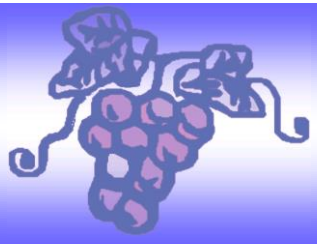


Cluster features of stable and unstable nuclei in p-shell region

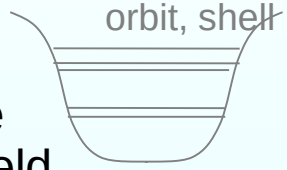
Y. Kanada-En'yo (Kyoto)

1. Introduction
2. Cluster gas, chain states
3. Cluster structures in Be isotopes
4. Summary

1. Introduction

Cluster & Mean field

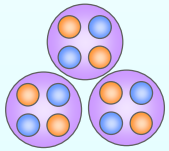
Nuclear system



1. Independent-particle feature
   in self-consistent mean-field
2. Strong nucleon-nucleon correlations

3. Saturation properties

   Energy/nucleon～constant

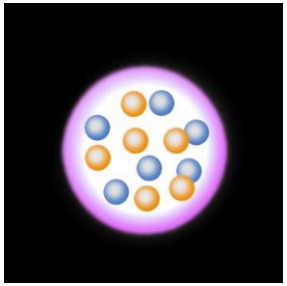


cluster

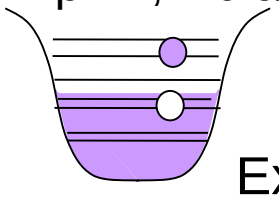
Single-particle motion
v.s.
Many-body correlation

Rich phenomena in ground and excited states

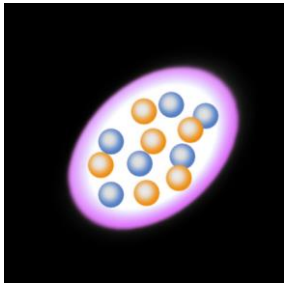
s.p. in mean field



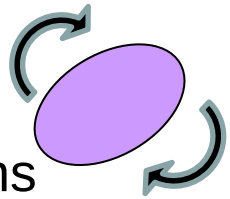
1p-1h, vibration



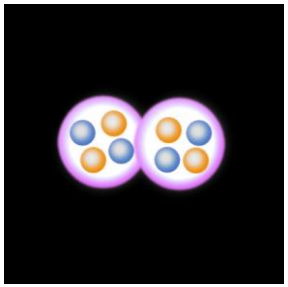
deformation



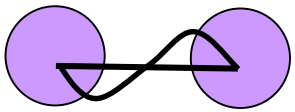
rotation



cluster

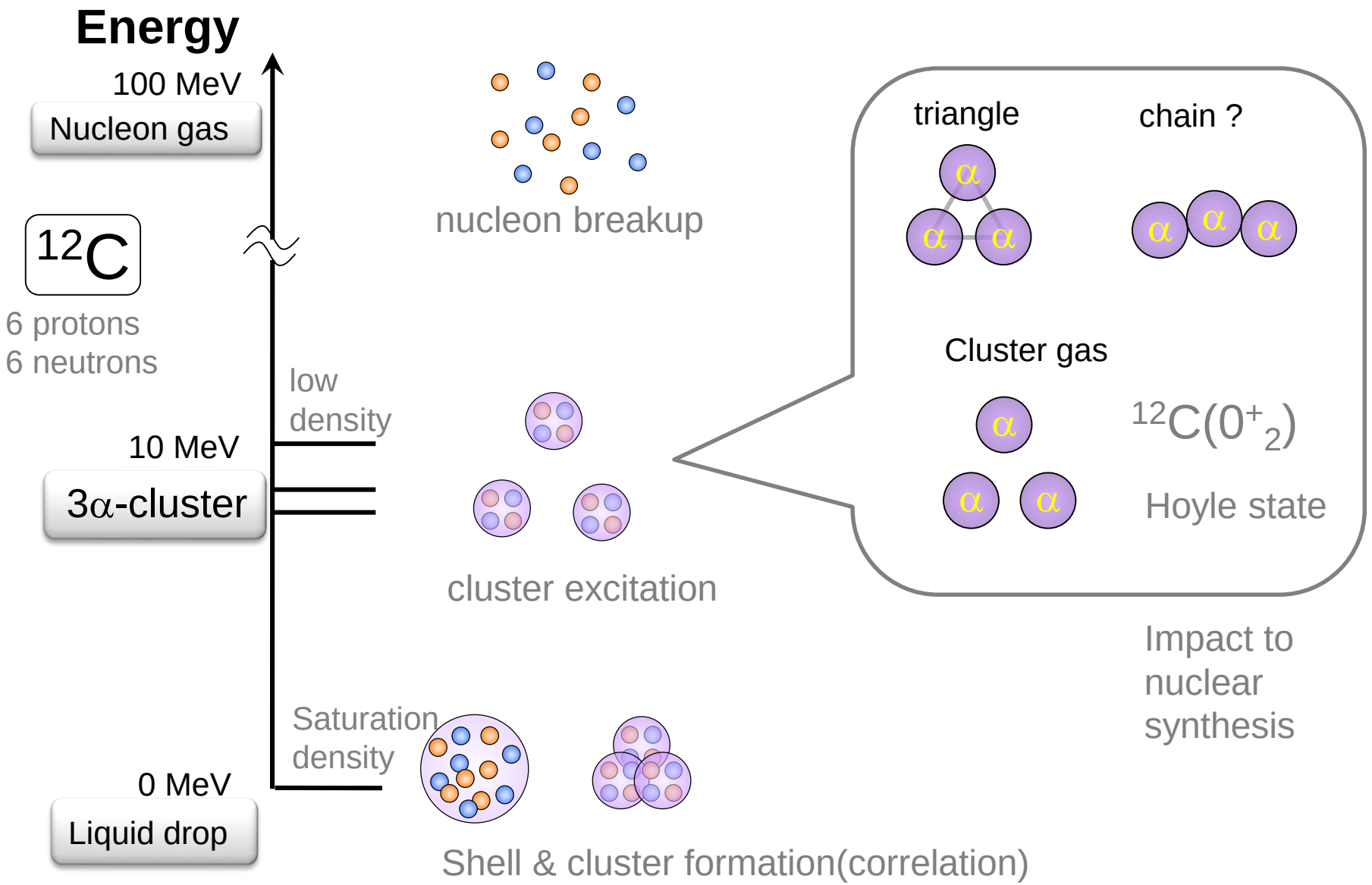


relative motion

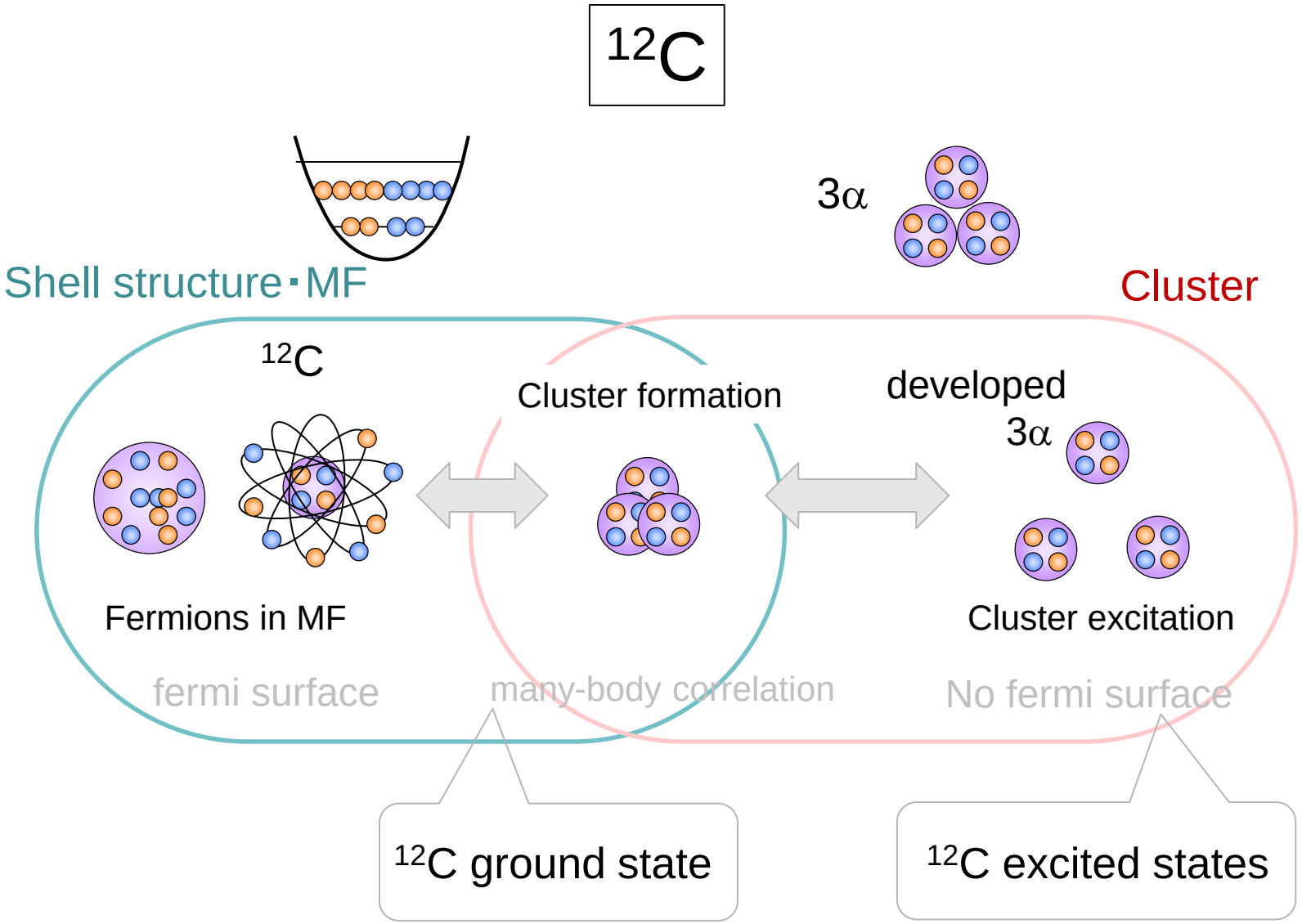


Excitations

Cluster states in low energy

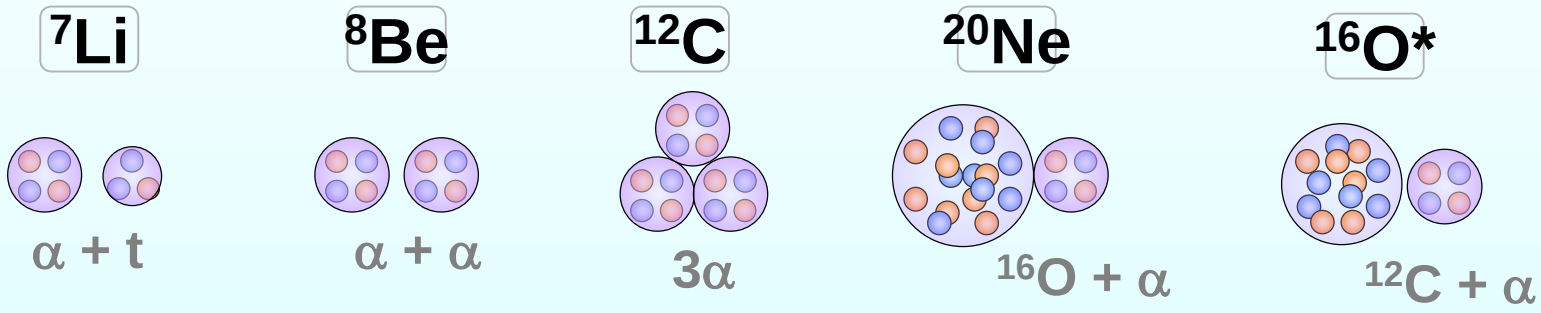


Coexistence of cluster and MF features

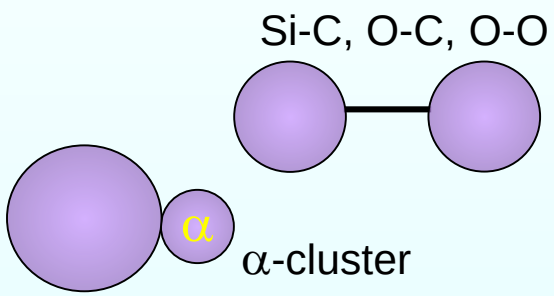


Cluster structures in stable and unstable nuclei

Typical cluster structures known in stable nuclei



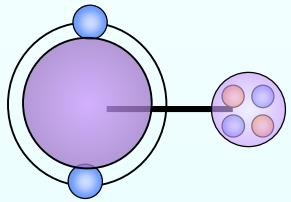
Heavier nuclei



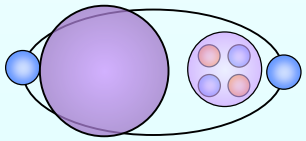
^{36}Ar-α, ^{24}Mg-α, ^{28}Si-α

^{40}Ca*, ^{28}Si*, ^{32}S*

Unstable nuclei (neutron-rich)

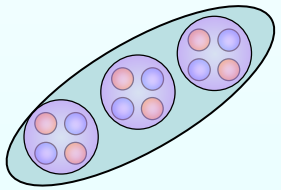


α-cluster excitation



Molecular orbital

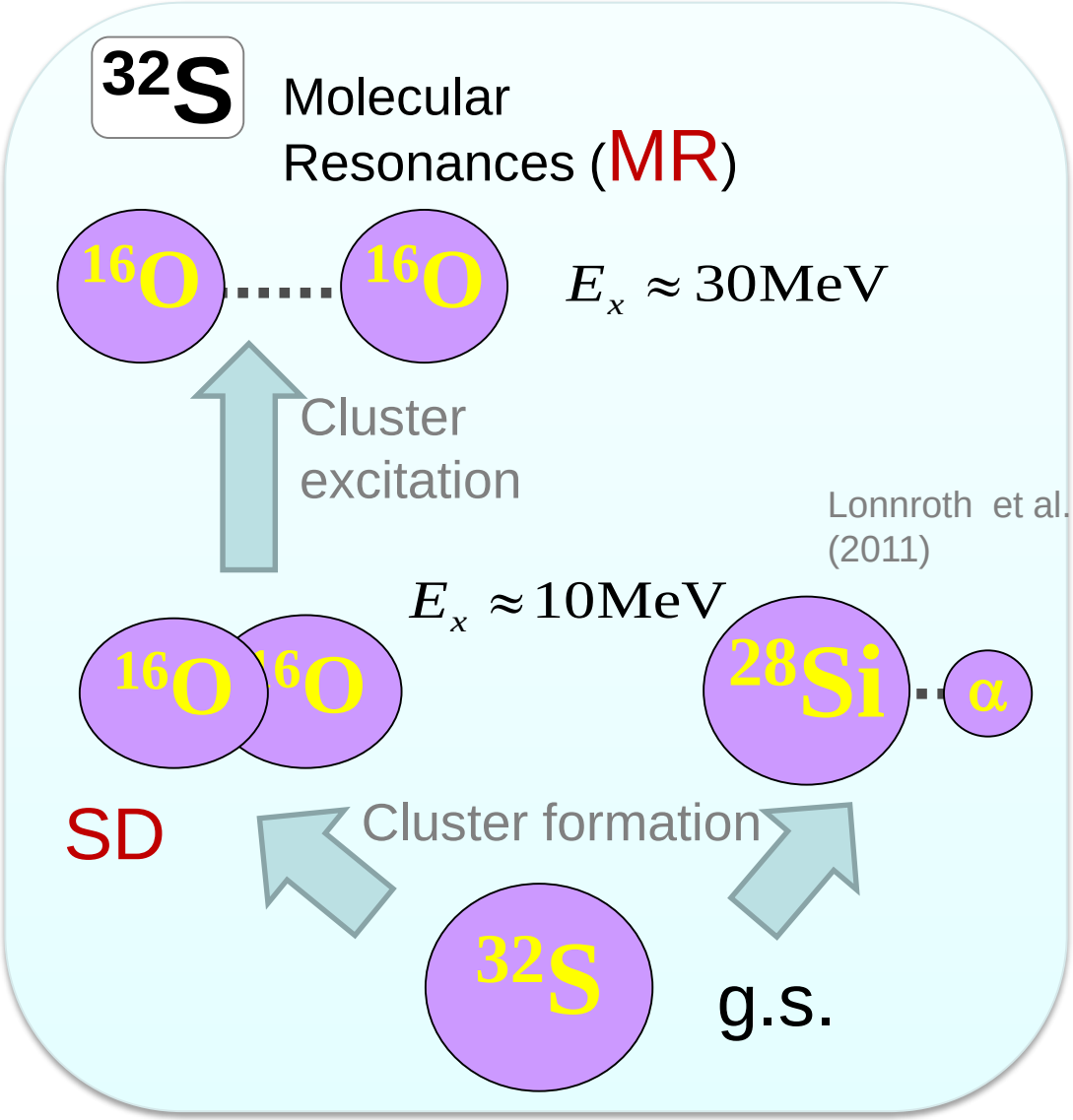
3α linear chain



^{14}C*

Be, C, O, Ne, F

In heavier-mass nuclei



- ✓ SuperDeformation(SD)
- ✓ Molecular Resonance
- ✓ α-cluster

^{32}S: O-O, Si-α

^{40}Ca: Si-C, Ar-α

^{44}Ti: Si-O, Ca-α

^{28}Si: Si-C (MR)

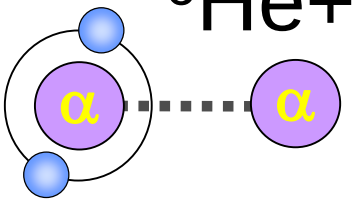
^{56}Ni: Si-Si (MR)

In neutron-rich nuclei

neutron-rich Be isotopes

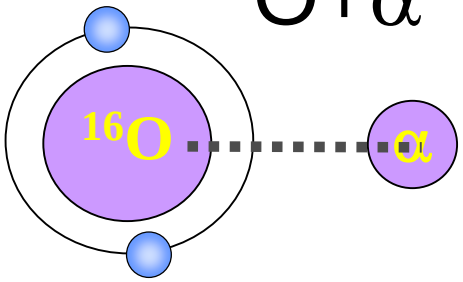
Seya, Von Oerzten, Descouvemont et al.,
Itagaki et al., K-E et al. M. Ito et al.

$^{6}He+\alpha$

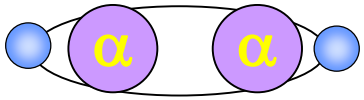


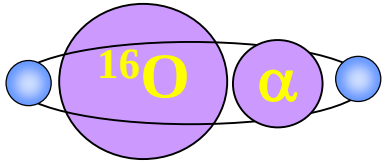
Atomic (resonance)

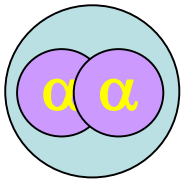
$^{18}O+\alpha$



molecular Bond

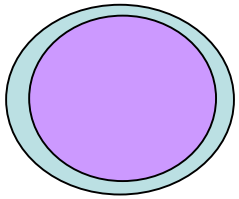






shell model-like

^{10}Be



Kimura et al.,
Yoshida et al.,
Furutachi et al.

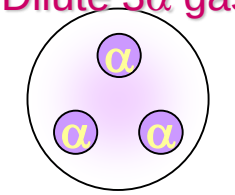
Ne, F, O isotopes

Cluster gas, linear chain

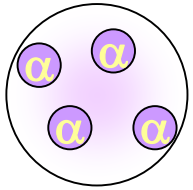
α-cluster gas

Dilute 3α gas

$^{12}C^*(0_2^+)$



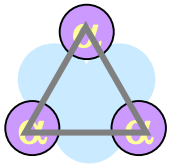
$^{16}O^*$



Tohsaki et al.,
Yamada et al.,
Funaki et al.
Wakasa et al.,

cluster crystalization

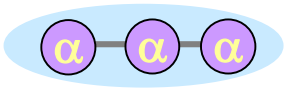
$^{14}C^*(3^-_2)$



triangle

Itagaki et al.,
Von Oertzen et al.

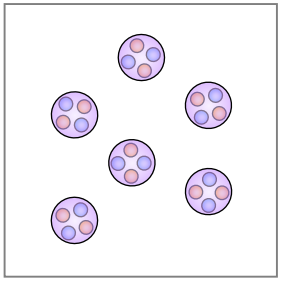
Price et al.
Suhara et al



$^{12,14,15,16}C^*$ linear chain

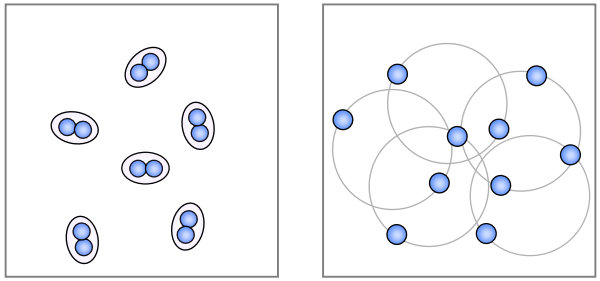
Nuclear matter

α-condensation



Roepche et al.

dineutron-cond.



BEC-BCS matsuo et al.

Rich cluster phenomena in nuclear systems

as functions of proton&neutron numbers and excitation energy

- ✓ Cluster formation/breaking in low-lying states
- ✓ Cluster excitation and resonances
- ✓ Molecular Bond in neutron-rich nuclei
- ✓ Many clusters : cluster gas, chain
- ✓ New types of cluster

t, ^{4}He, ^{12}C, ^{16}O,

^{6,8}He+He in Be, ^{10}Be+α in ^{14}C,

^{14}C+α in ^{18}O, ^{18}O+α in ^{22}Ne

Rich cluster phenomena in nuclear systems

as functions of proton&neutron numbers and excitation energy

- ✓ Cluster formation/breaking in low-lying states
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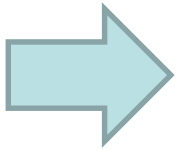
Theoretical framework that can describe those Cluster phenomena



AMD: antisymmetrized molecular dynamics

2. A theoretical model: AMD

AMD method for structure study

AMD wave fn.

$$\Phi = c\Phi_{\mathrm{AMD}} + c'\Phi'_{\mathrm{AMD}} + c''\Phi''_{\mathrm{AMD}} + \cdots$$

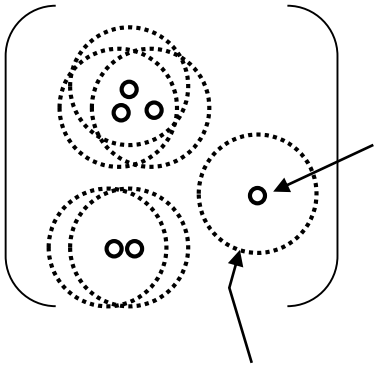
$$\Phi_{\mathrm{AMD}} = \det\{\varphi_1, \varphi_2, \cdots, \varphi_A\}$$ Slater det.

Gaussian

$$\varphi_i = \phi_{Z_i}\chi_i \begin{cases} \text{spatial} & \phi_{Z_i}(\mathbf{r}_j) \propto \exp\left[-\nu\left(\mathbf{r} - \frac{\mathbf{Z}_i}{\sqrt{\nu}}\right)^2\right] \\ \text{Intrinsic spins} & \chi_i = \begin{pmatrix} \frac{1}{2} + \xi_i \\ \frac{1}{2} - \xi_i \end{pmatrix} \times \quad p \text{ or } n \quad \text{isospin} \end{cases}$$

Variational parameters:
Gauss centers, spin orientations

det



Gaussian wave packet

Energy Variation

$$\delta \frac{\langle \Phi | H | \Phi \rangle}{\langle \Phi | \Phi \rangle} = 0$$

Model wave fn. Φ

Effective nuclear force
phenomenological)

$$H^{\mathrm{eff}} = \sum_{i=1} t_i + \sum_{i<j} v_{ij}^{\mathrm{eff}} + \sum_{i<j<k} v_{ijk}^{\mathrm{eff}}$$

AMD model space

det

a variety of cluster st.

det

shell model state

Energy variation

Energy surface

$$\frac{d\mathbf{Z}}{dt} = (\lambda + i\mu)\frac{1}{i\hbar}\frac{\partial E}{\partial \mathbf{Z}^*}$$

$\Phi(\mathbf{Z}^0)$

model space (Z plane)

randomly chosen initial state

$$\delta \frac{\langle \Phi | H | \Phi \rangle}{\langle \Phi | \Phi \rangle} = 0$$

optimum solution is obtained

AMD wave function is similar to FMD wave function. Difference is effective interaction

3. Some topics of cluster phenomena

Topics of cluster phenomena

- Cluster gas, chain states
- Cluster structures in Be isotopes

Topics of cluster phenomena

- Cluster gas, chain states
- Cluster structures in Be isotopes

Cluster states in excited states

Various modes of cluster excitation,
and their rotation

^{12}C

$0^+_{3,4}$

2^+_2

3^-_1

7.65 MeV

$^8Be+\alpha$

0^+_2

Hoyle st.

0^+_1

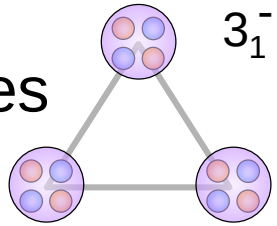
p3/2-shell

+

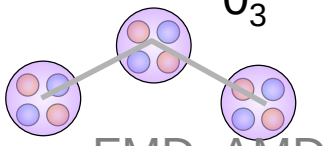
3α

Geometric ?

triangles



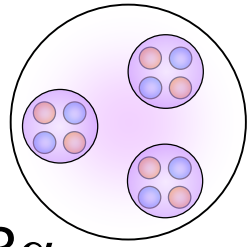
Bending chain?



FMD, AMD

dilute cluster gas

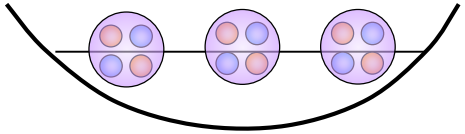
Uegaki et al. (1977)
Tohsaki et al.(2001)



3α

bosonic behavior

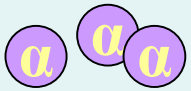
Funaki et al. (2003)



analogy to **BEC**
in nuclear matter
Roepke et al., PRL(1998)

Cluster gas

^{12}C



chain ?

$0^+_{3,4}$

10.3 MeV

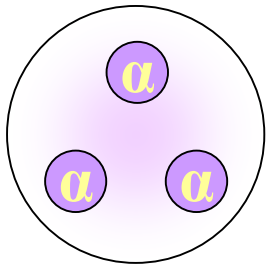
0^+_2 7.65 MeV

$^8Be+\alpha$

A.Tohsaki et al., (2001)
Funaki et al.(2003)

Dilute cluster gas

Bosonic behavior



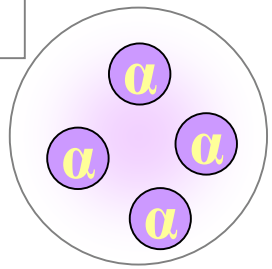
0^+_1

+ $p_{3/2}$

$3\alpha+p_{3/2}$closed

^{16}O

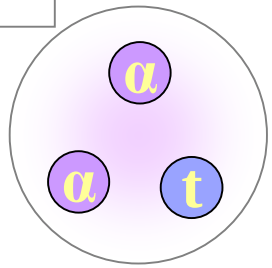
Tohsaki et al., Yamada et al.,
Funaki et al. Wakasa et al.,



$^{16}O(0^+_6)$?

^{11}C, ^{11}B

K-E. et al., Suhara et al



Problems

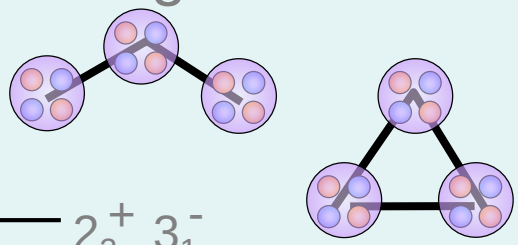
- ✓ Cluster gas in other nuclei
- ✓ rotation of clusters gas?

2α+t cluster in $^{11}B(3/2^-_3)$

AMD by Y.K-E., Suhara

^{12}C

triangle ?

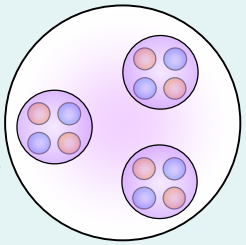


0_3^+

2_2^+ 3_1^-

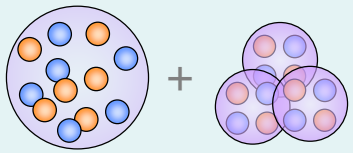
0_2^+ 7.65 MeV

$^8Be+\alpha$



cluster gas of 3α

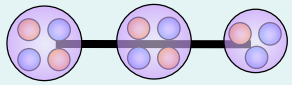
0_1^+



^{11}B, ^{11}C

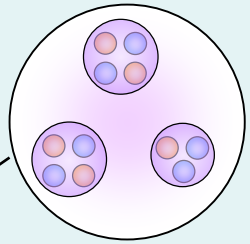
PRC75, 024302 (2007)
PRC85, 054320 (2012)

2α+t chain?



2a+t

2α+t gas

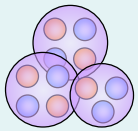


^7Li+a

$3/2^-_3$

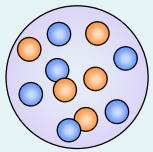
8.5

$3/2^-_2$



Strong E0
Weak M1,GT

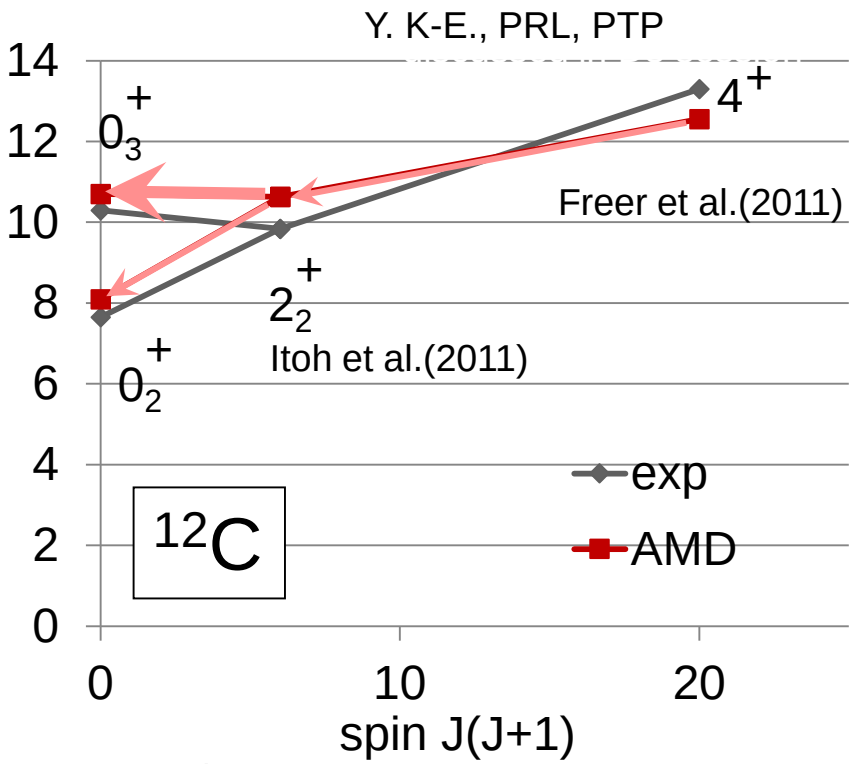
$3/2^-_1$

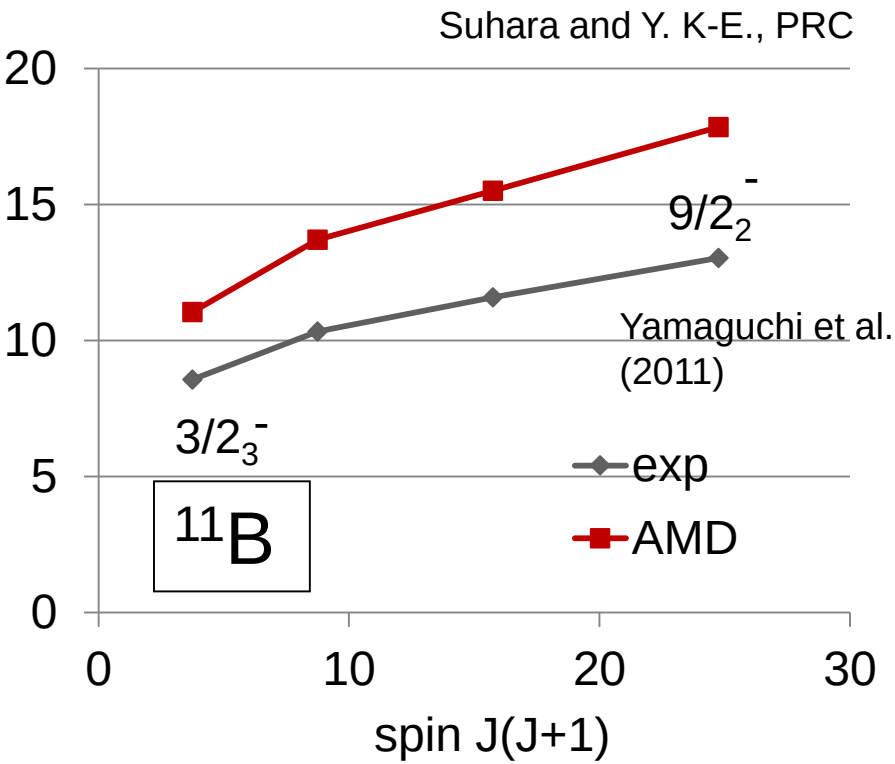


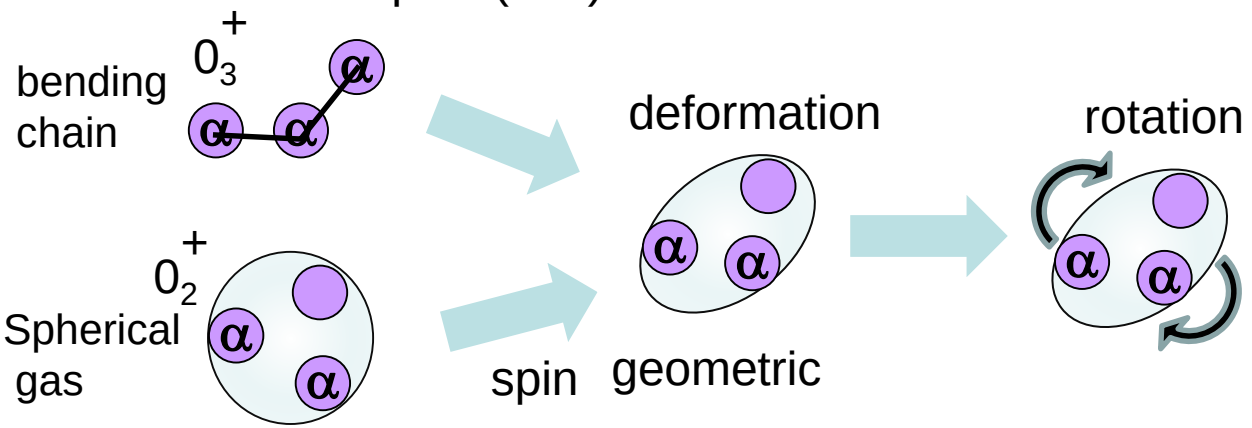
Kawabata et al.
PLB646, 6 (2007)

Rotational(?) band from cluster gas

Structure change with spin increasing -> change of moment of inertia







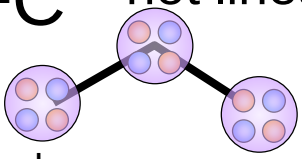
rotation of 3α, 4α gas
Ohkubo et al., PLB684(2010)
Funaki et al. PTPS196 (2012)

Linear chain state in $^{14}C^*$

Neutron-rich

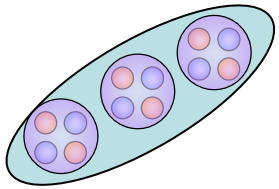
^{12}C → $^{14,16}C$

$^{12}C^*$ not linear



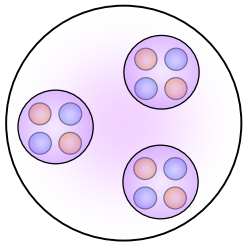
0_3^+ Y.K-E.et al., T. Neff et al.

$^{14}C^*, ^{16}C^*$

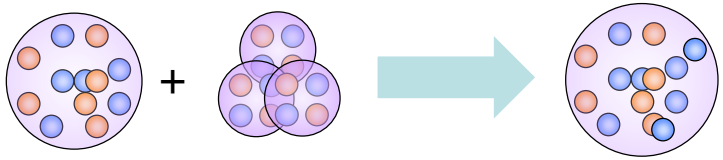


Linear chain?

von Oertzen et al.
Itagaki et al.
Y.K-E.et a.
Suhara et al.



0_2^+

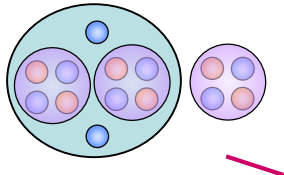


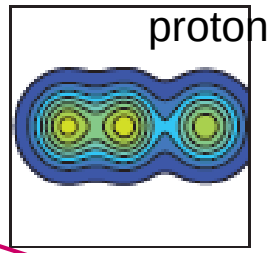
^{12}C g.s. ^{14}C g.s.

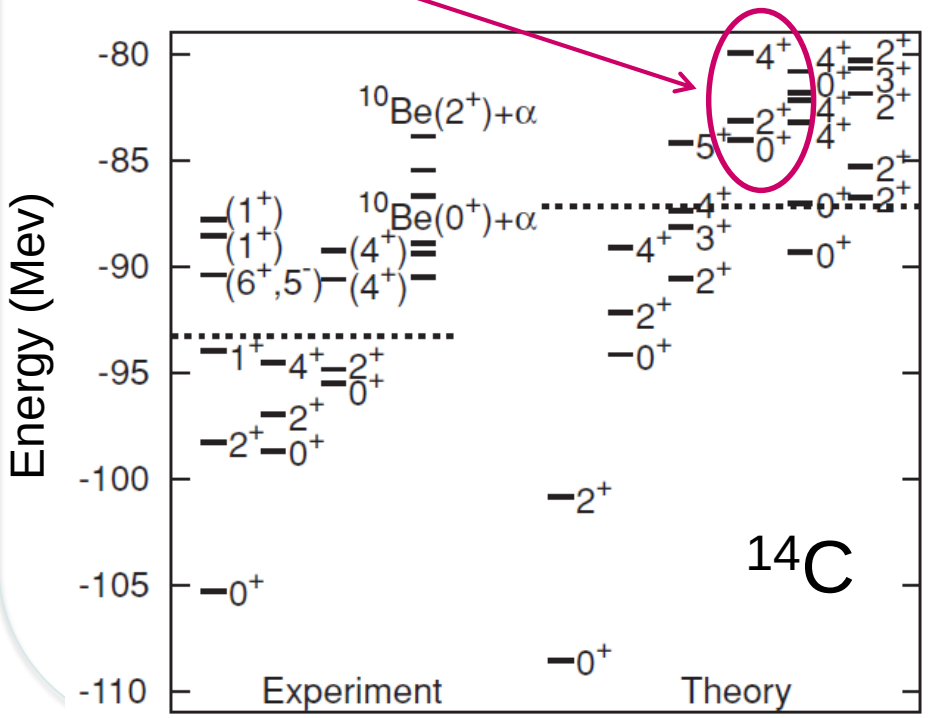
^{14}C

AMD by T.Suhara and Y.K-E, Phys.Rev.C82:044301,2010.

3α linear chain







Topics of cluster phenomena

- Cluster gas, chain states

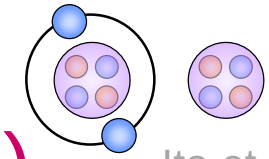
- Cluster structures in Be isotopes

Cluster structures in neutron-rich Be

Atomic (cluster Resonance)

MO bond

Normal

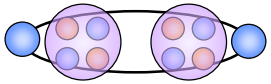


$^{6}He+^{4}He$

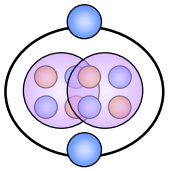
0_3^+

Ito et al.
Kobayashi et al.
Kuchera et al.

Molecular orbital

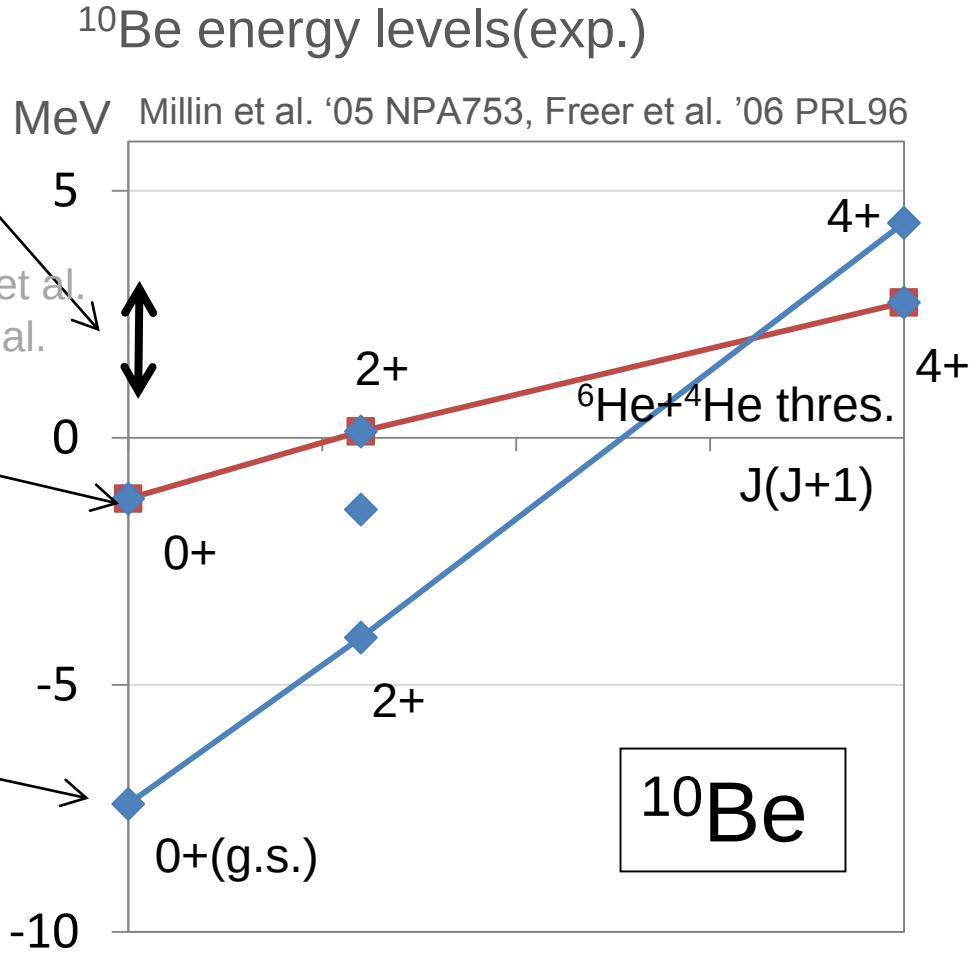


0_2^+



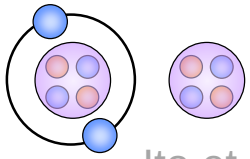
0_1^+

Normal state

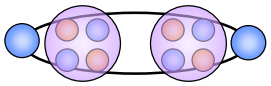


Cluster structures in neutron-rich Be

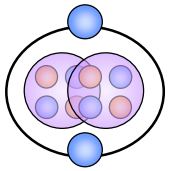
$^{6}He+^{4}He$



Ito et al.
Kobayashi et al.
Kuchera et al.



Molecular orbital



Normal state

Atomic: cluster resonance

He+He resonances in Be
He+t res. In ^{9}Li

MO bond

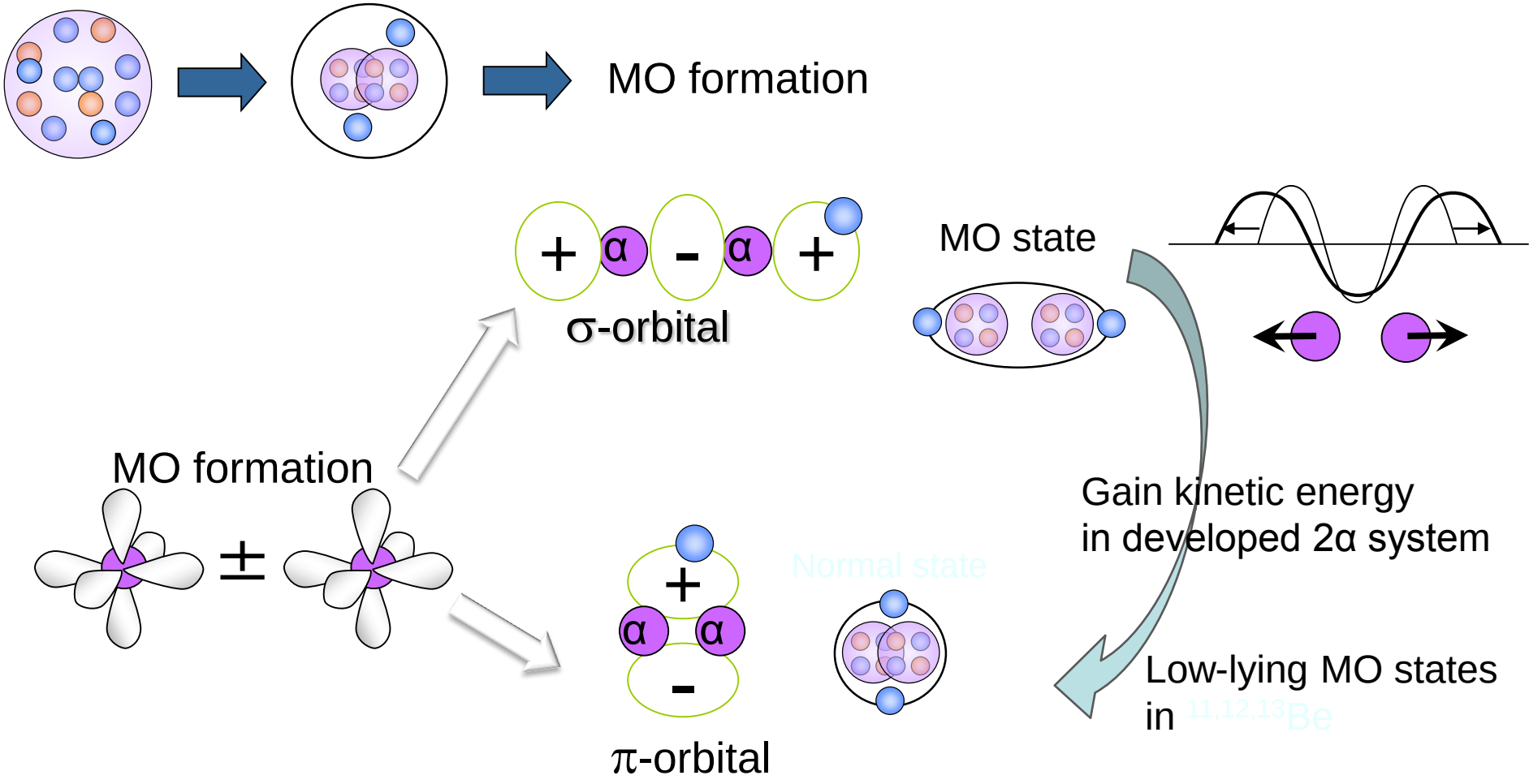
Vanishing of magic number in ^{11}Be, ^{12}Be, ^{13}Be

Normal: shell-model like

MO bond and vanishing of magic number N=8 in Be

Molecular orbital(MO) bond in Be

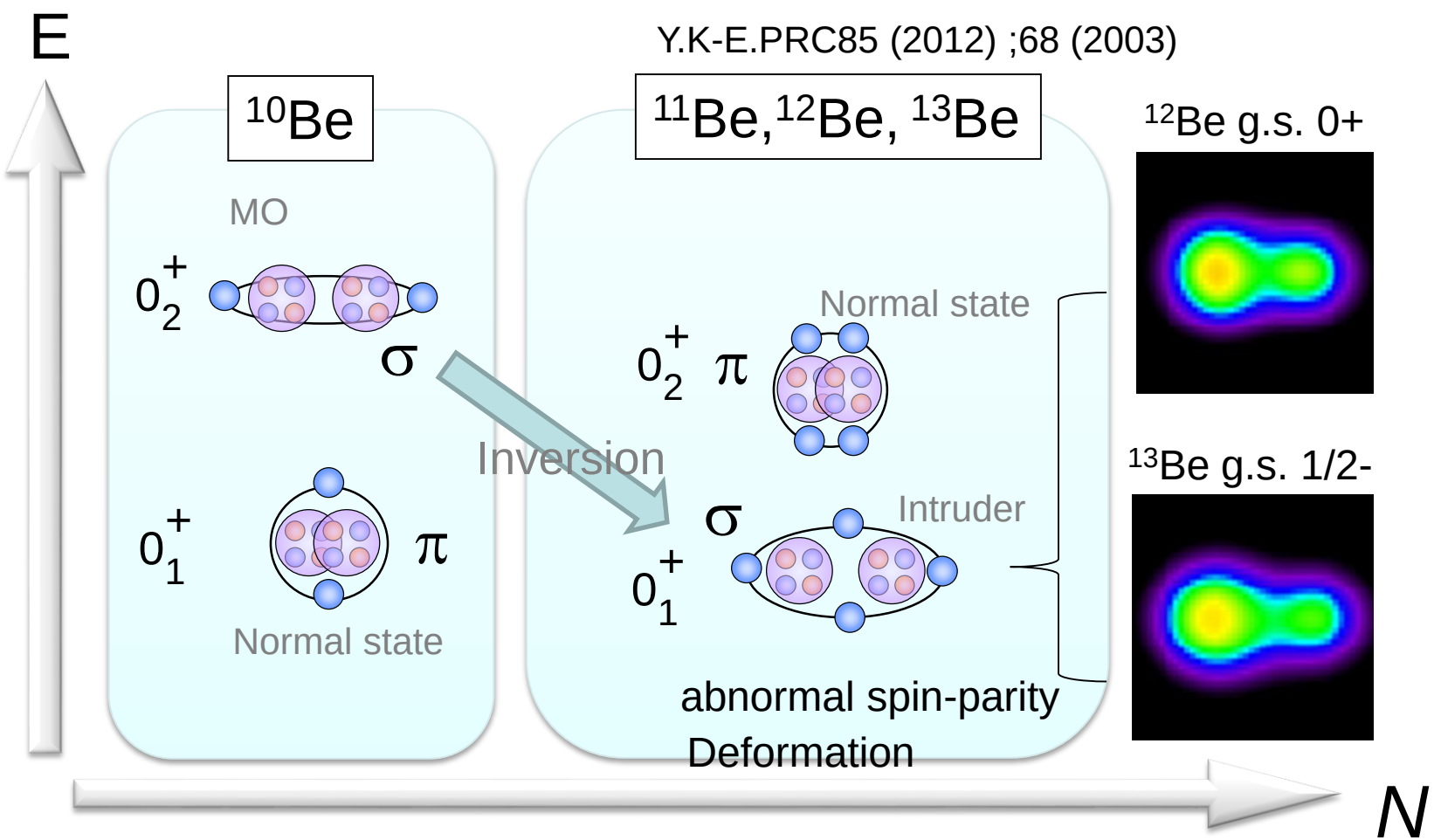
Seya et al. Von Oertzen et al.,



vanishing of magic number in ^{11}Be, ^{12}Be, ^{13}Be

Recent exp. for ^{13}Be
Kondo et al. PLB690(2010)

Vanishing of N=8 magic number in neutron-rich Be



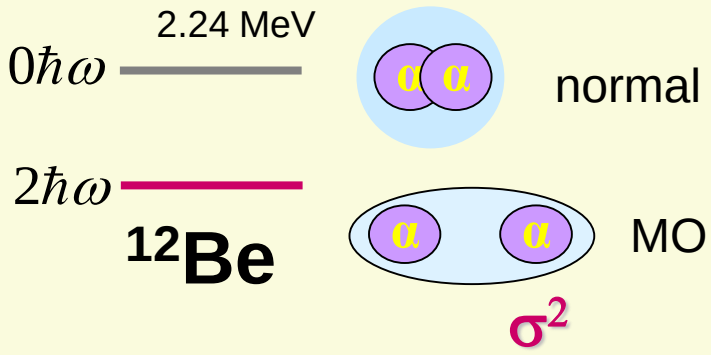
Exp:Iwasaki et al., Navin et al., Pain et all. Kondo et al.

^{12}Be:Vanishing of magic number N=8

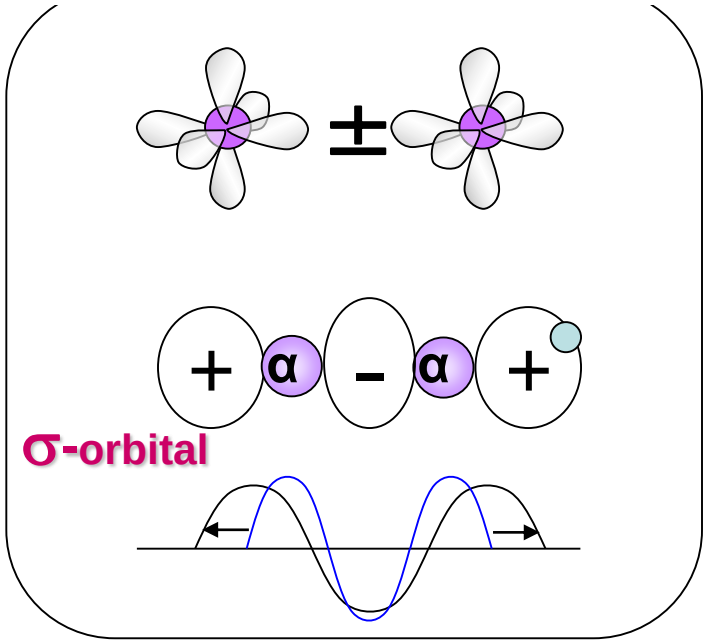
Breaking of magicity (N=8) in ^{12}Be

0_2^+ (2.24MeV) $0\hbar\omega$

0_1^+ intruder $2\hbar\omega$ state



Formation of 2α+molecular orbitals



Deformed ground state with d-wave components

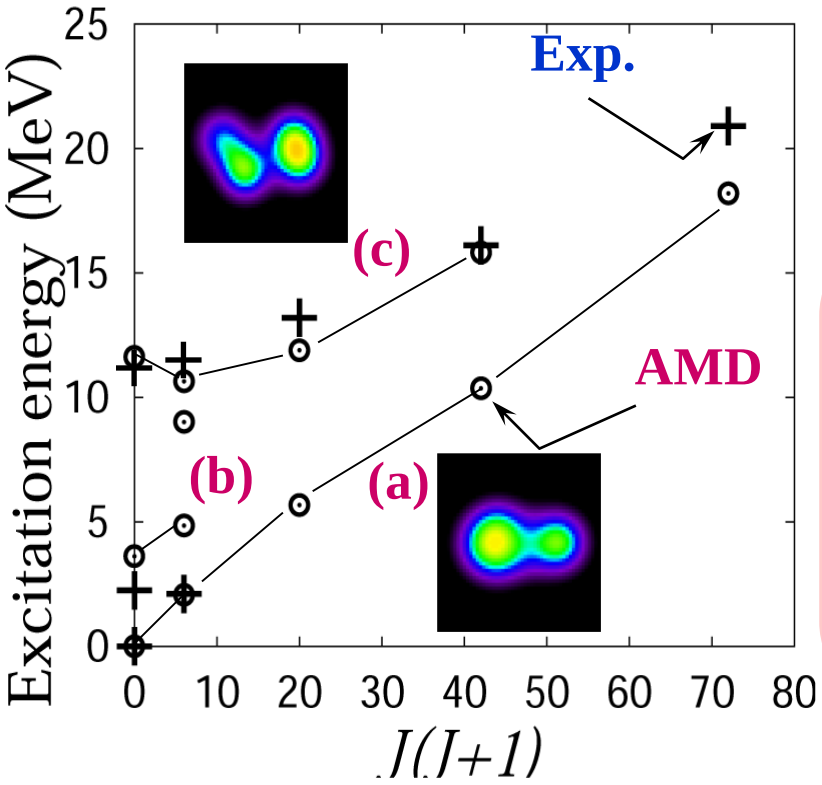
Experiments: Iwasaki et al.,
Navin et al., Pain et all.

AMD result of ^{12}Be

VAP calculation with AMD method

^{12}Be

positive parity states with normal spins

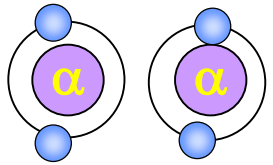


Y.Kanada-En'yo et al., PRC 68, 014319 (2003)

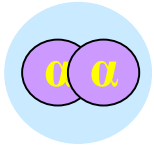
Highly excited states

^{6}He+^{6}He

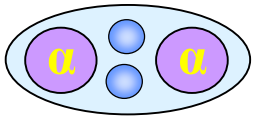
0^+_3



0^+_2 (2.24MeV) $0\hbar\omega$



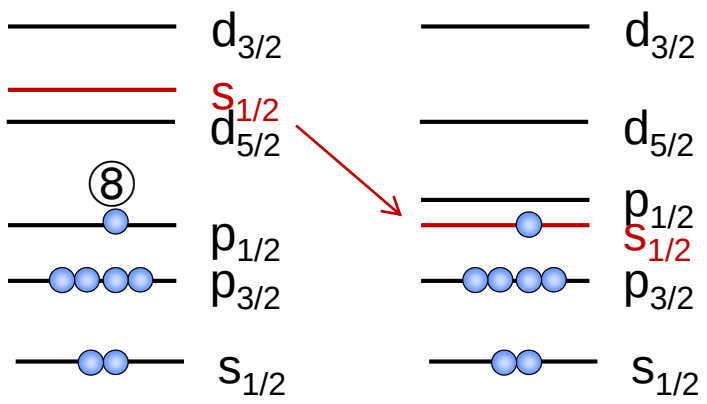
0^+_1 intruder $2\hbar\omega$



Breaking of N=8 magicity

Formation of 2α+molecular orbitals

Parity inversion of ^{11}Be(1/2+,1/2-)



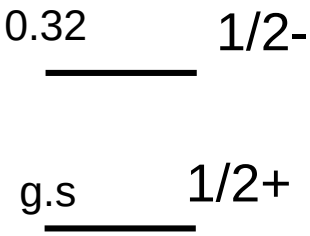
Intruder !

1/2- g.s.

Normal
N=7 nuclei

1/2+ g.s.
in 11Be

Z=4, N=7

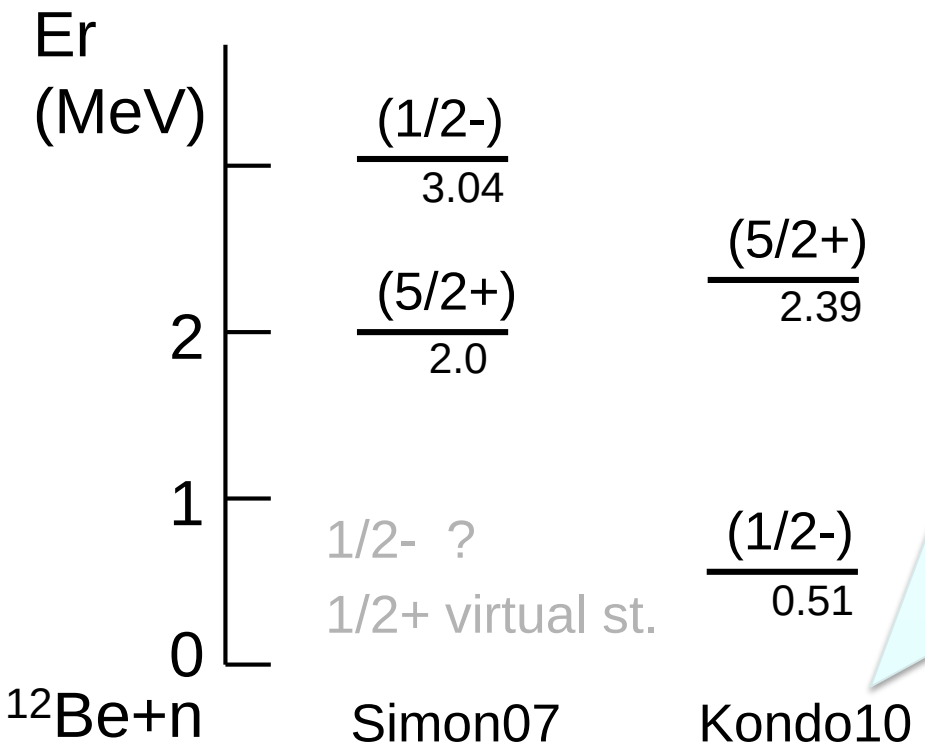


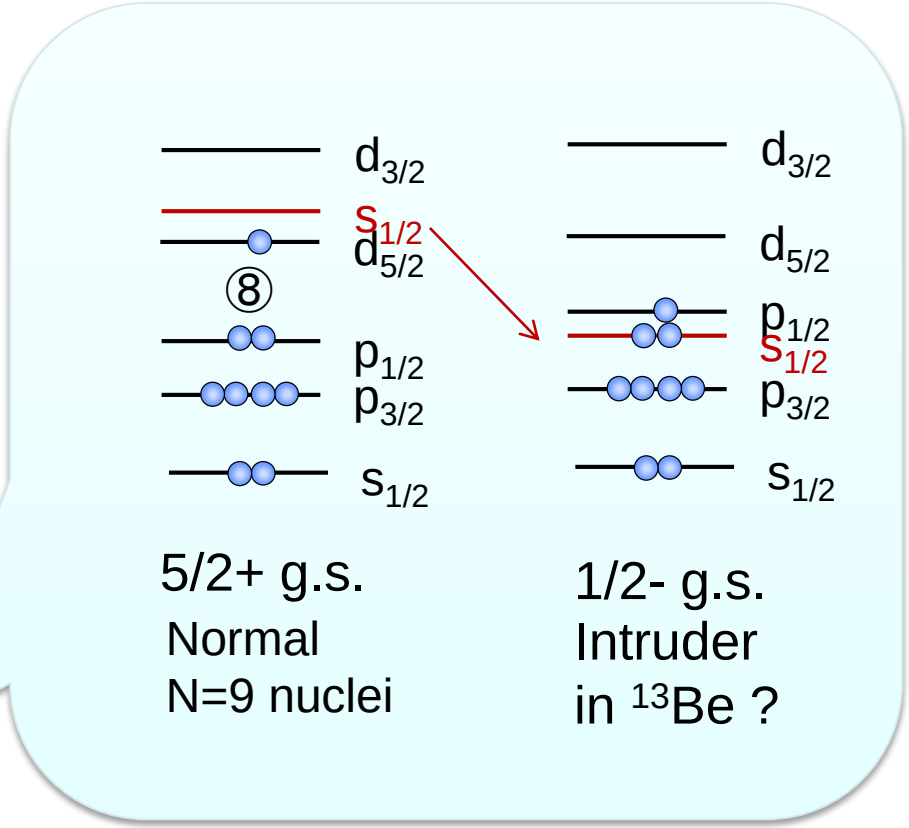
^{11}Be

^{13}Be spectra

^{13}Be: unbound

^{13}Be spectra has been measured by 1n knock-out reactions at GSI(Simon et al. 2007) and RIKEN(Kondo et al.,2010)

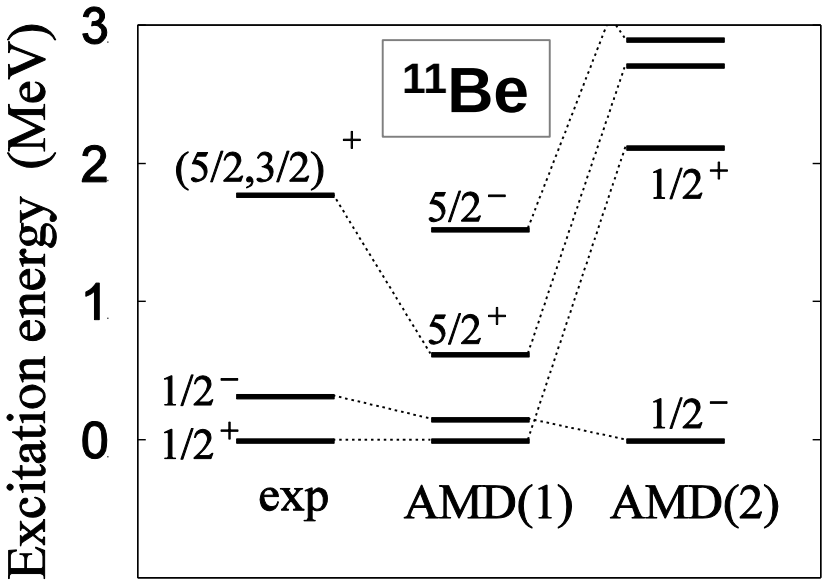




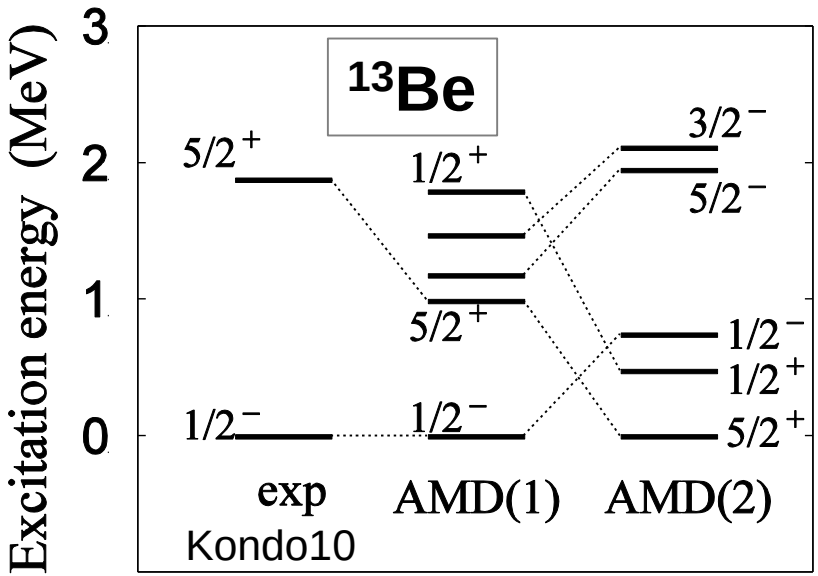
Be isotopes calculated with AMD+VAP

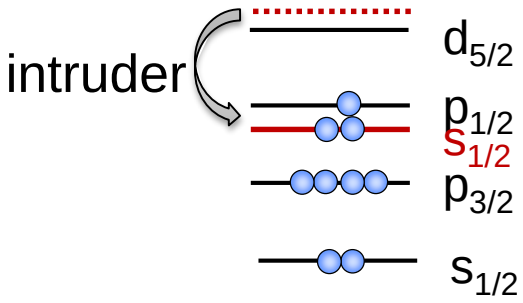
Eff. interactions
MV1(m=0.65)+G3RS force
- set(1) : u=3700 MeV (ls force)
- set(2) : u=2500 MeV

AMD calculation using set(1) interaction:
- 1/2+ ground state in 11Be.
- Intruder ground state in 12Be.
- lowest 1/2- state in 13Be.



Y. K-E. et al. PRC66, 024305(2002); PRC68, 014319 (2003)

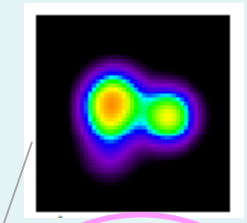




1/2- is lowest in ^{13}Be

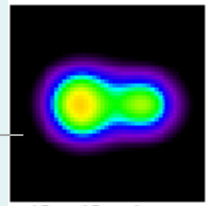
Cluster structures in Be isotopes

^{11}Be

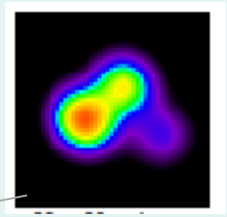


1/2- 0$\hbar\omega$

1/2+ 1$\hbar\omega$



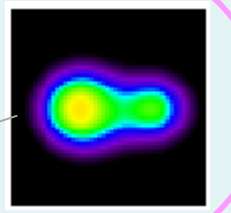
^{12}Be



^{12}Be(0hw)

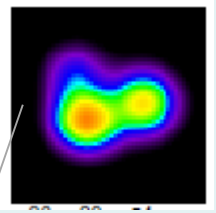
$0+_2$ 0$\hbar\omega$

$0+_1$ 2$\hbar\omega$



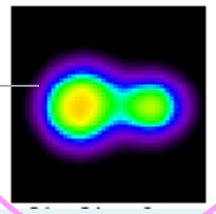
^{12}Be(2hw)

^{13}Be



5/2+ 0$\hbar\omega$ ^{12}Be(0hw)+n

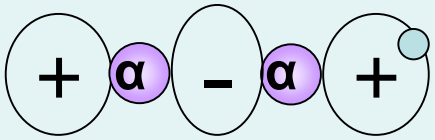
1/2- 1$\hbar\omega$



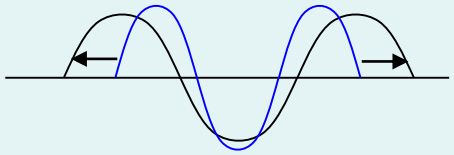
^{12}Be(2hw)+n

Intruder states are well deformed states with developed 2-alpha cores.
Similar structures in Be isotopes.

Molecular
σ-orbital



von Oertzen et al.
Seya et al.



Cluster resonances in Be and 9Li

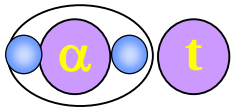
3. ^{6}He+t cluster states in ^{9}Li

cluster resonances

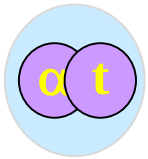
Search for ^{6}He+t cluster state in 9Li

Cluster res. ?

^{6}He+^{3}H



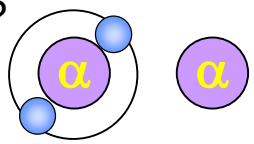
MO bond ?



^{9}Li

Freer et al.'99 PRL.82:1383
Freer et al. '06 PRL.042501

$0^{+}_{3,4?}$ ^{6}He+^{4}He

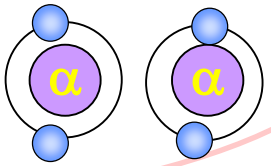


Cluster res.

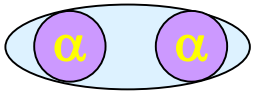
Kuchera et al.
Ito et al.
Kobayashi et al.

^{6}He+^{6}He

0^{+}_{3}



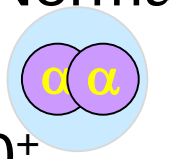
0^{+}_{2}



MO bond

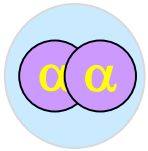
Millin et al. '05 NPA753,
Freer et al. '06 PRL96
2+(7.54) and 4+(10.2)

Normal



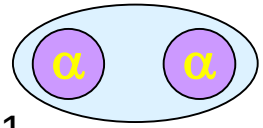
0^{+}_{2}

$K=0^{+}_{1}$



Normal

0^{+}_{1}



MO

^{10}Be

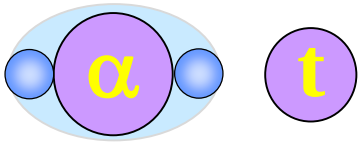
von Oertzen '96, '97, ZPA 354, 37
Seya et al. '81 PTP65, 204

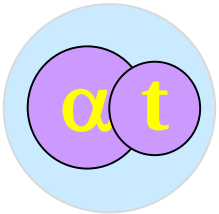
^{12}Be

Developed $^{6}He+^{3}H$ cluster states in ^{9}Li

K=1/2- band with $^{6}He+^{3}H$ cluster structure is suggested

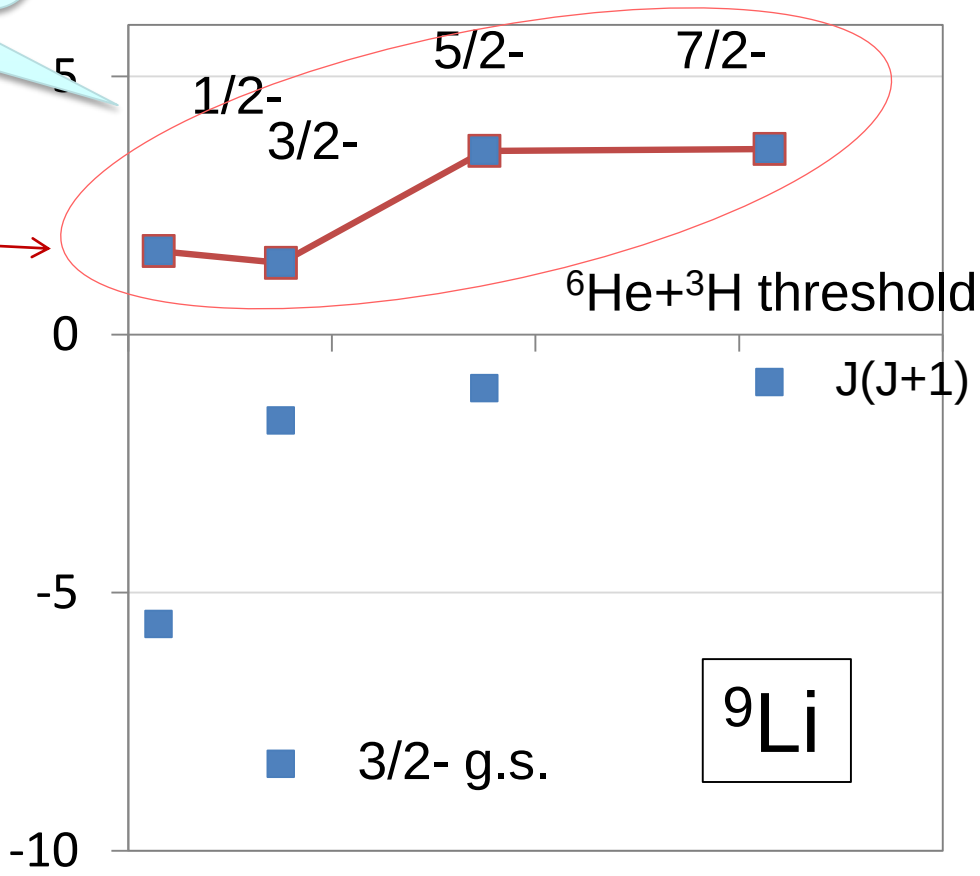
$^{6}He+^{3}H$ resonance



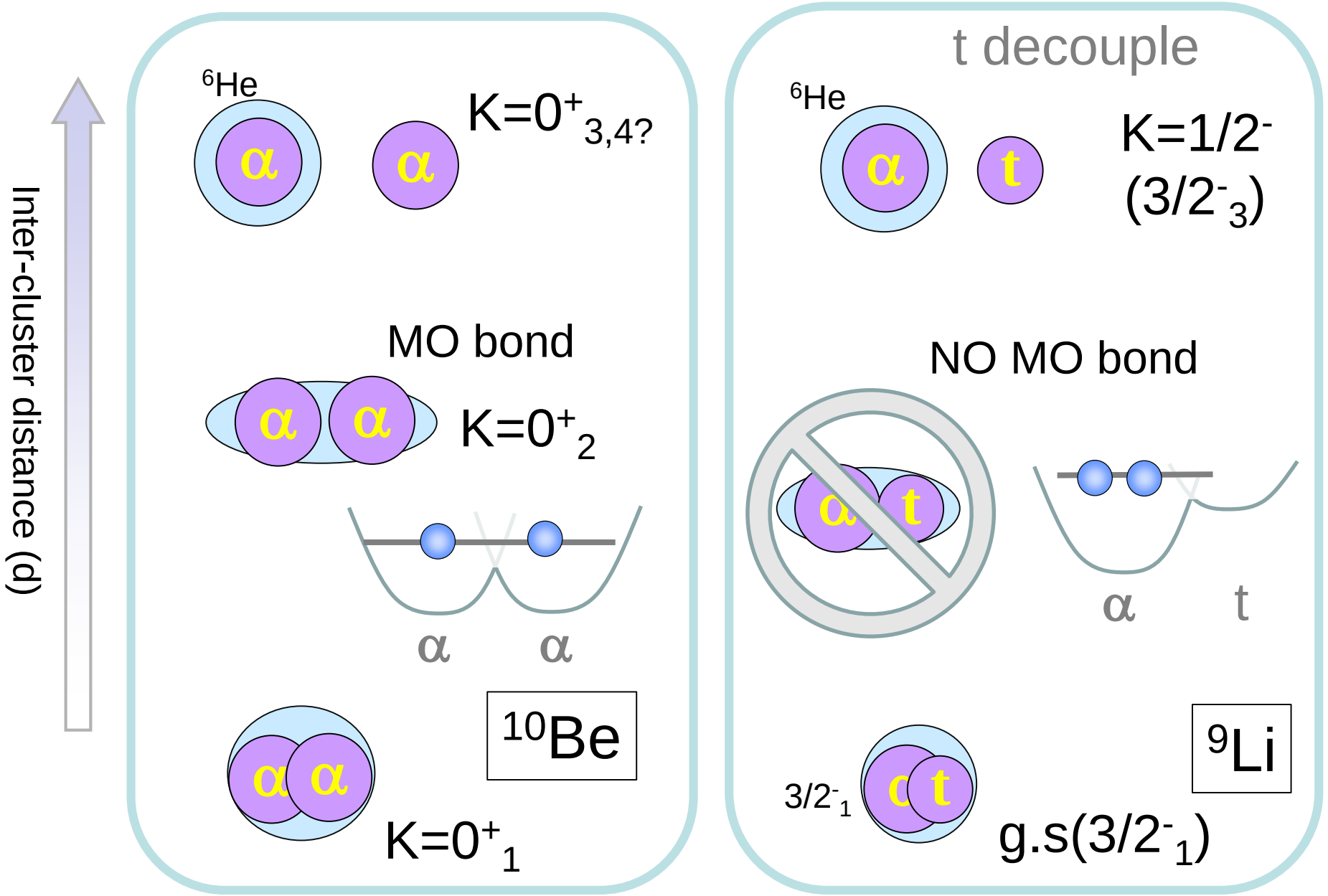


^{9}Li

^{9}Li: energy levels(calculation)



Cluster structures in ^{10}Be and ^{9}Li



5. Summary

Cluster aspects in ground and excited states

◆Cluster gas, chain states

- Cluster gas often appears in general nuclei
- Cluster gas is not stable in the rotation
- Chain structure of alpha clusters in neutron-rich C

◆Cluster structures in Be isotopes

- 2α clusters and valence neutron
- MO bond structure and breaking of magic number N=8
- 6He+α Cluster resonances , and 6He+t resonances