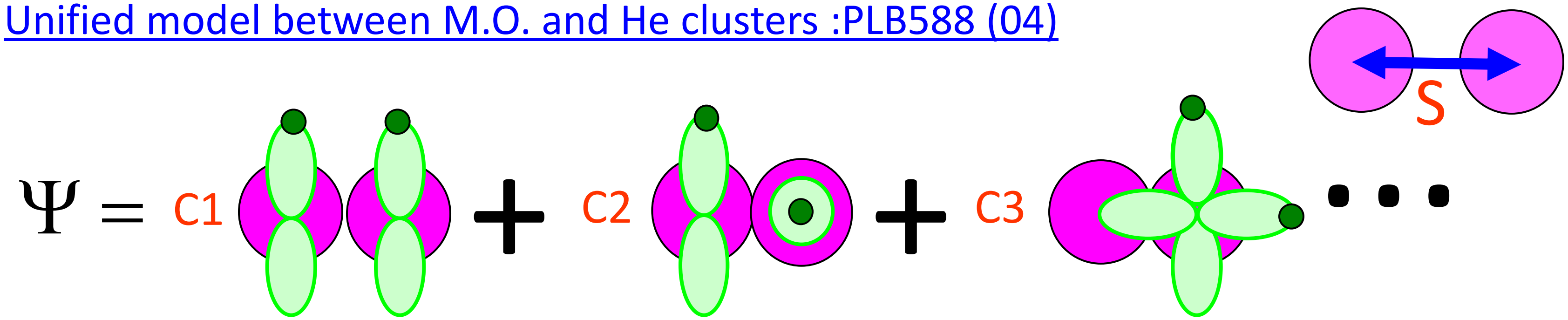


Extension of microscopic cluster model (Test calculation for ^{10}Be)

^{10}Be=α+α+N+N



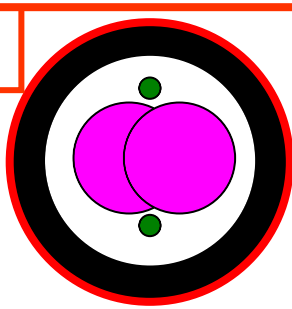
Unified model between M.O. and He clusters :PLB588 (04)



0Pi (i=x,y,z) Coupled channels with Atomic orbitals

S, Ci : Variational PRM.

Absorbing B.C. → Decay widh PTP113 (05)

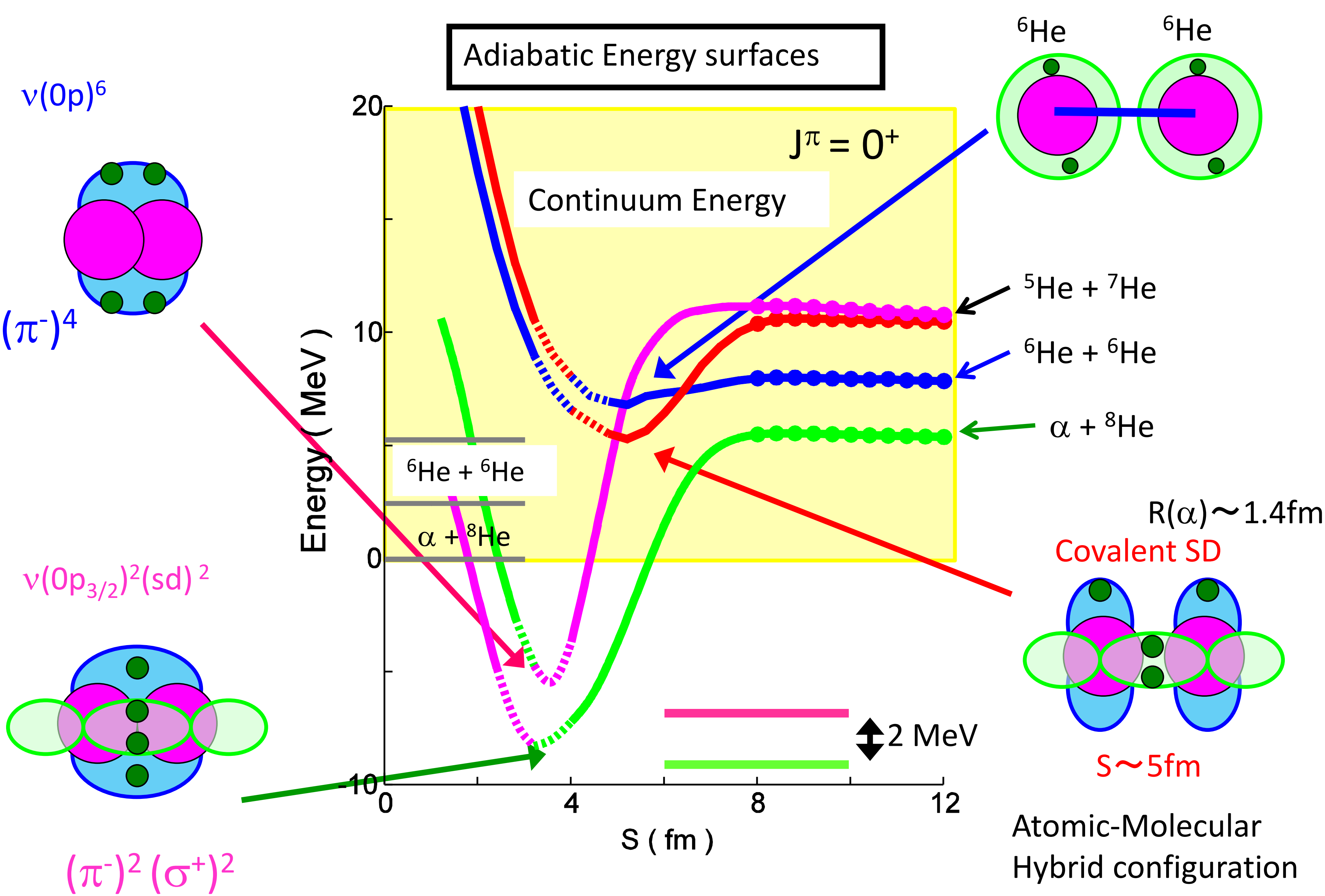


Scattering B.C. → α+^{6}He Cross sections PLB636 (06)

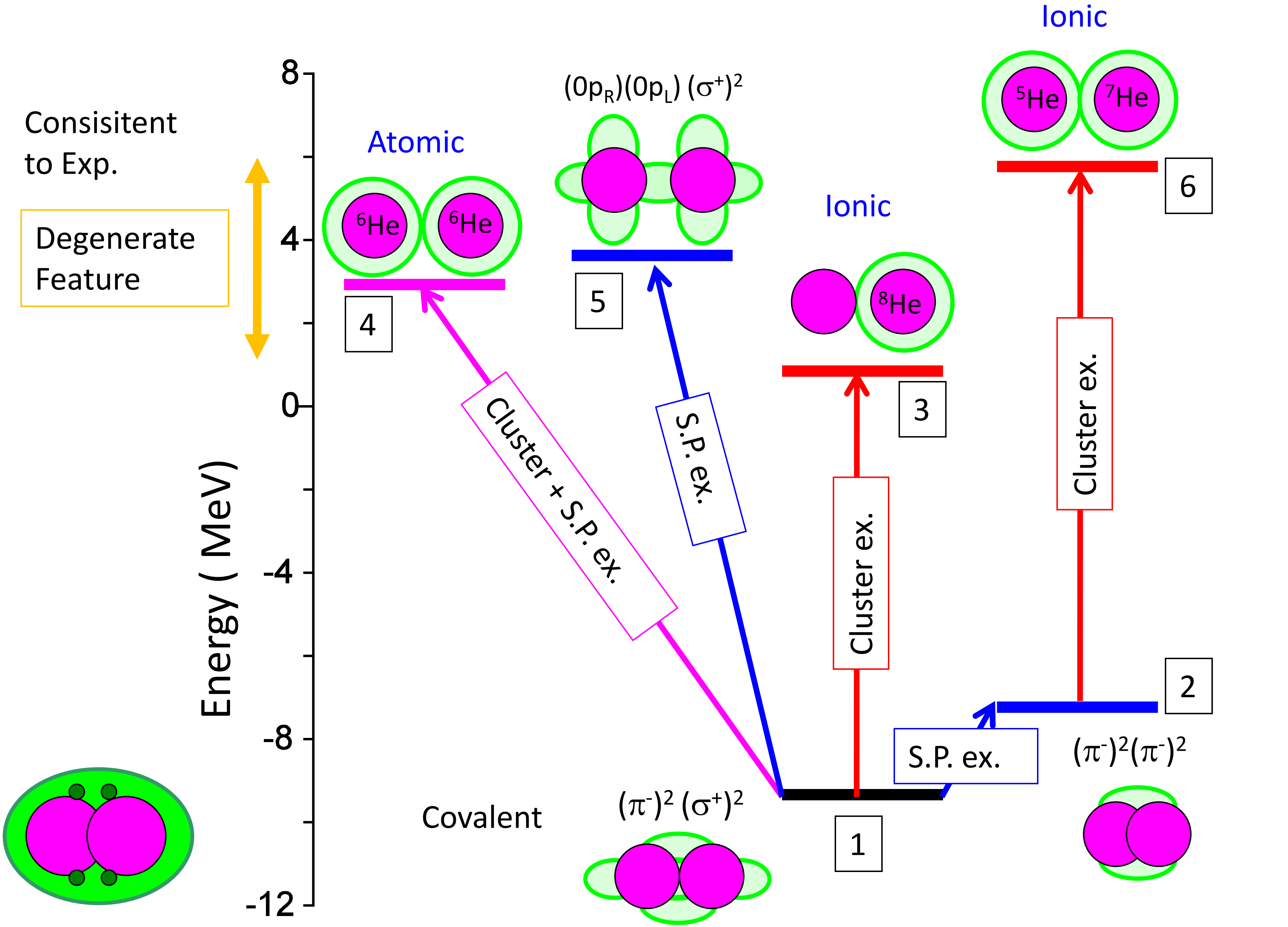
Tr. densites → $<\Psi \mid \rho \mid \Psi>$ → ^{10}Be → α+^{6}He Breakup

Energy surfaces in ^{12}Be = α+α+4N (38 channels)

V_{NN} : Volkov No.2+G3RS



Femto-Molecules : $^{12}Be=\alpha+\alpha+4N\ J^{\pi}=0^{+}$



Future perspectives : Combination of MF models, AMD and scattering

Open channels Compound states (Closed)

$$\Psi_c^{(+)} = \sum_\beta \mathrm{A}\left\{\varphi_\beta \chi_{\beta,c}^{(+)}\right\} + \sum_\nu b_\nu \Omega_\nu^{K=0}$$

$$(H-E)\Psi^{(+)} = 0$$

$$\left\langle \Omega_\nu^{K=0} \left| H \right| \Omega_{\nu'}^{K=0} \right\rangle = \varepsilon_\nu \delta_{\nu,\nu'}$$

$$\chi_{\beta c}^{(+)}(R_\gamma) = \sum_{i=0}^{n} C_{\beta i}^{(c)} u_{\beta i}(R_\beta)$$

$$b_\nu = \frac{-1}{\varepsilon_\nu - E} \left\langle \Omega_\nu^{K=0} \left| (H-E) \right| \sum_\beta \mathrm{A}\left\{\varphi_\beta \chi_{\beta,c}^{(+)}\right\} \right\rangle$$

In AMD

~~C.M. part~~

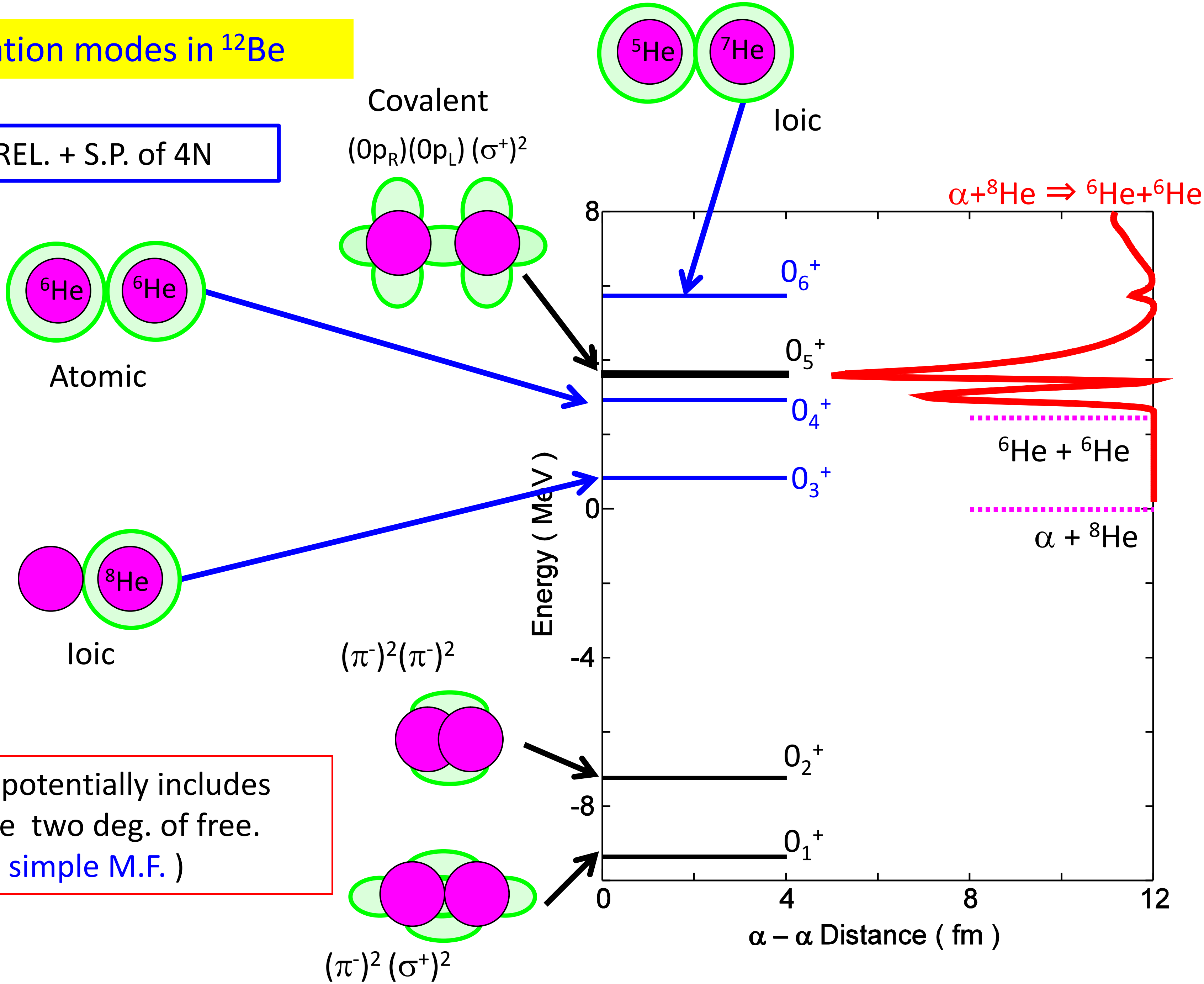
$$= \frac{-1}{\varepsilon_\nu - E} \sum_{\beta,i} C_{\beta i}^{(c)} \left\langle \Omega_\nu^{K=0} \left| (H-E) \right| \mathrm{A}\left\{\varphi_\beta u_{\beta,i}(R_\beta)\omega(x_G)\right\} \right\rangle$$

S.D. (AMD,HF,…)

Brink W.F. (S.D. by H.O.)

Excitation modes in ^{12}Be

α-α REL. + S.P. of 4N



G.S. potentially includes these two deg. of free. (Not simple M.F.)

Present subject on Be isotopes and Framework of our model

Introduction

Duality in nuclei and anomalous features of Cluster state

Application to structure problem of ^{12}Be and Be isotopes

enhancement phenomena
in transfer reaction
$\alpha + {}^{8}He \Rightarrow {}^{6}He + {}^{6}He$