Clustering in light neutron-rich nuclei

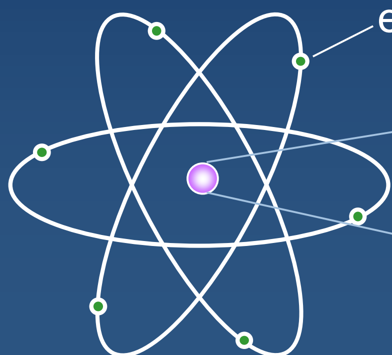
Y. Kanada-En'yo (Kyoto Univ.)

Collaborators:
Y. Hidaka(Riken), M. Kimura(Hokkaido),
F. Kobayashi(Niigata), H. Morita(Kyoto),
T. Suhara (Matsue) ,Y. Taniguchi(NIMS),
Y. Yoshida (Kyoto)

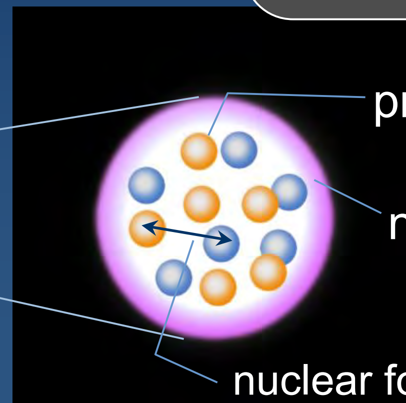
1.Introduction

Nuclear system

atom



nucleus

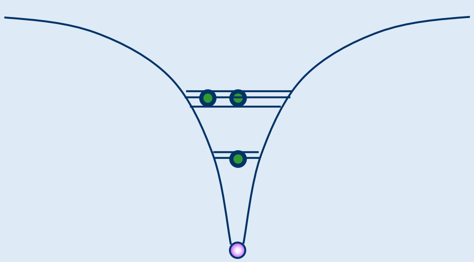


A finite quantum many-body system of protons and neutrons

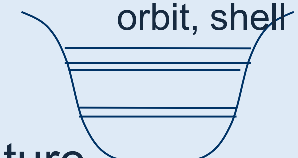
Analogy & Differences

Electron motion

Confined by the external field



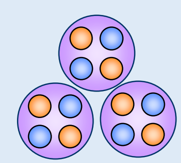
Nucleon motion



Self-bound

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

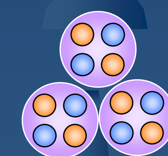
cluster



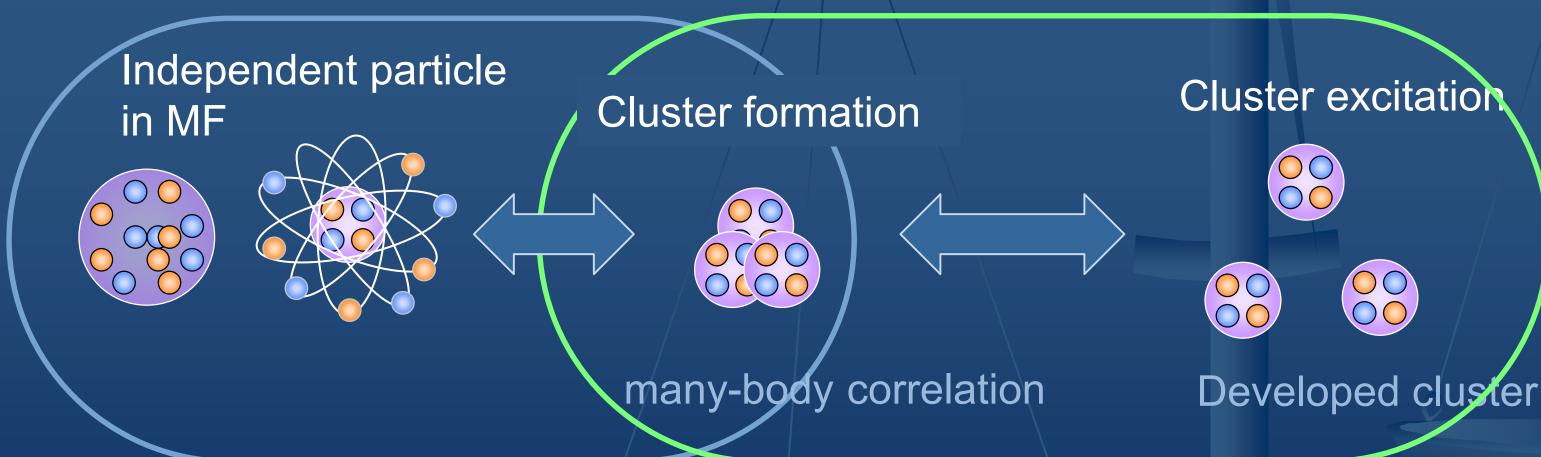
Cluster & Mean field

Mean field, shell structure
Independent single-particle

Cluster:
Many-body correlation



Shell structure・MF v.s. Cluster



no correlation | cluster correlation | excited states

Cluster structures

Nuclear structure

^{12}C

Energy

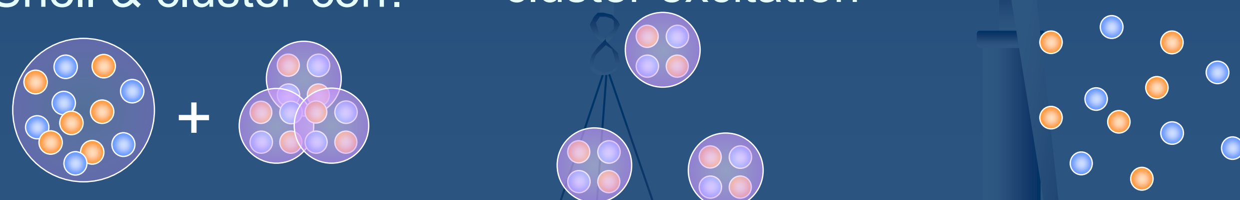
0 MeV

Shell & cluster corr.

10 MeV

cluster excitation

100 MeV



Nucleon liquid
Fermi gas, BCS, DW

Cluster gas, crystal

Nucleon gas

high density ↔ low density

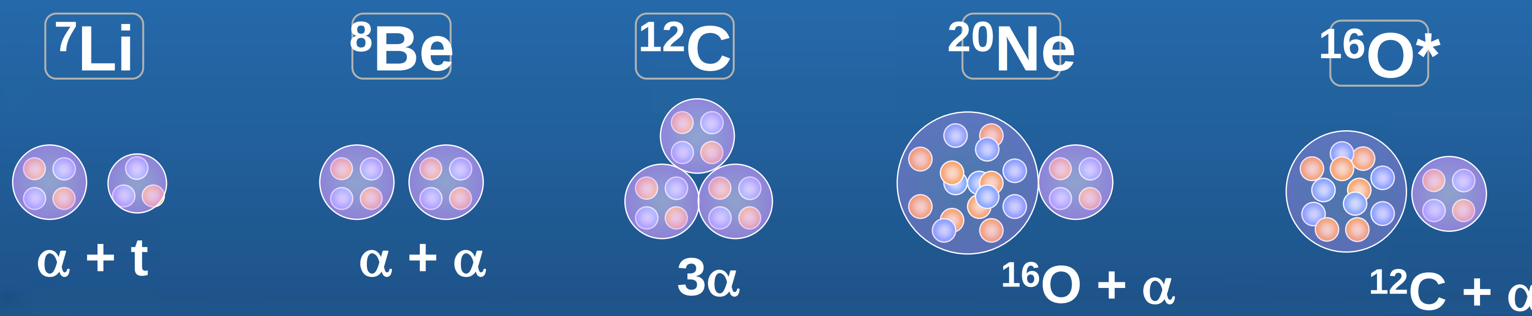
ρ_0

$\rho_0/3\sim\rho_0/5$

Cluster enhancement

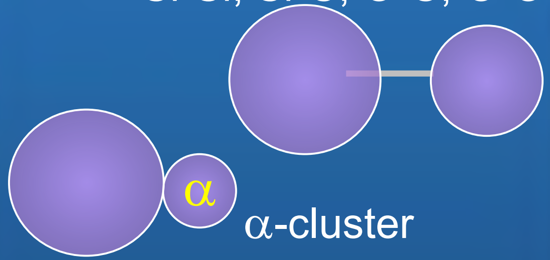
Cluster structures in stable and unstable nuclei

Typical cluster structures known in stable nuclei



Heavier nuclei

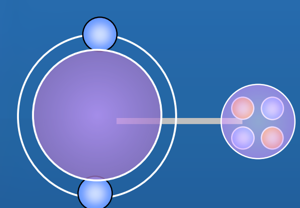
Si-Si, Si-C, O-C, O-O



^{36}Ar-α, ^{24}Mg-α, ^{28}Si-α

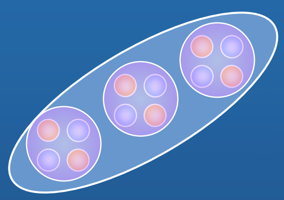
^{40}Ca*, ^{28}Si*, ^{32}S*

Unstable nuclei

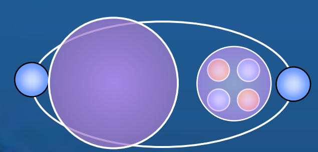


α-cluster excitation

3α linear chain



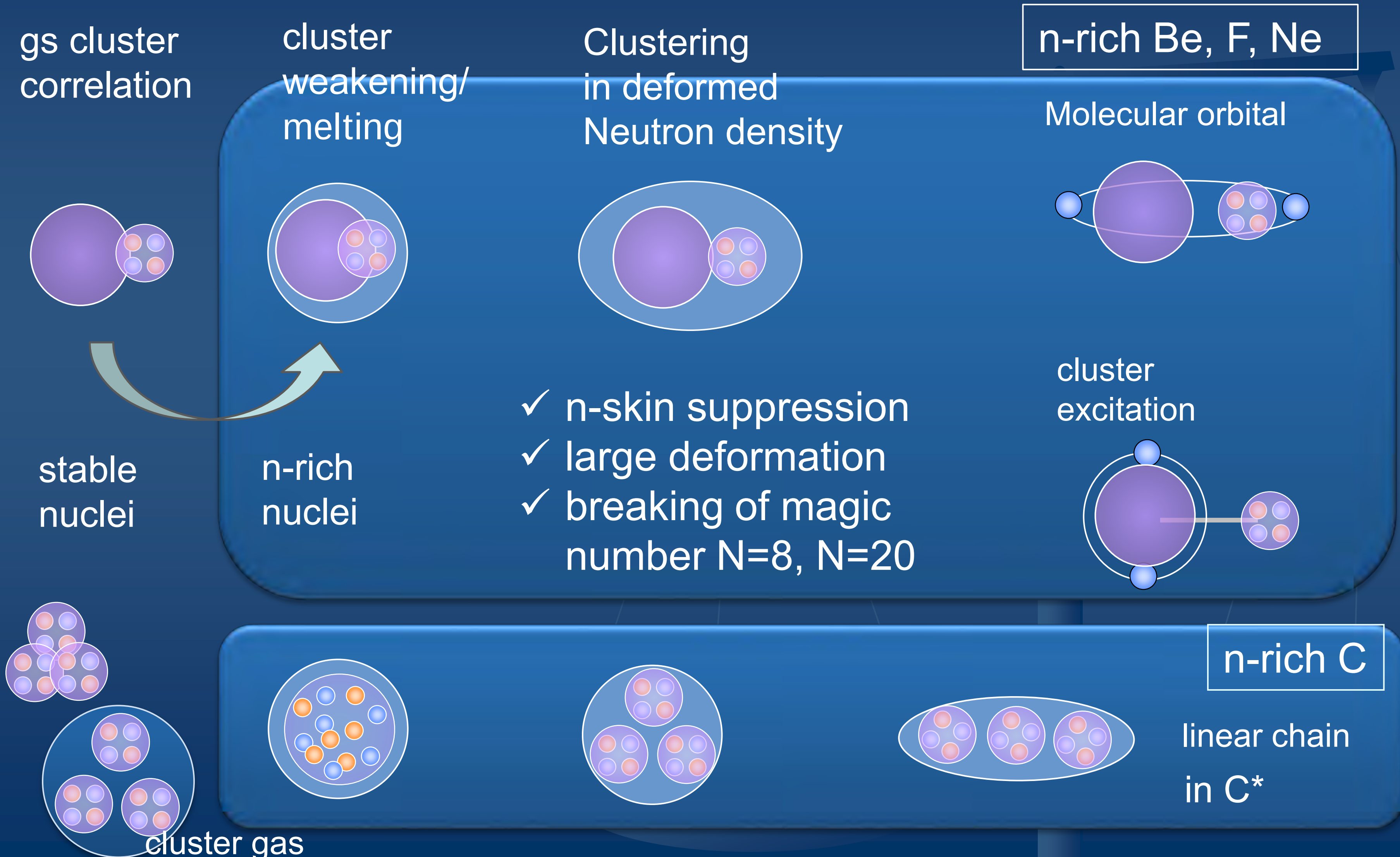
^{14}C*



Molecular orbital

Be, C, O, Ne, F

Cluster structures in n-rich nuclei



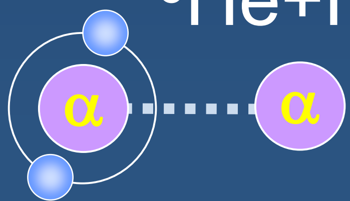
Two modes in n-rich nuclei with cluster structures

^{10}Be

Soic et al., Freer et al., Saito et al., Curtis et al., Milin et al., Bohlen et al., Seya, Von Oerzten, Descouvemont et al., Itagaki et al., Dote et al., K-E et al. Arai et al., M. Ito et al.

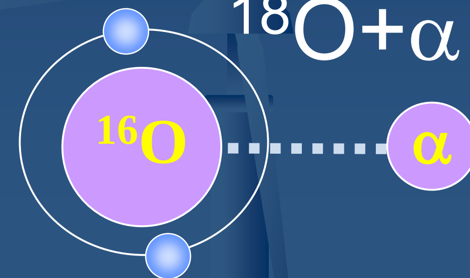
Scholz et al., Rogachev et al., Goldberg et al., Ashwood et al., Yildiz et al., Descouvemont, Kimura,

^{6}He+He

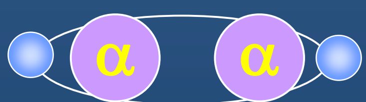


Atomic:
Cluster resonance

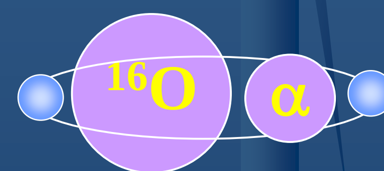
$^{18}O+\alpha$



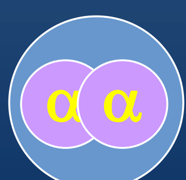
Weak coupling



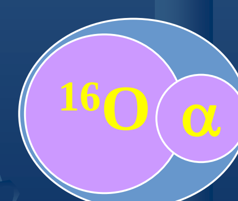
Molecular Orbital:
σ-bond structure



Strong coupling



Normal states



shell model-like

Be isotopes

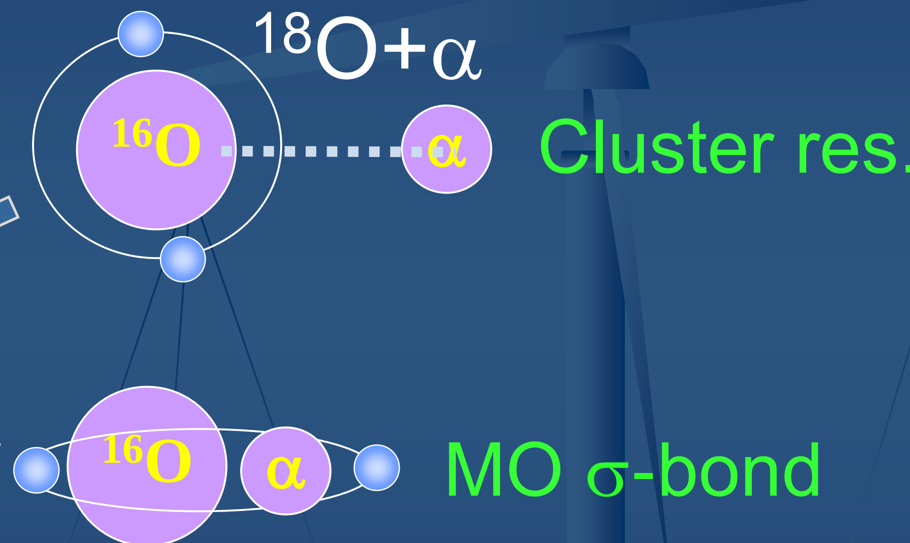
Ne, F, O isotopes

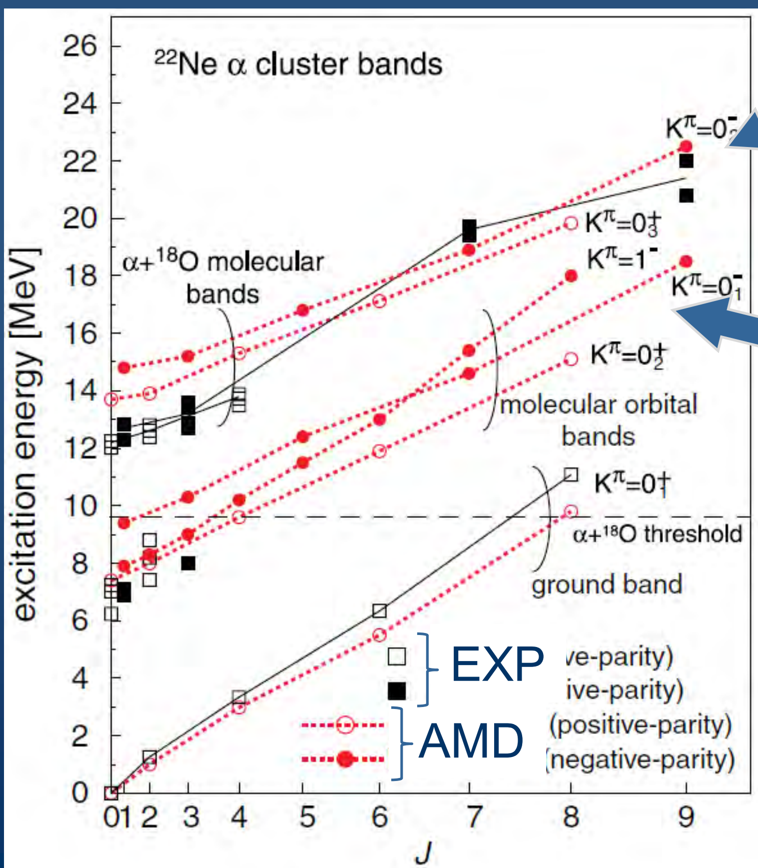
MO bond and Cluster res. in ^{22}Ne

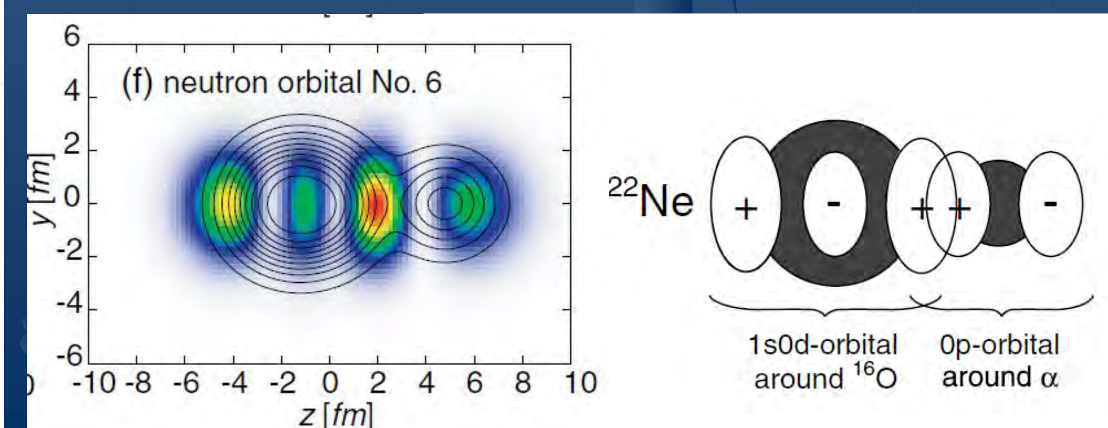
Exp Scholz et al., Rogachev et al., Goldberg et al.,Ashwood et al., Yildiz et al.,
Theor: Descouvemont, Kimura,

^{22}Ne

AMD study by Kimura, PRC75 (2007)

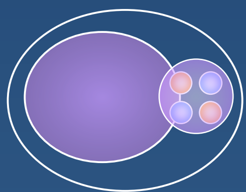






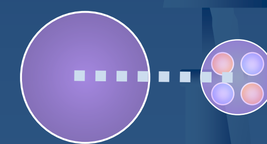
Two kinds of cluster structure

strong coupling cluster V.S. weak coupling cluster



- Cluster core at surface
- Clusters are overlapping
- s.p excitation in MF
- below cluster threshold
- Indirect evidence:

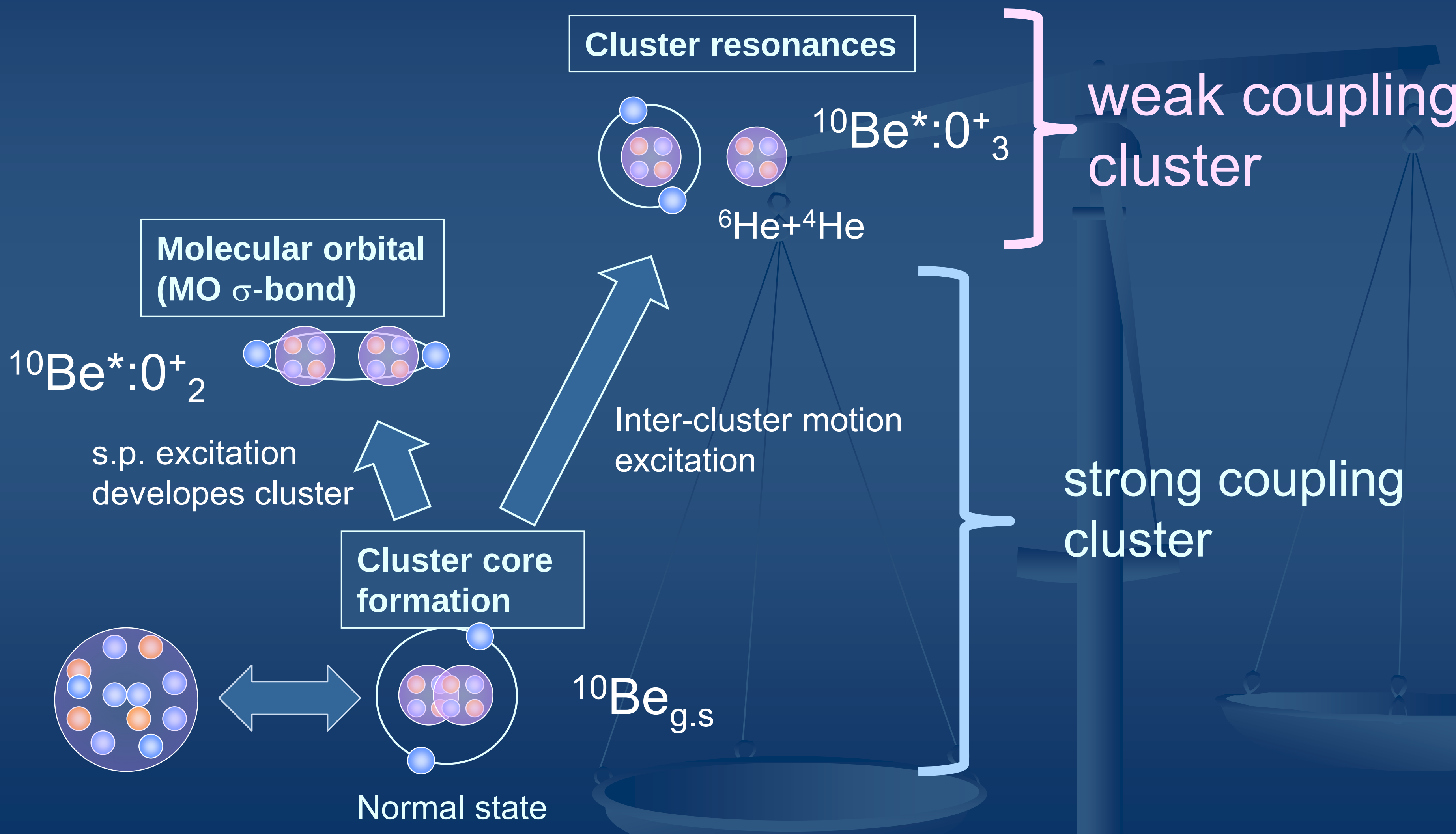
deformation, trancitions, charge radii, s.p. config.



- Excitation of relative motion
- No overlap. far from each other
- Excited states near or resonances above threshold
- more direct evidence

alpha-decay, alpha scattering

Cluster phenomena in n-rich Be



Rich cluster phenomena in nuclear systems

as functions of proton&neutron numbers and excitation energy

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

  ^{6,8}He+He in Be, ^{10}Be+α in ^{14}C, ^{14}C+α in ^{18}O, ^{18}O+α in ^{22}Ne

A theoretical method:

AMD (antisymmetrized molecular dynamics)

2. A theoretical model: AMD

An approach for nuclear structure to study

- cluster and mean-field aspects
- Stable and unstable nuclei
- Ground and excited states

AMD method for structure study

AMD wave fn.

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

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

Gaussian

spatial

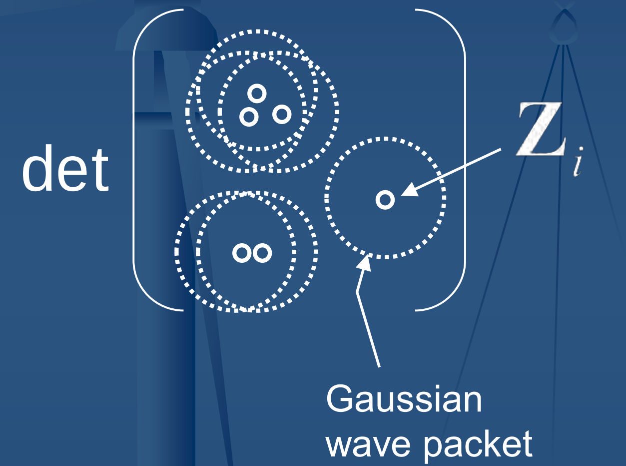
$$\varphi_i = \phi_{Z_i}\chi_i \begin{cases} \phi_{Z_i}(\mathbf{r}_j) \propto \exp\left[-\nu\left(\mathbf{r} - \frac{\mathbf{Z}_i}{\sqrt{\nu}}\right)^2\right] \\ \chi_i = \begin{pmatrix} \frac{1}{2} + \xi_i \\ \frac{1}{2} - \xi_i \end{pmatrix} \times \quad p \text{ or } n \end{cases}$$

Intrinsic spins　　isospin

$$\Phi_{AMD}(\mathbf{Z})$$

$$\mathbf{Z} = \{\mathbf{Z}_1, \mathbf{Z}_2, \cdots, \mathbf{Z}_A, \xi_1, \cdots, \xi_A\}$$

Variational parameters:
Gauss centers, spin orientations



Similar to FMD wave fn.

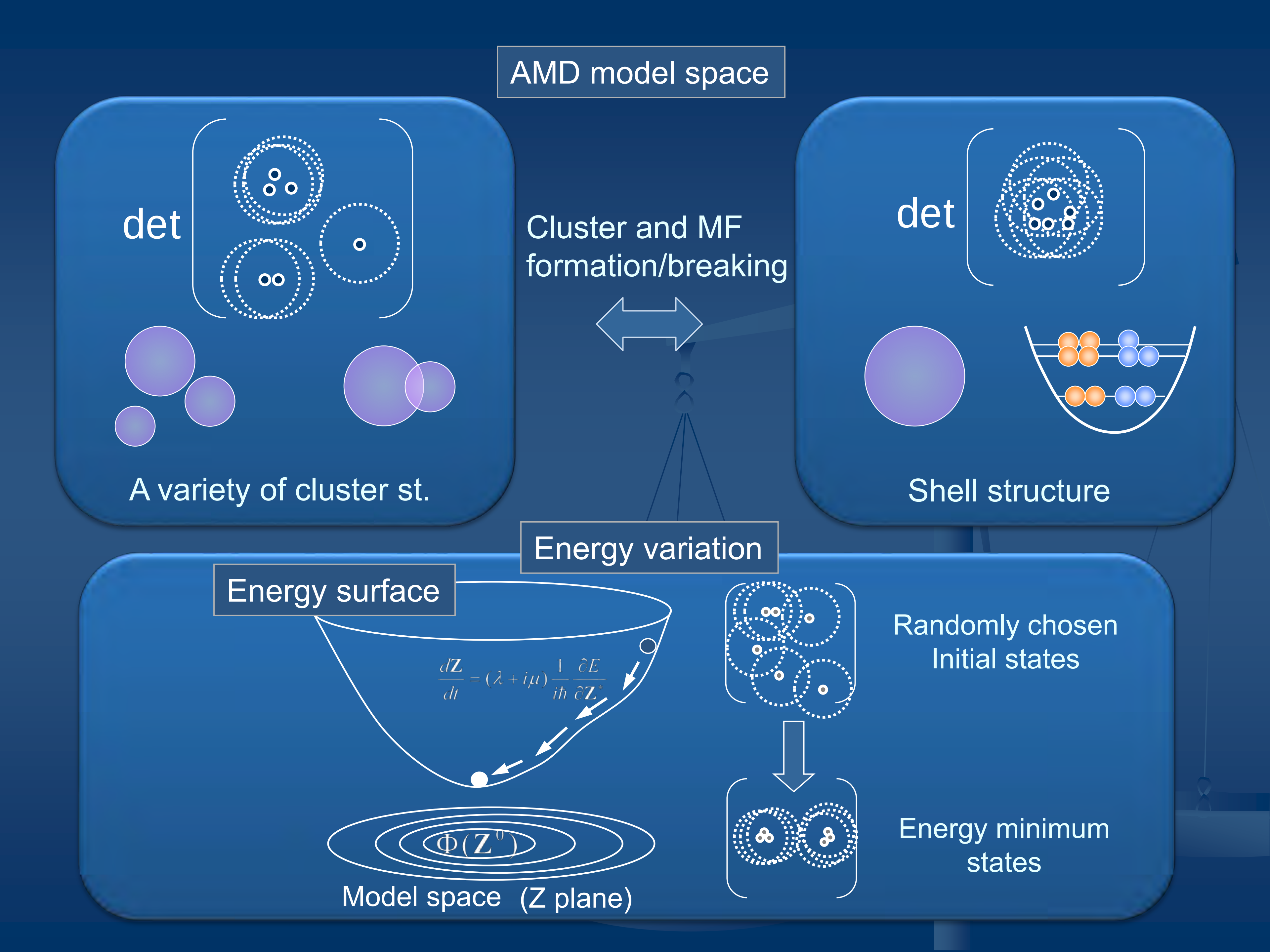
Energy Variation

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

Model wave fn. Φ

Effective nuclear force
phenomenological)

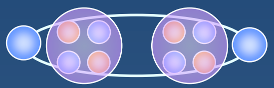
$$H^{eff} = \sum_{i=1} t_i + \sum_{i<j} v_{ij}^{eff} + \sum_{i<j<k} v'^{eff}_{ijk}$$



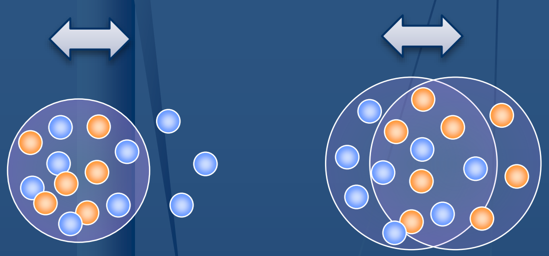
AMD model space
det
A variety of cluster st.
Cluster and MF
formation/breaking
det
Shell structure
Energy variation
Energy surface
$\frac{d\mathbf{Z}}{dt} = (\lambda + i\mu)\frac{1}{i\hbar}\frac{\partial E}{\partial \mathbf{Z}^*}$
$\Phi(\mathbf{Z}^0)$
Model space (Z plane)
Randomly chosen
Initial states
Energy minimum
states

3. Some topics of cluster phenomena

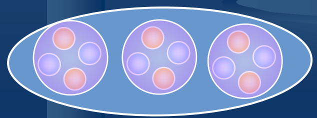
3-1. MO σ-bond in n-rich Be & Cluster resonances



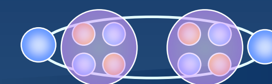
3-2. Dipole resonances



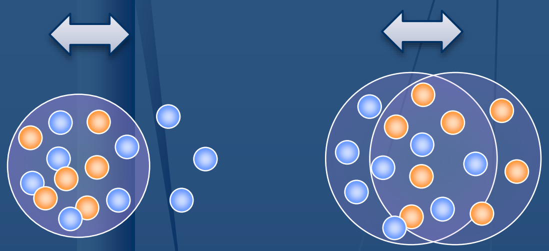
3-3. Linear chain in n-rich C



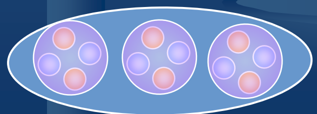
3-1. MO bond in n-rich Be & Cluster resonances



3-2. Dipole resonances



3-3. Linear chain in n-rich C



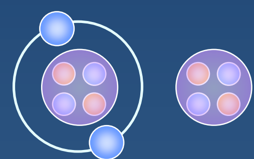
Cluster structures in neutron-rich Be

^{10}Be: energy levels

AMD calc. Y. K-E, et al. PRC (98)
Exp: Milin et al. '05, Freer et al. '06

cluster res.

^{6}He+^{4}He



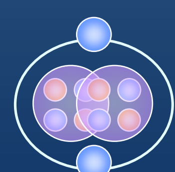
$0^+_{3,4}$

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

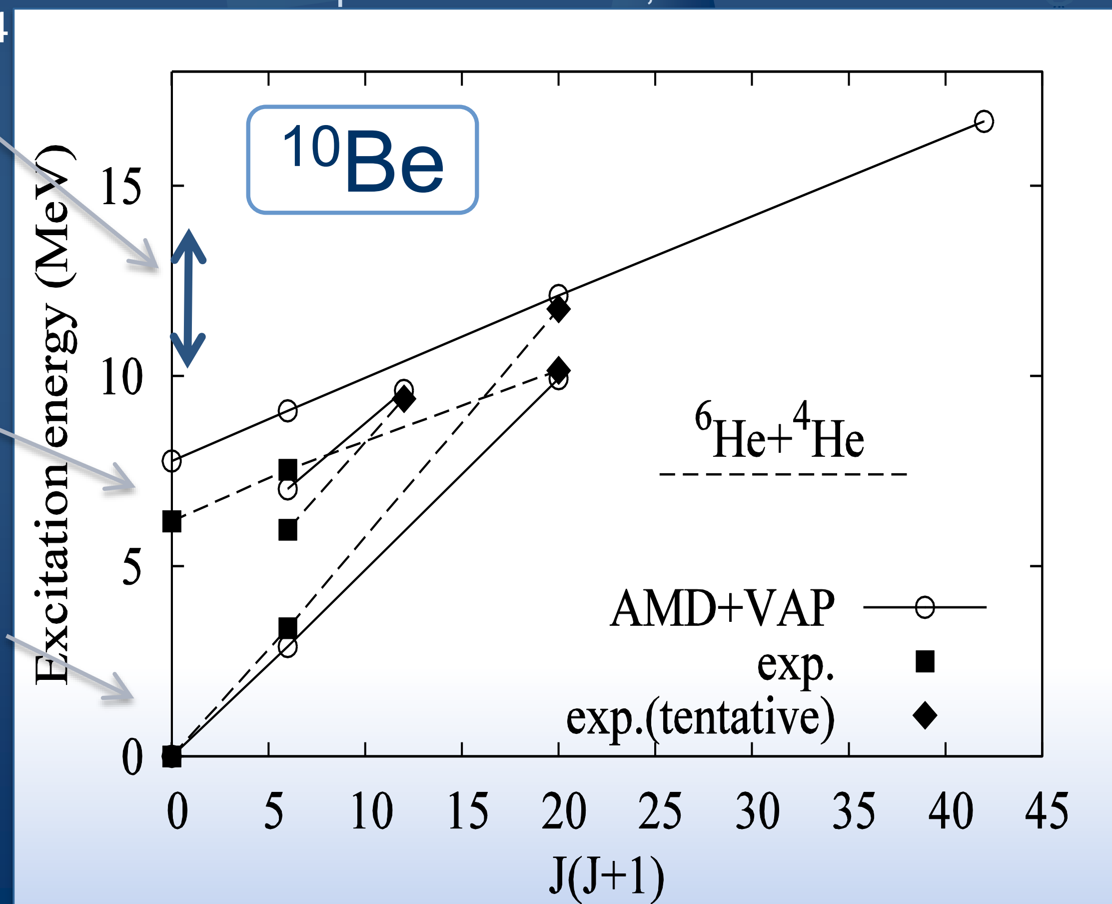
MO σ-bond

0^+_2

Normal



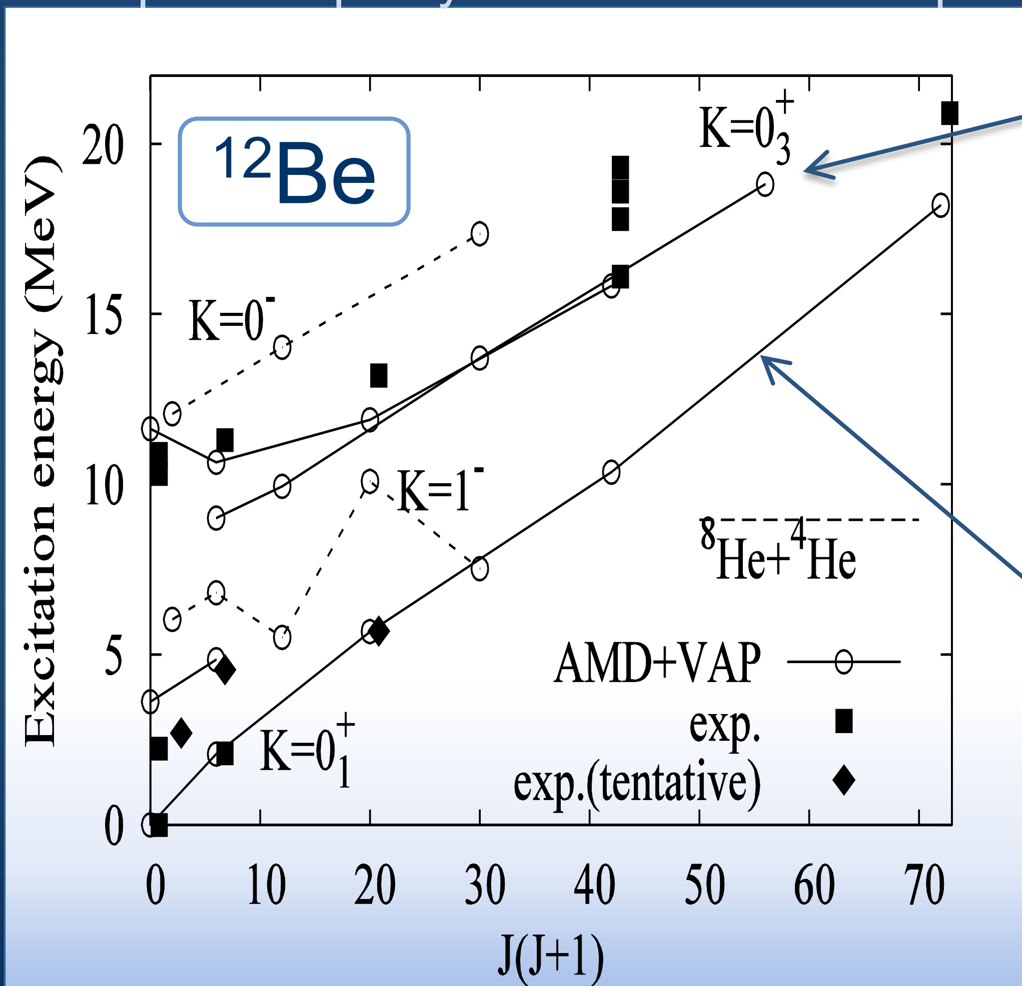
0^+_1



Energy levels of ^{12}Be

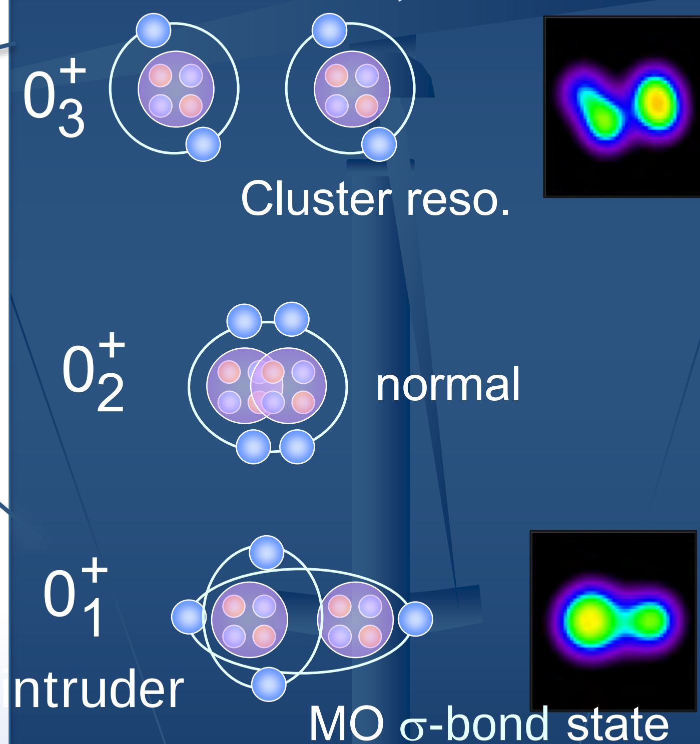
VAP calculation with AMD method

positive parity states withnormal spins



^{12}Be

^{6}He+^{6}He, ^{8}He+^{4}He?

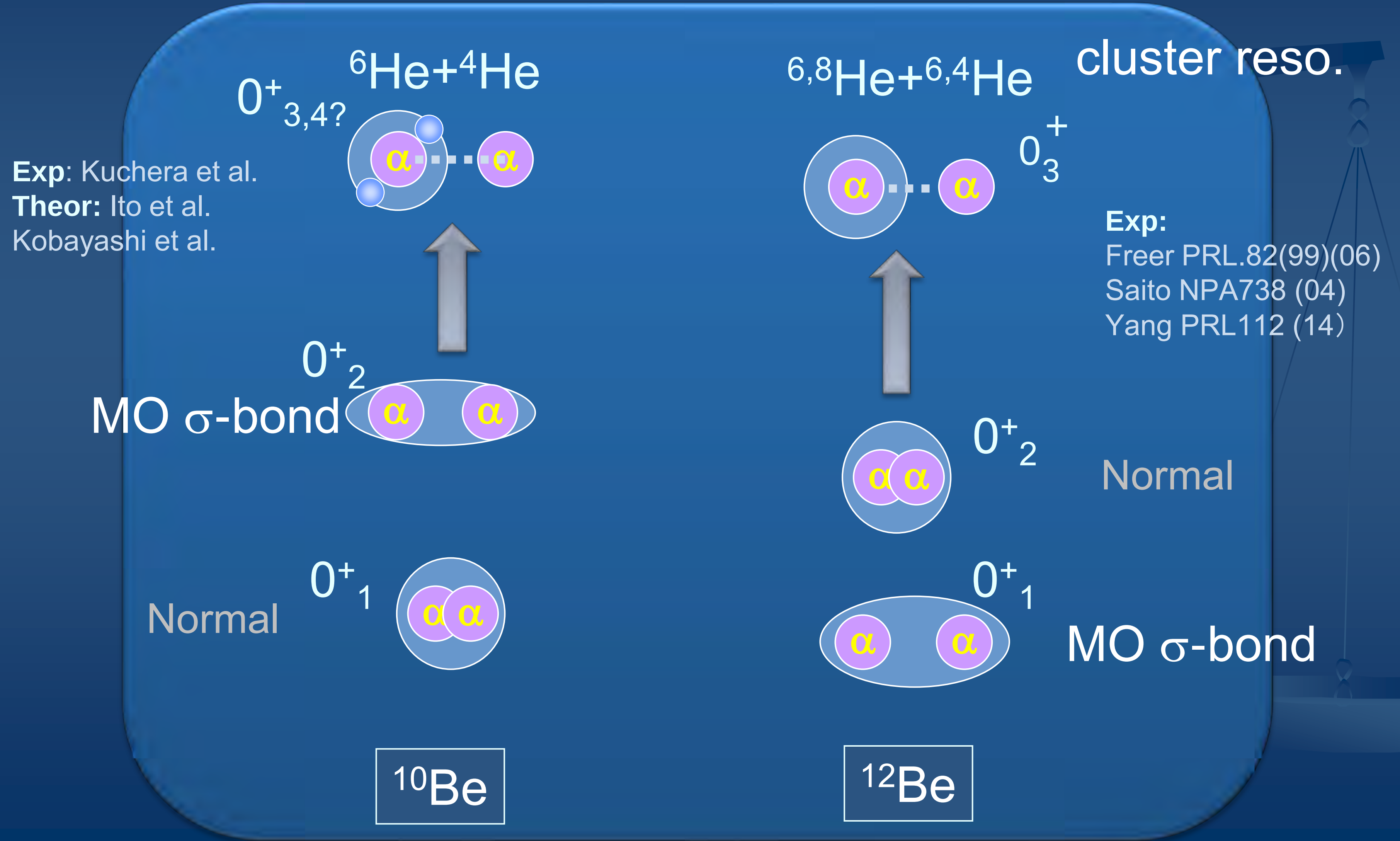


Breaking of N=8 magicity

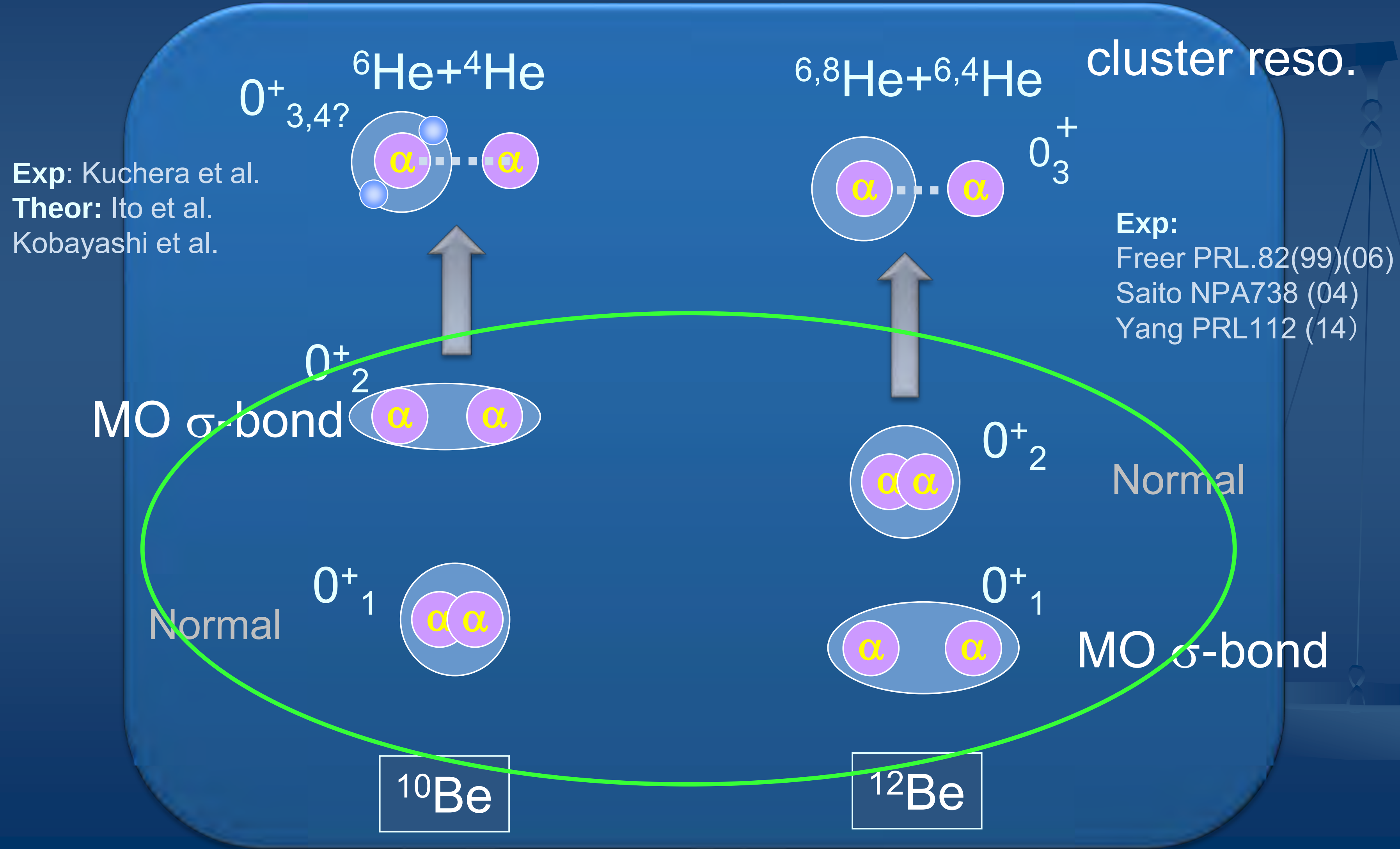
Formation of 2a+molecular orbitals

Y.K et al., PRC 68, 014319 (2003)

Cluster formation, MO, and Cluster resonance

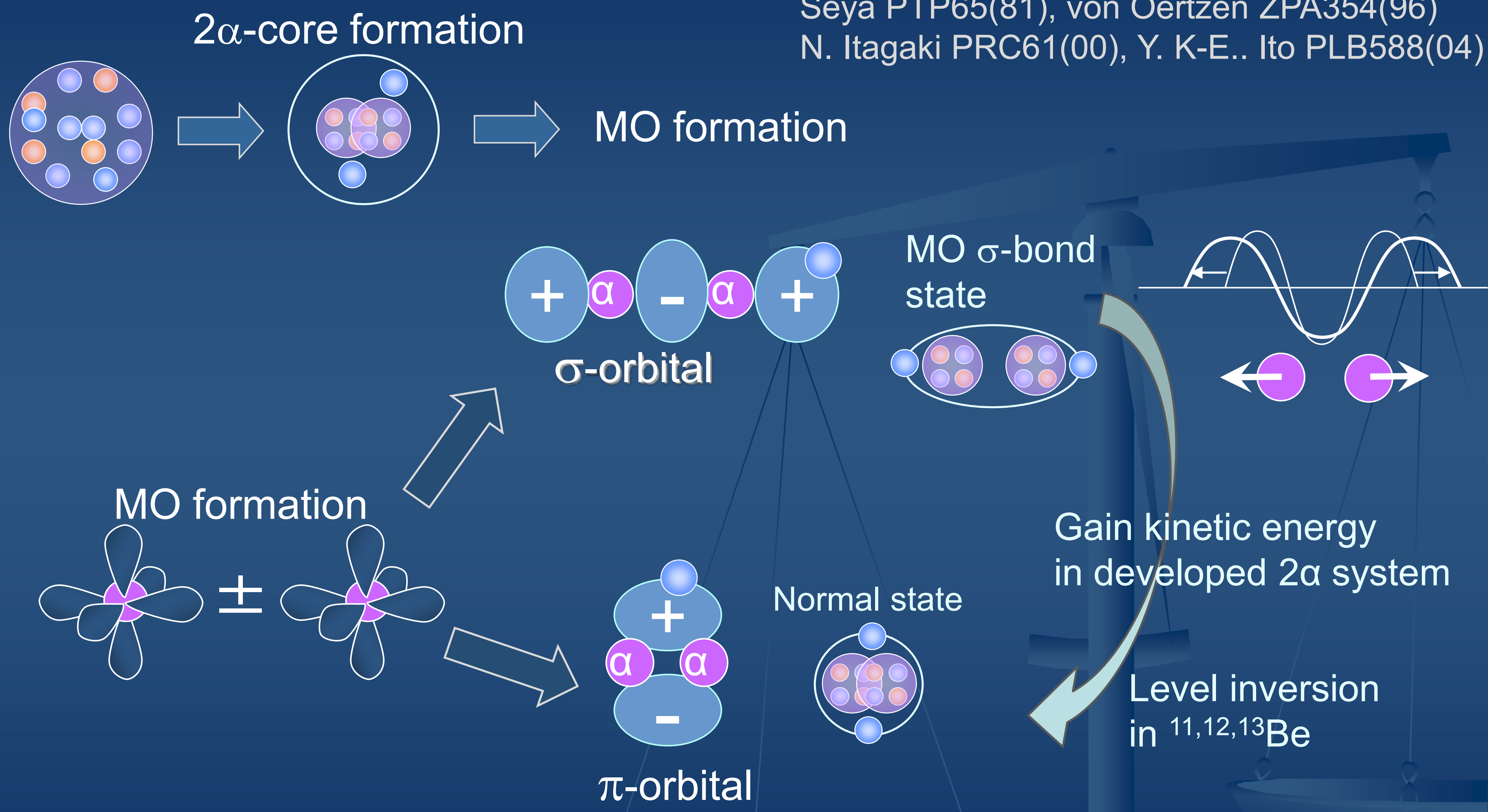


Cluster formation, MO in low-energy region



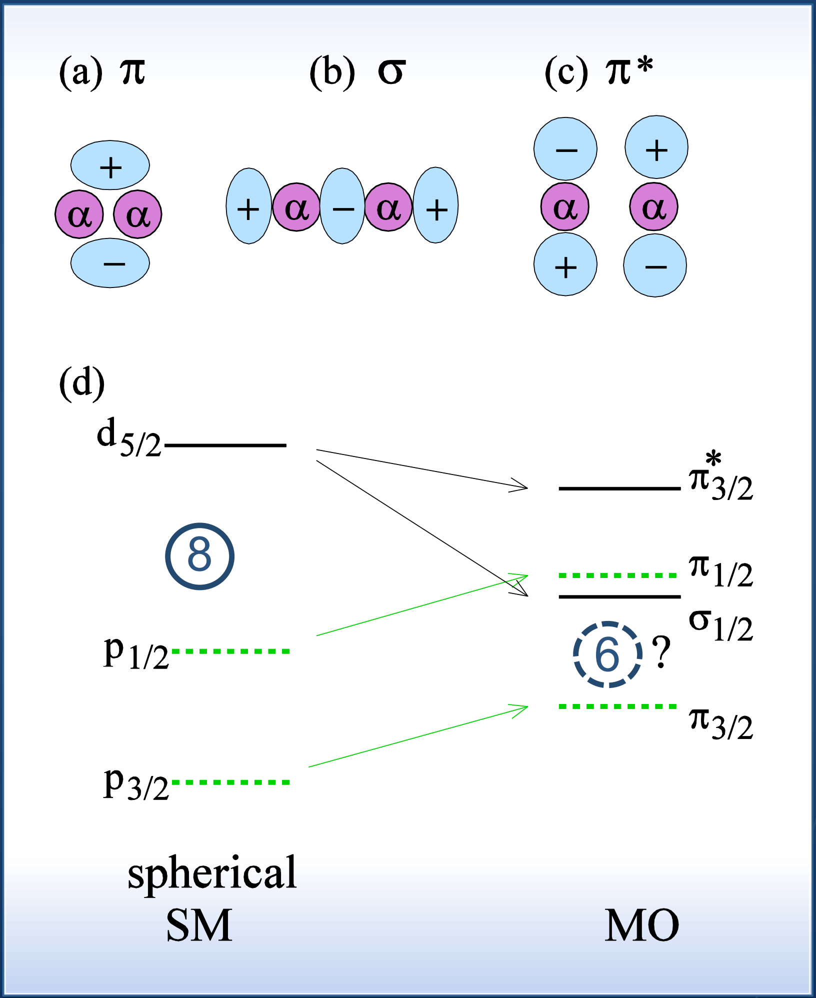
Molecular orbital(MO) structure in Be

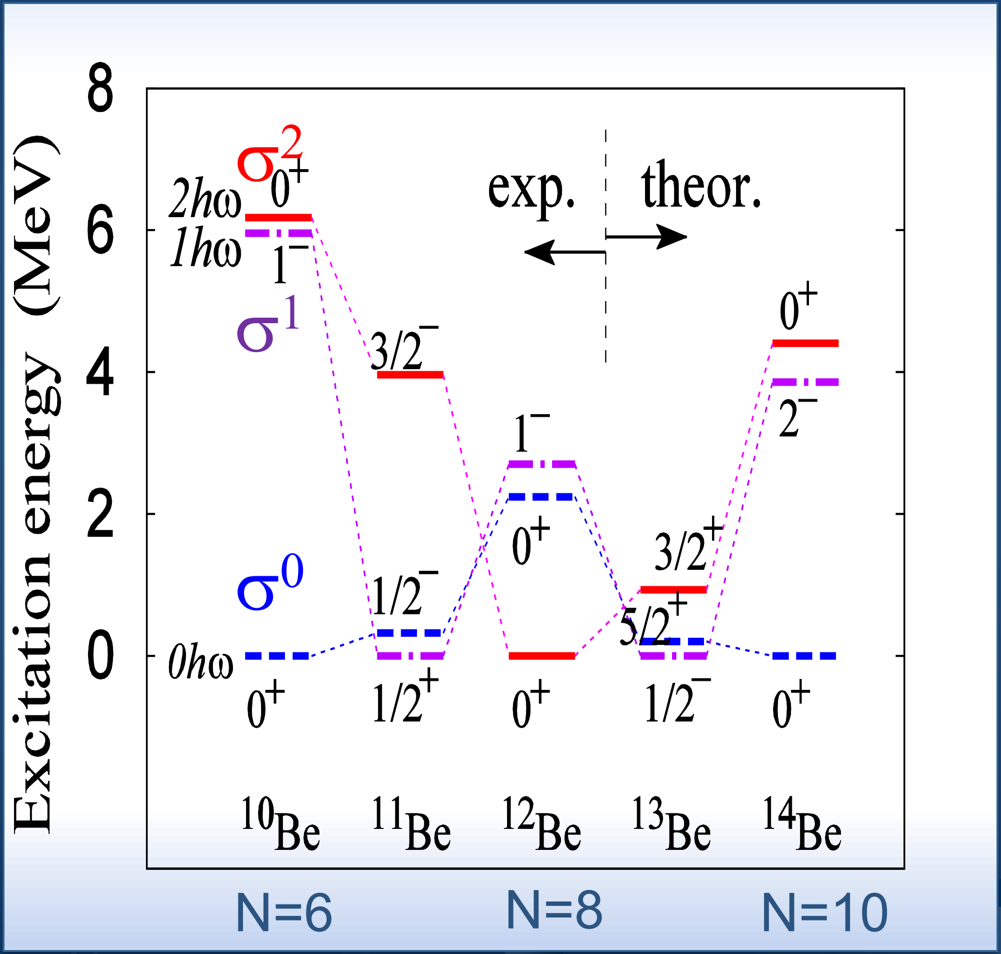
Seya PTP65(81), von Oertzen ZPA354(96)
N. Itagaki PRC61(00), Y. K-E.. Ito PLB588(04)



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

N=8 magic number breaking

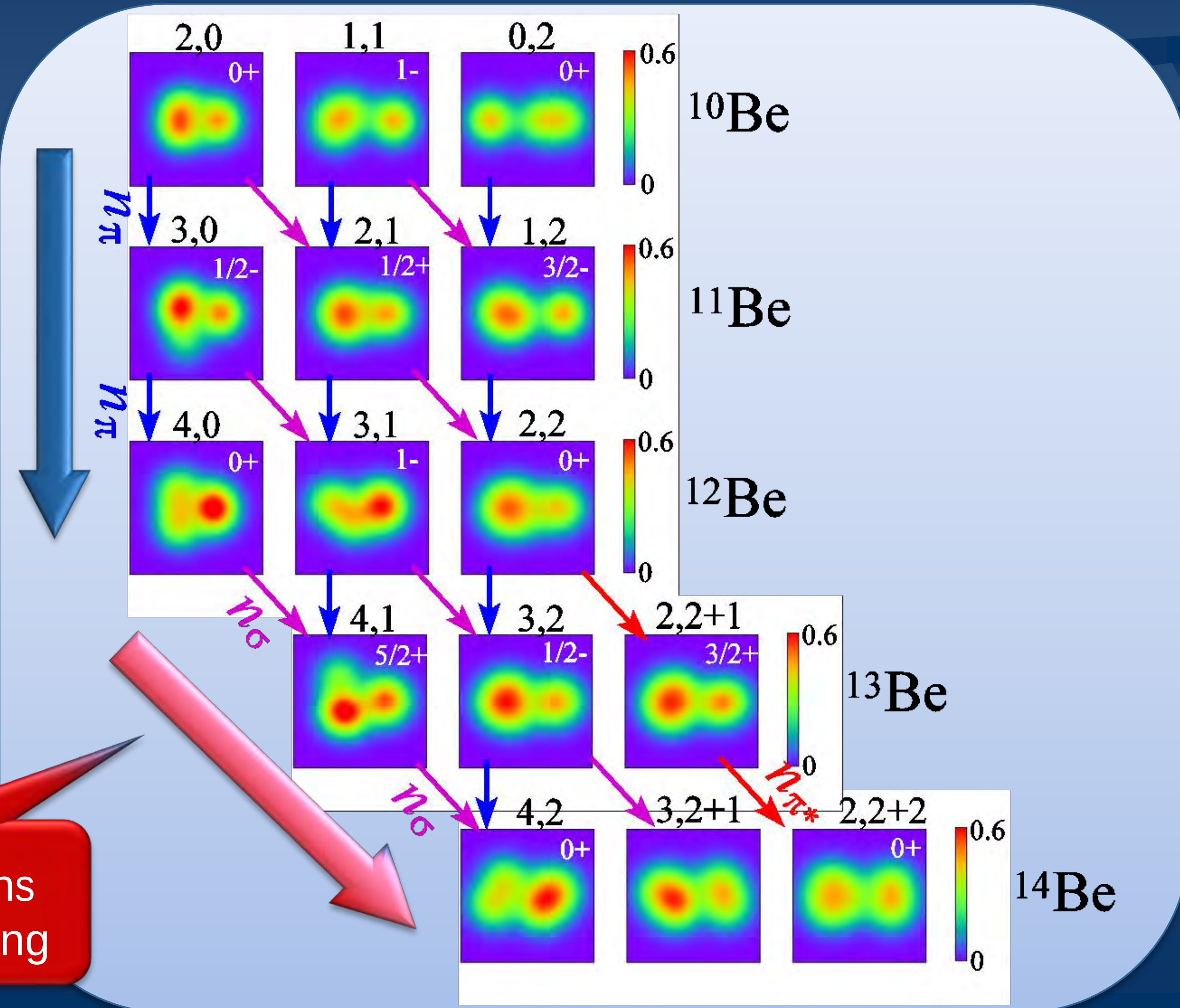




spherical

enhanced
cluster core

cluster enhancement by σ-orbital neutrons



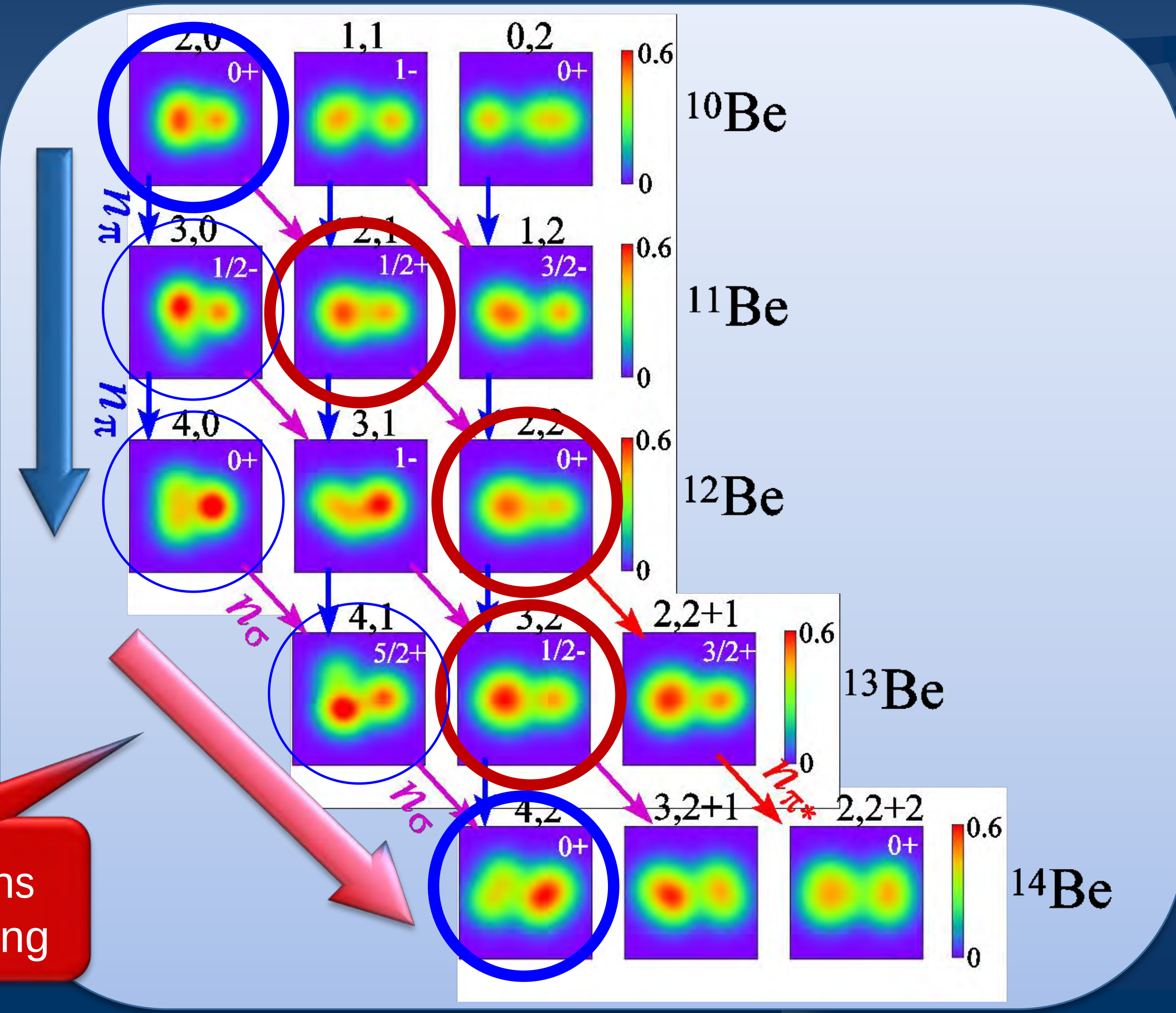
π-orbital neutrons suppress clustering.

σ-orbital neutrons enhance clustering

cluster enhancement by σ-orbital neutrons

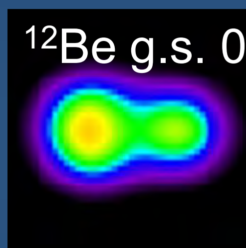
π-orbital neutrons suppress clustering.

σ-orbital neutrons enhance clustering



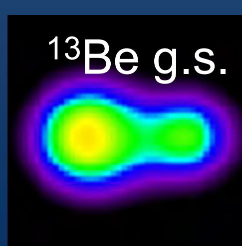
Experimental probes for magic number breaking in Be

Y.K-E.PRC (03),(12) , Ito PRL(08) Dufour NPA(10)
Fortune PRC(06), Blanchon PRC(10)



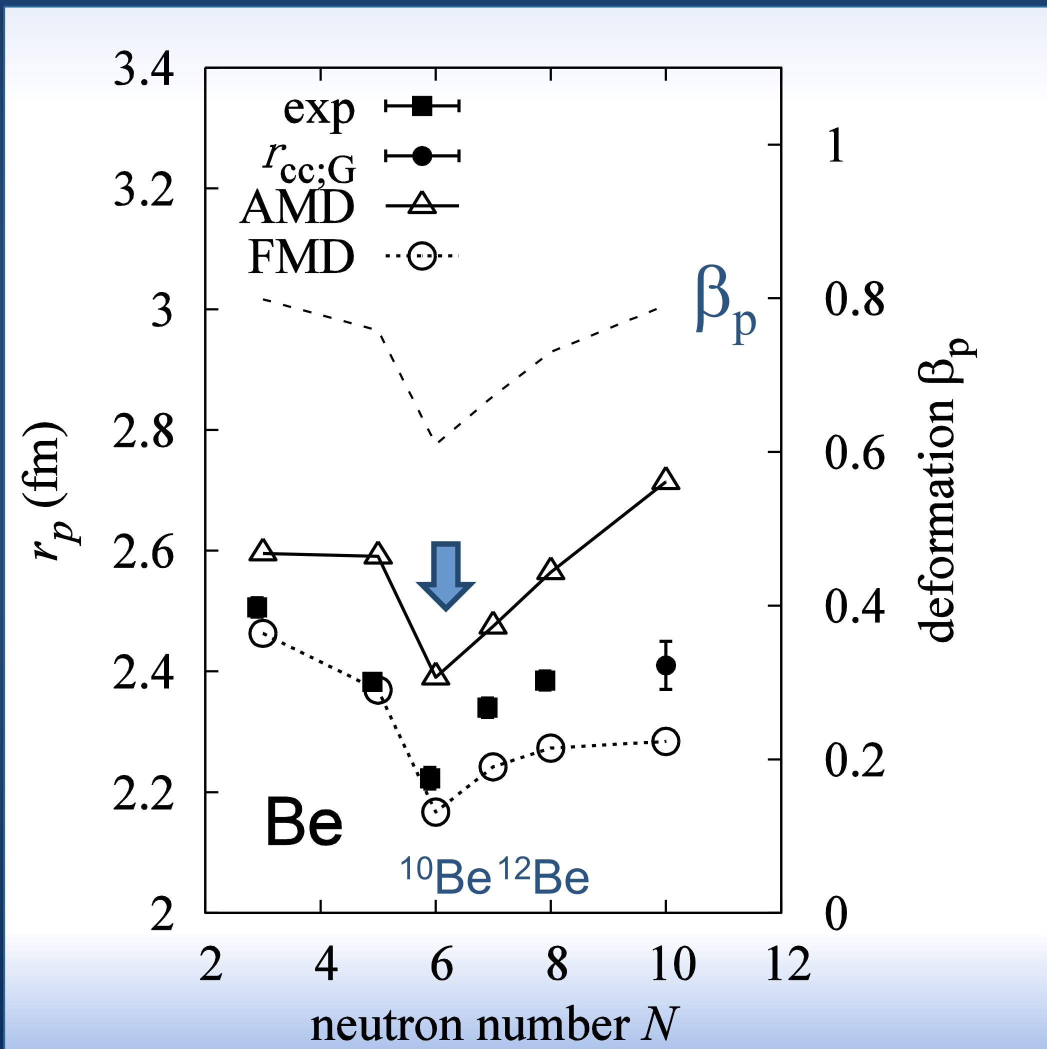
- deformation in ^{12}Be(gs)
  Inelastic scat. life time:
  Iwasaki PLB481(00),
  Imai PLB673(09)
- intruder config. in ^{12}Be(gs)
  1n-knockout reac.:
  Navin PRL85(00),
  Pain PRL96(06)
- ^{12}Be(0_2^+) with p-shell config.
  Shimoura PLB654 (07)

  B(GT) with charge ex.:
  Meharchand PRL108 (12)



- abnormal parity of ^{13}Be(gs) now on discussion
  Kondo et al. PLB690 (10)

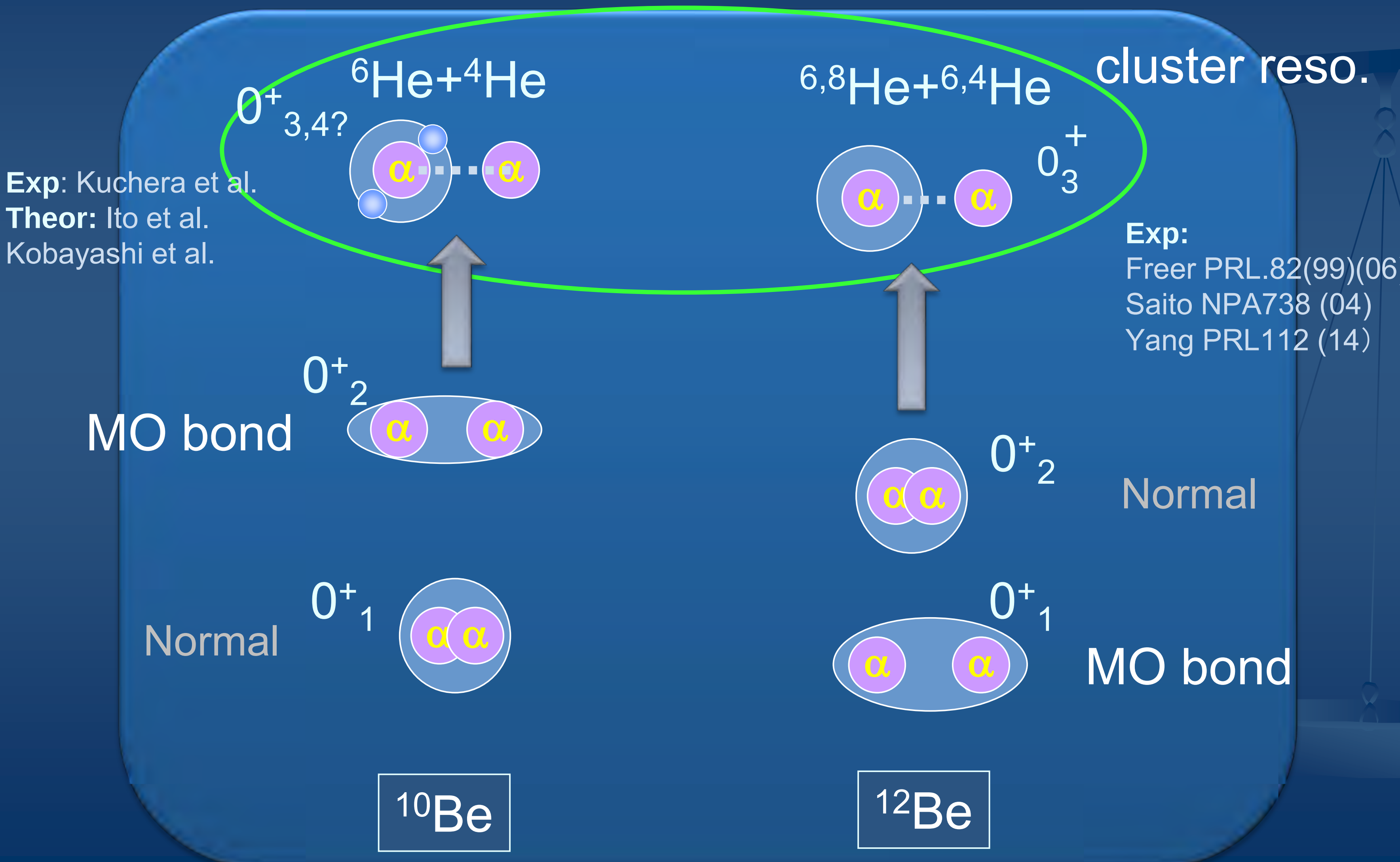
proton radii along isotope chain



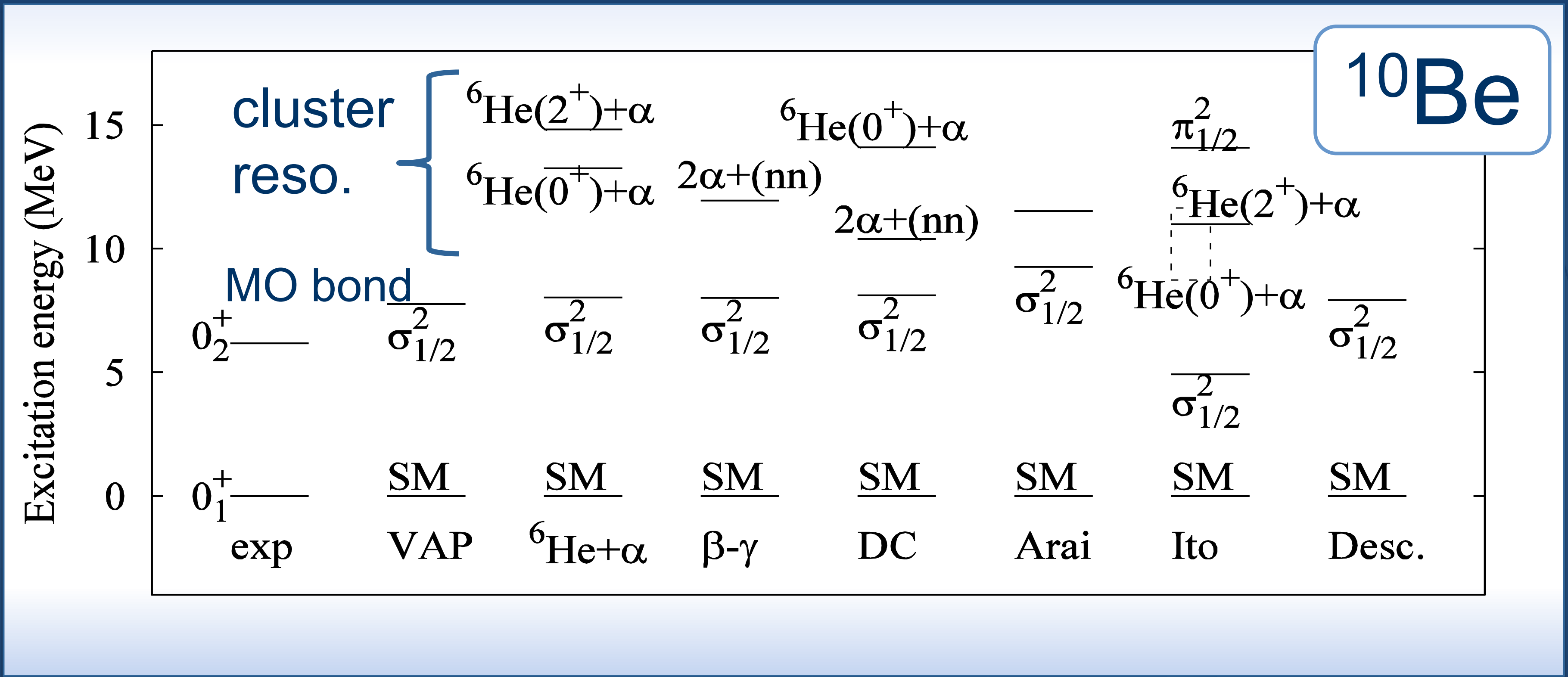
Change of clustering (deformation)
Is reflected in proton radii(charge radii)

Point-proton radius is minimum at N=6 (^{10}Be)

Cluster resonances



Theoretical predictions of cluster resonances in ^{10}Be

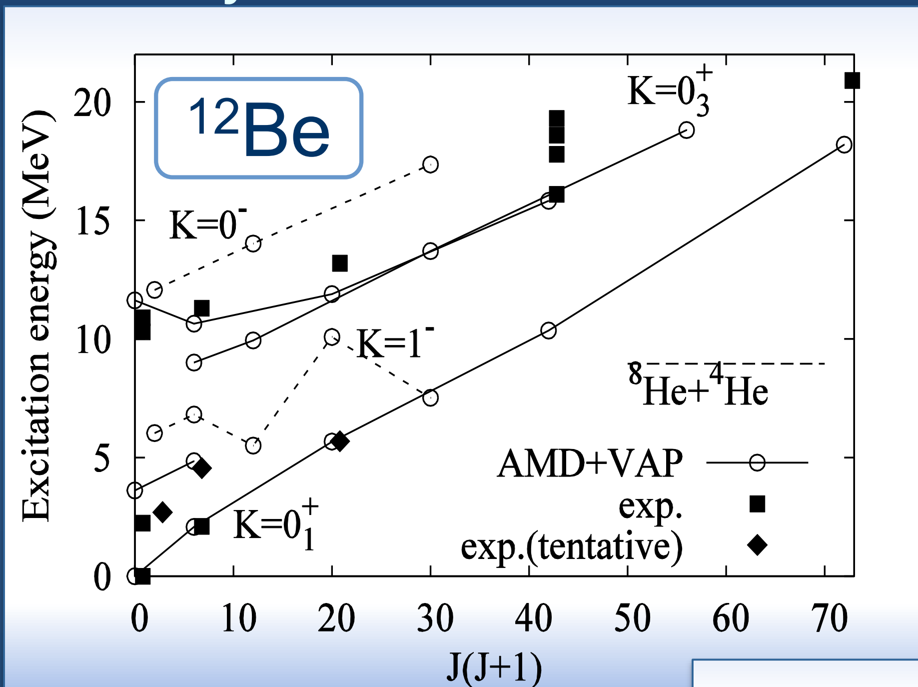


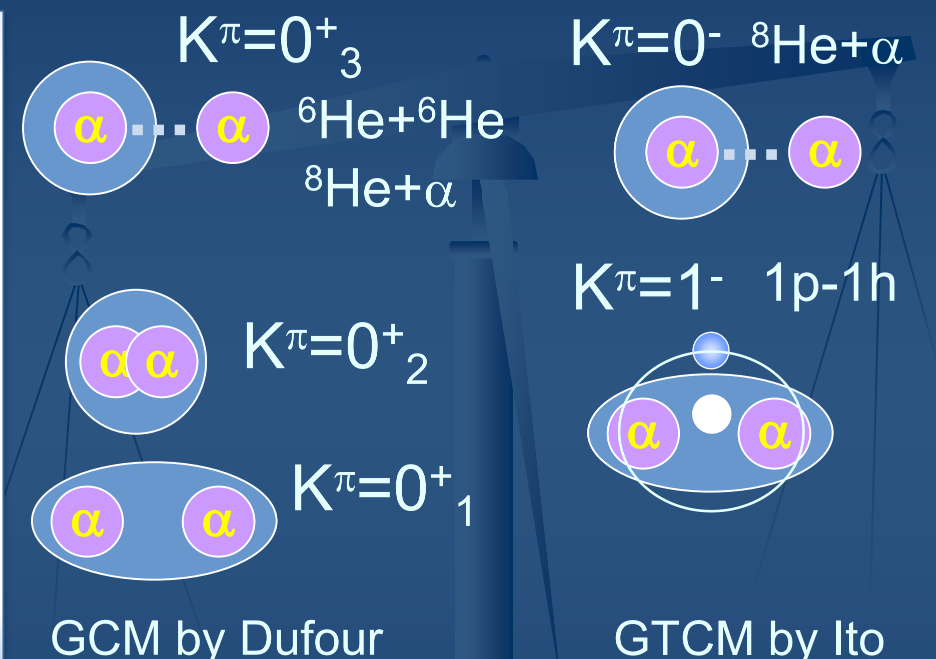
Exp.
Kuchera et al.PRC 84, 054615 (2011).

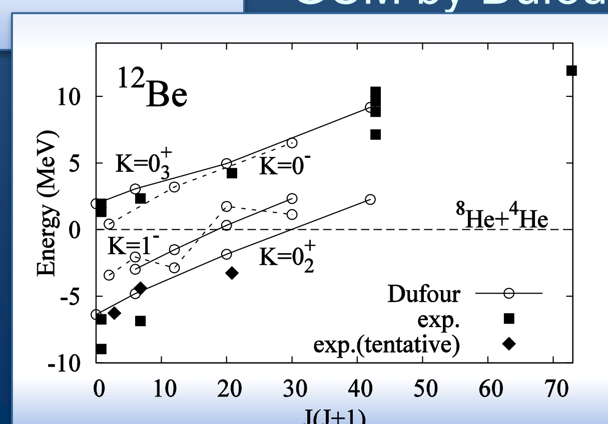
Theor.
Y. K-E. et al. PRC60, 064304 (1999)
T. Suhara and Y. K-E. et al., PTP123, 303 (2010)
F. Kobayashi and Y. K-E., Phys.Rev. C 86, 064303 (2012)
Arai et al., PRC69, 014309 (2004).
Ito et al., PLB636, 293 (2006).
P. Descouvemont et al., NPA 699 (2002) 463

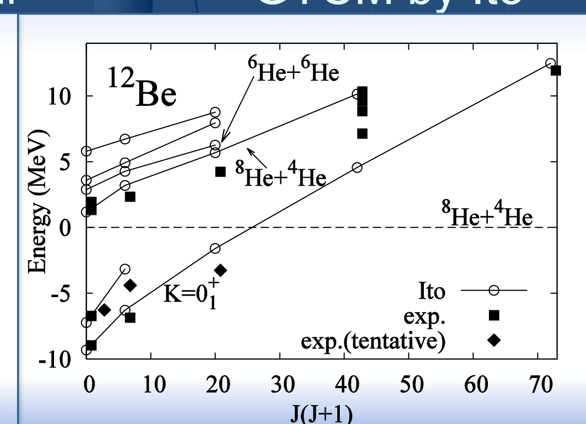
Theoretical predictions and observed states in ^{12}Be

AMD by K-E.





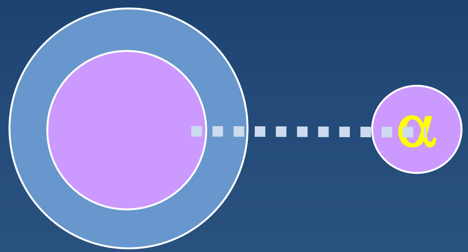




Exp. Freer PRL.82(99)(06)
Saito NPA738 (04)
Yang PRL112 (14)

Theor.
Y. K-E. et al. PRC68 (03)
Ito et al., PRC85 (12)
Dufour et al., NPA836 (10) 242

α-cluster states in n-rich nuclei



Cluster resonances

New states discovered and suggested at

Ex = several ~ 20 MeV

in α-decay, α-transfer, α-scattering

^{6,8}He+α in Be*
Exp: Soic et al., Freer et al., Saito et al., Curtis et al., Milin et al., Bohlen et al.,
Theor: Seya, von Oerzten, Descouvemont et al.,Itagaki et al., K-E et al.
Arai et al., M. Ito et al.

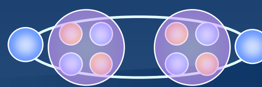
^{10}Be+α in ^{14}C*
Exp Soic 04, von Oertzen '04, Price 07, Haigh 08, Fritsch '16, Yamaguchi
Theor: Suhara '10

^{14}C+α in ^{18}O*
Exp Scholz et al., Rogachev et al., Goldberg et al.,Ashwood et al., Yildiz et al.,
Theor: Descouvemont, Kimura,

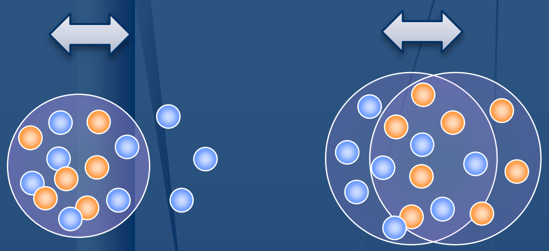
^{18}O+α in ^{22}Ne*
Exp Scholz '72, Rogachev '01, Goldberg '04, Ashwood '06, Yildiz et al.,
Theor: Descouvemont '88, Kimura '07

Universal phenomena?
Further experimental and theoretical studies are requested.

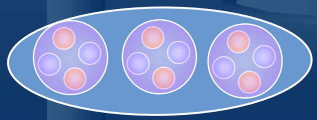
3-1. MO bond in n-rich Be & Cluster resonances



3-2. Dipole resonances



3-3. Linear chain in n-rich C

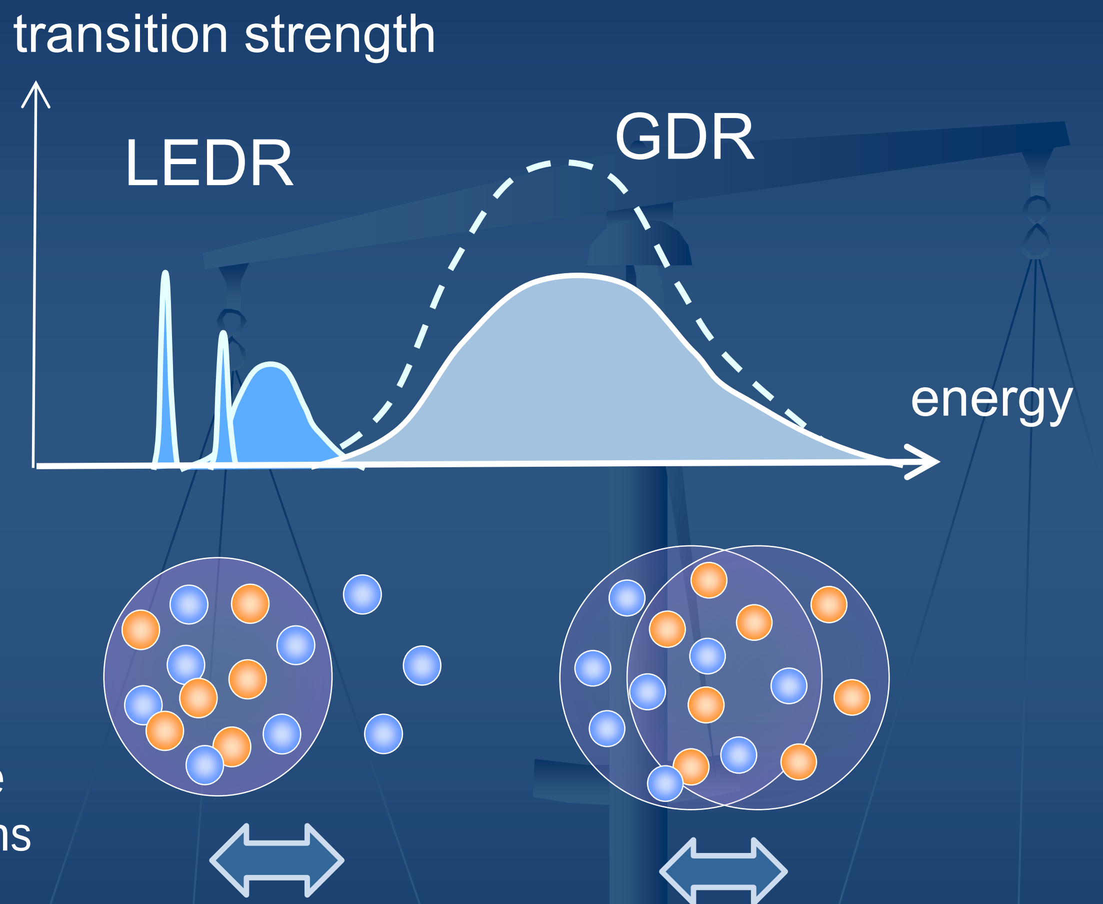


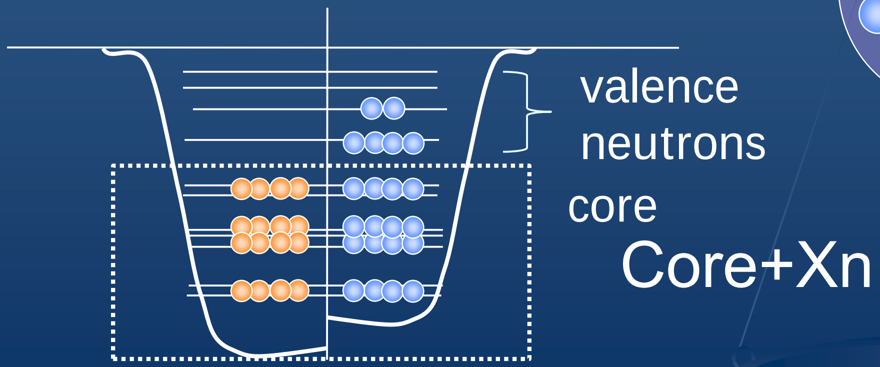
E1(Dipole) resonances

Separation of LEDR From GDR

⇩

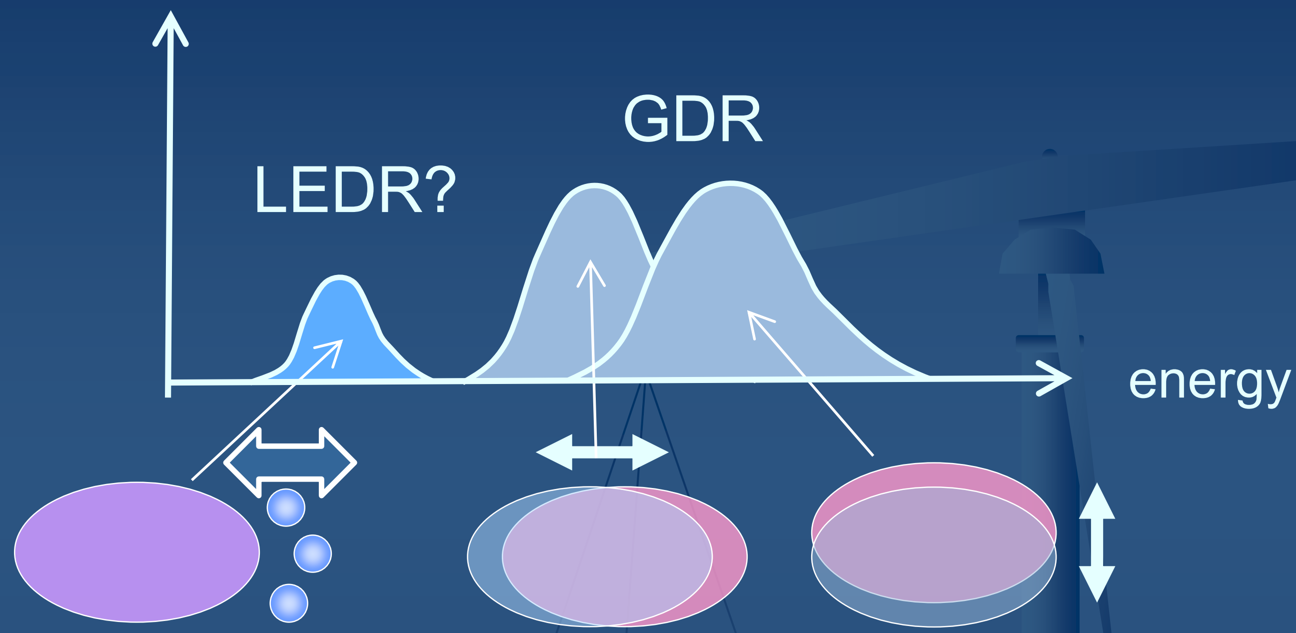
New excitation modes





LEDR: low-energy dipole resonace
PDR: collective LEDR

deformed neutron-rich nuclei

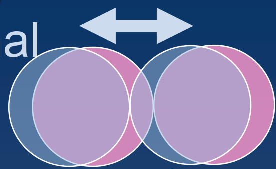


Valence neutron modes against core

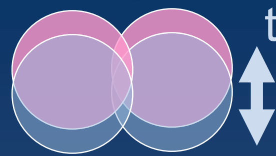
Two peak structure in prolate deformation

B(E1) of Be isotopes calculated by shifted AMD

longitudinal



transverse



smearing factor 2MeV

■ GDR in ^{8}Be core

two peaks in prolate state

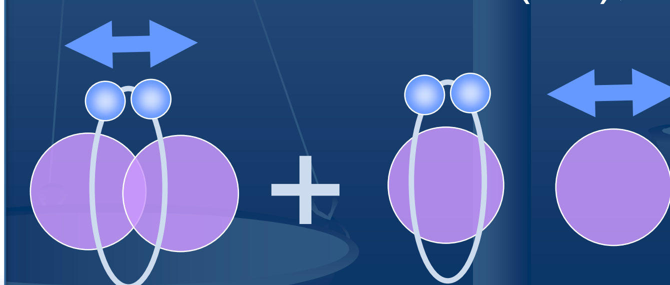
Lower peak not affected

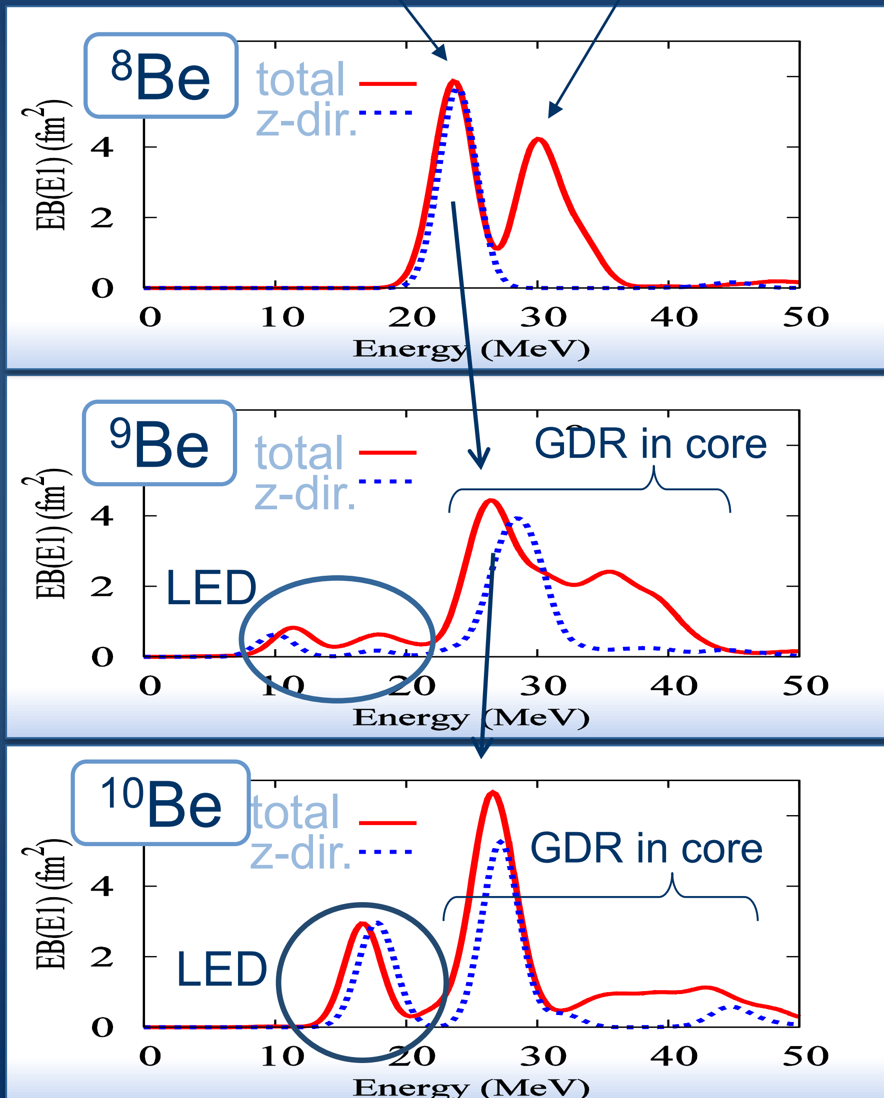
higher peak broadened

■ LEDR:

Coherent two-neutron motion coupling with 6He+α

B(E1), B(ISD) ↗

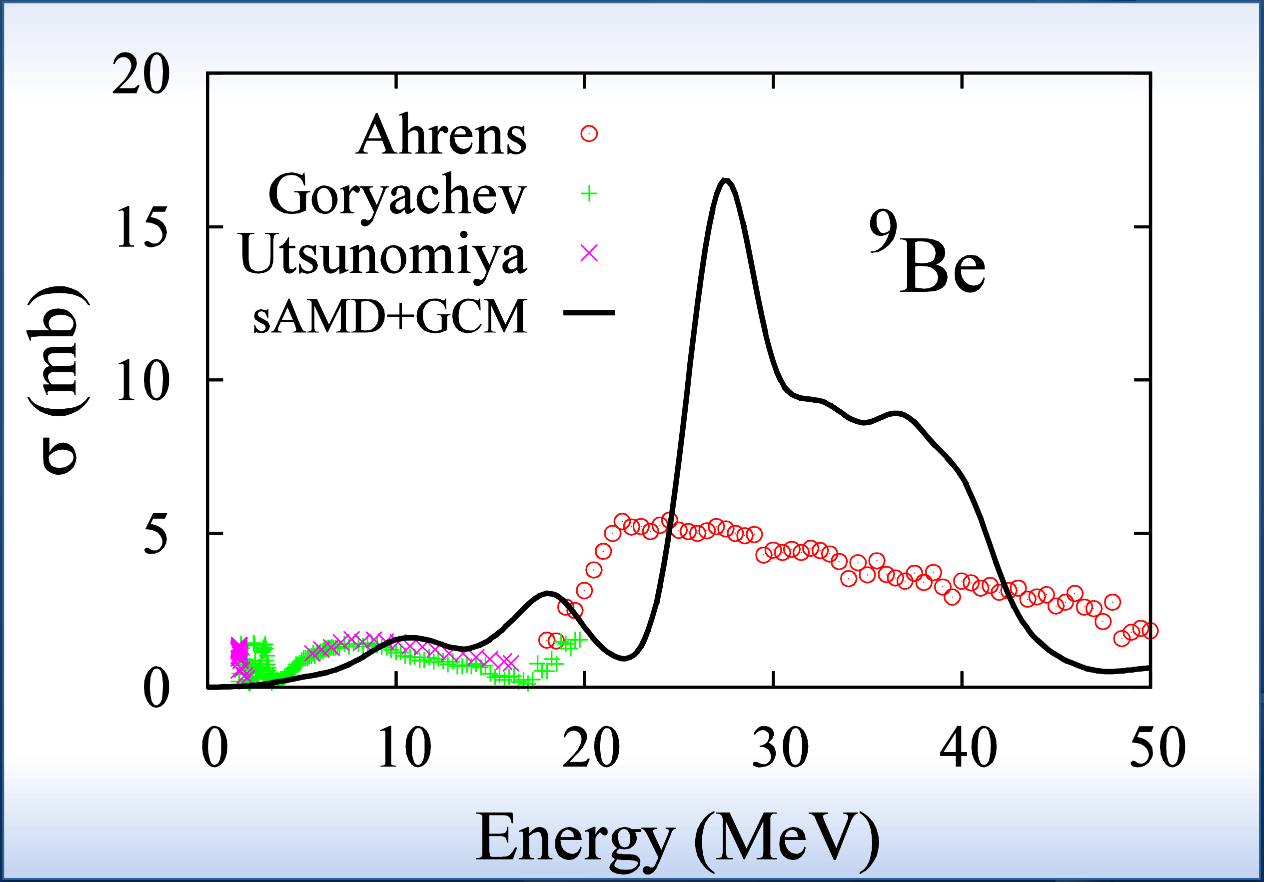




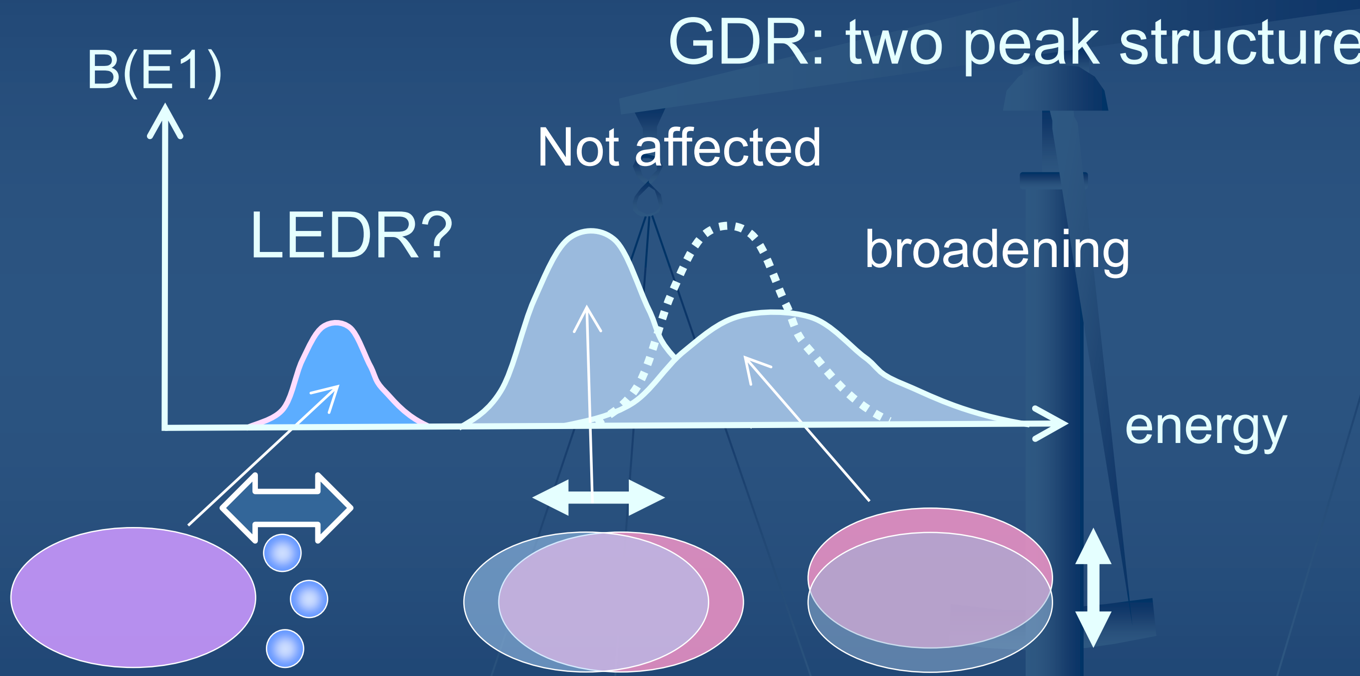
B(E1) in ^{9}Be compared with experimental data

Photonuclear cross section v.s.
sAMD+αGCM calc.

Ahrens et al.(1975)
Goryachev et al. (1992)
Utsunomiya et al.,(2015)

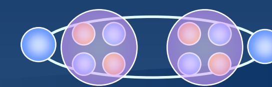


Roles of excess neutrons in deformed neutron-rich nuclei



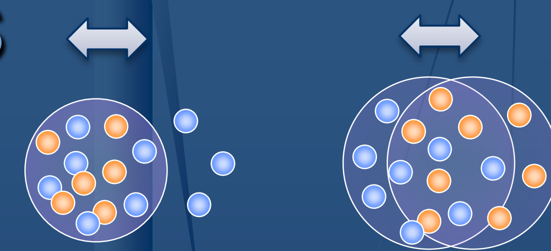
Valence neutron modes against core

3-1. MO bond in n-rich Be

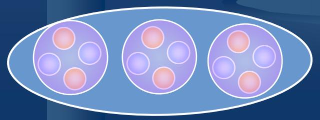


& Cluster resonances

3-2. Dipole resonances



3-3. Linear chain in n-rich C

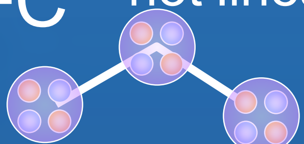


Linear chain state in $^{14}C^*$

Neutron-rich

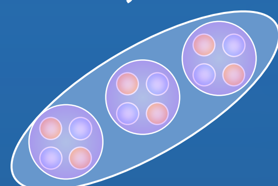
^{12}C | $^{14,16}C$

$^{12}C^*$ not linear

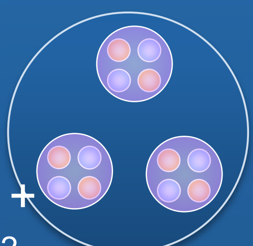


0_3^+ Y.K-E.et al., T. Neff et al.

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



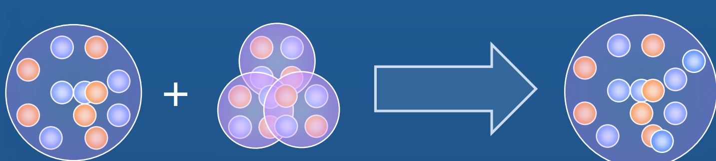
Linear chain?



0_2^+

Tohsaki et al., Funaki et al.

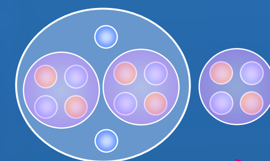
von Oertzen ZPA354(96)
EPJA21(04),PR 432(06)
Itagaki PRC64(01)
Suhara PRC82(10)
Maruhn NPA833(10)
Baba PRC90(14).

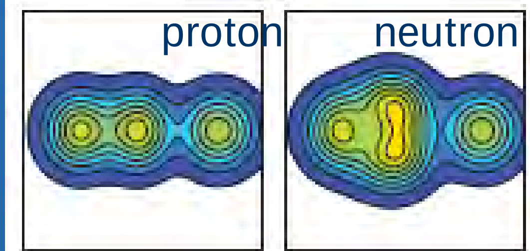


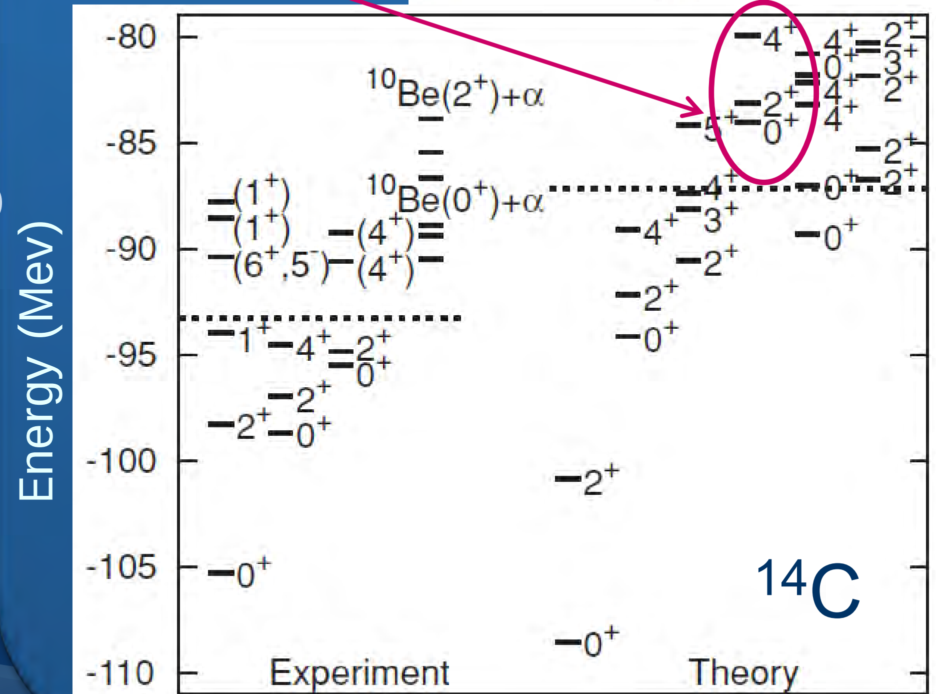
^{12}C g.s. ^{14}C g.s.

^{14}C AMD by T.Suhara and Y.K-E,
Phys.Rev.C82:044301,2010.

3α linear chain







Experimental searching for linear chain states

- UK group: up reactions

Price et al.PRC75(2007), 014305. 10Be+a break up

Haigh et al. PRC78 (2008) 014319. 10Be+a break up

Freer et al. PRC90(2014) 054324. 10Be+a scattering

- US group:

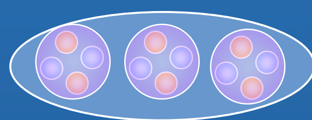
Fritsch et al., PRCC93 (2016) 014321. 10Be+a scattering.

- Jpn group:

Yamaguchi et al., New results are coming soon !

Linear chain in n-rich C

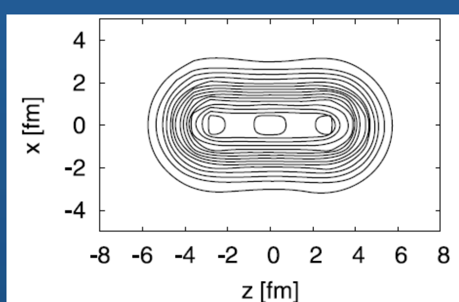
Meta stable for bending motion



- ✓ MO model for $^{14,16}C$

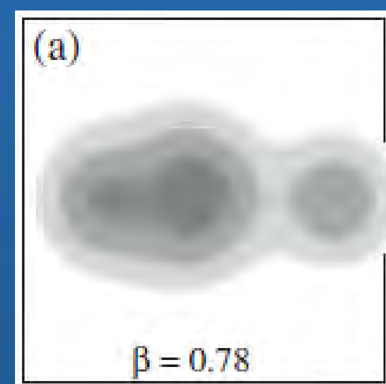
  Itagaki et al. PRC64(01)
- ✓ HF calc. for $^{16,20}C$

  by Maruhn et al. NPA833(10)



Stretching effect in rotation

AMD by Y.K-E,
PR432(2006)

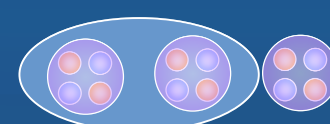


$^{15}C^*(19/2-)$

$\beta=0.78$

suggested
to be a
yrast state

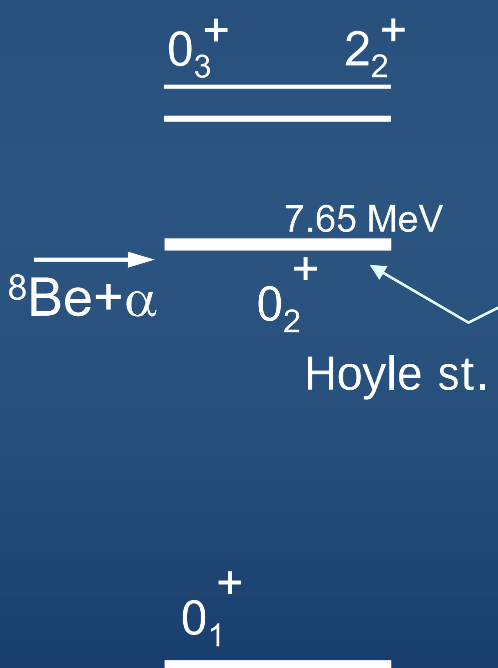
$^{11}Be+\alpha$

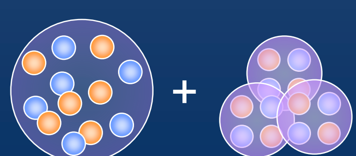


Largely deformed ^{11}Be
with MO-bond

Cluster gas states in excited states

^{12}C



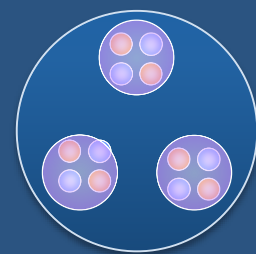


Tohsaki et al.(2001)

cluster gas

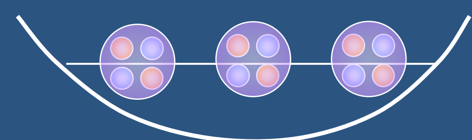
Uegaki et al. (1977)

3α



α condensation

Funaki et al. (2003)



Dilute cluster gas

Bosonic behavior:

α particles condensate in the same orbit.

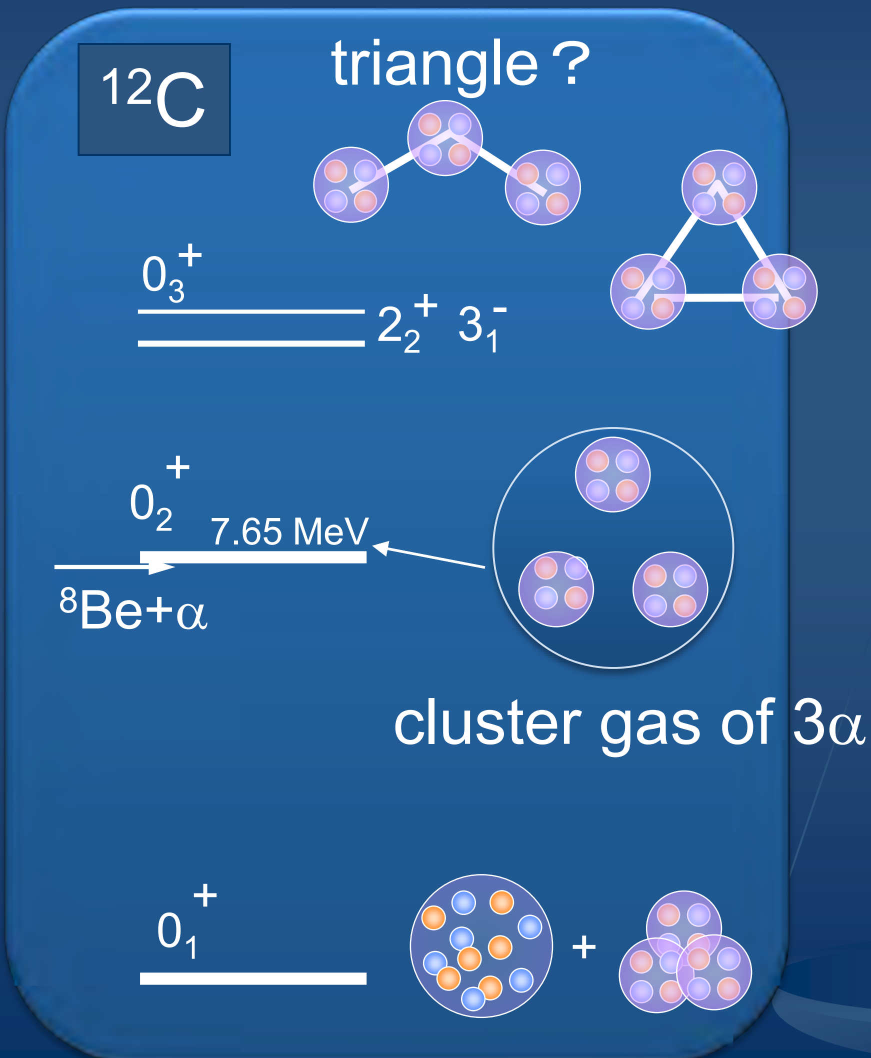
BEC in nuclear matter

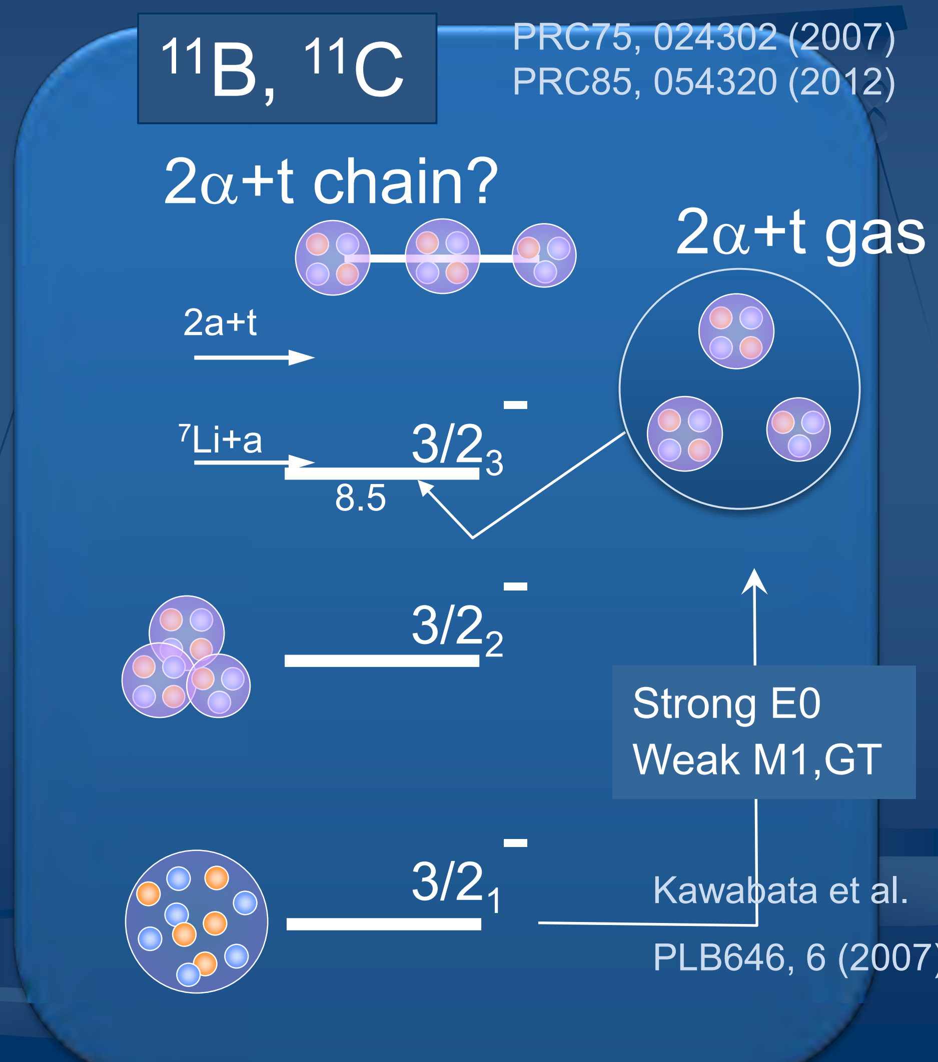
Roepke et al., PRL(1998)

4α condensation in ^{16}O suggested by Funaki et al. (2008,2010)

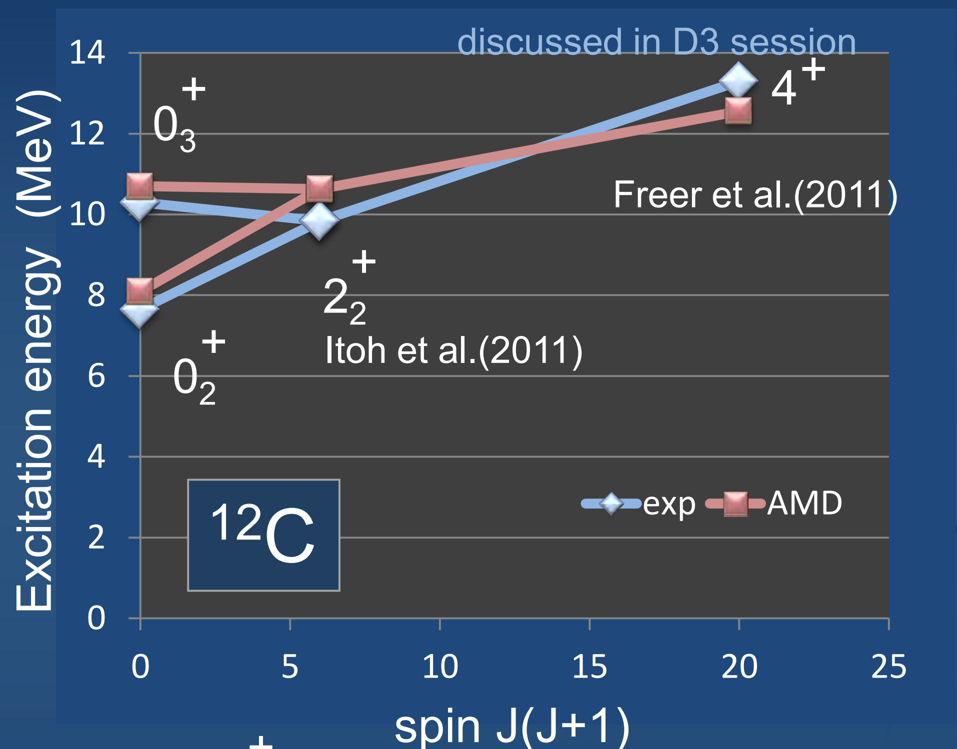
2α+t cluster in $^{11}B(3/2^-_3)$

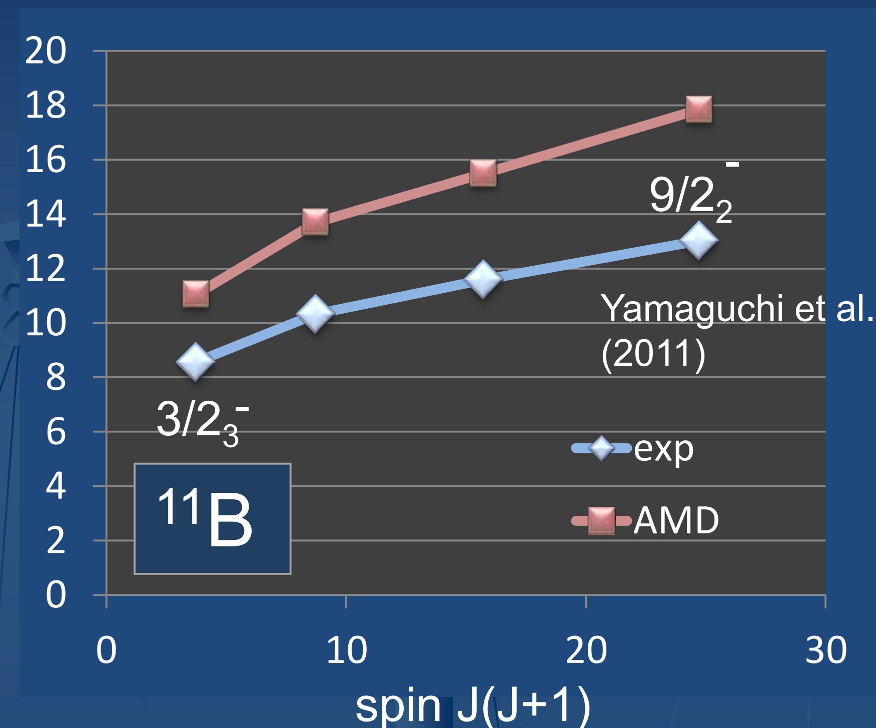
AMD by Y.K-E., Suhara

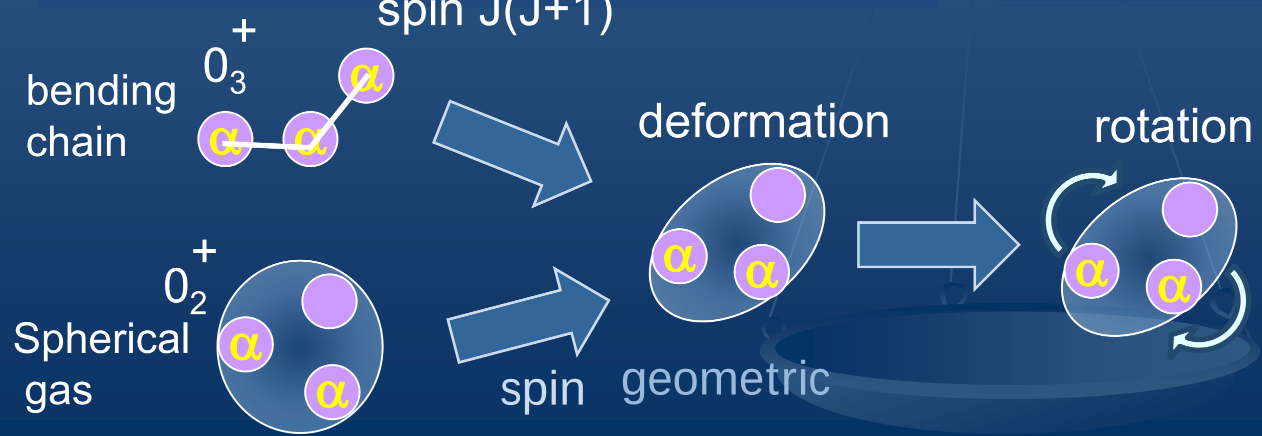




Rotational band from cluster gas







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

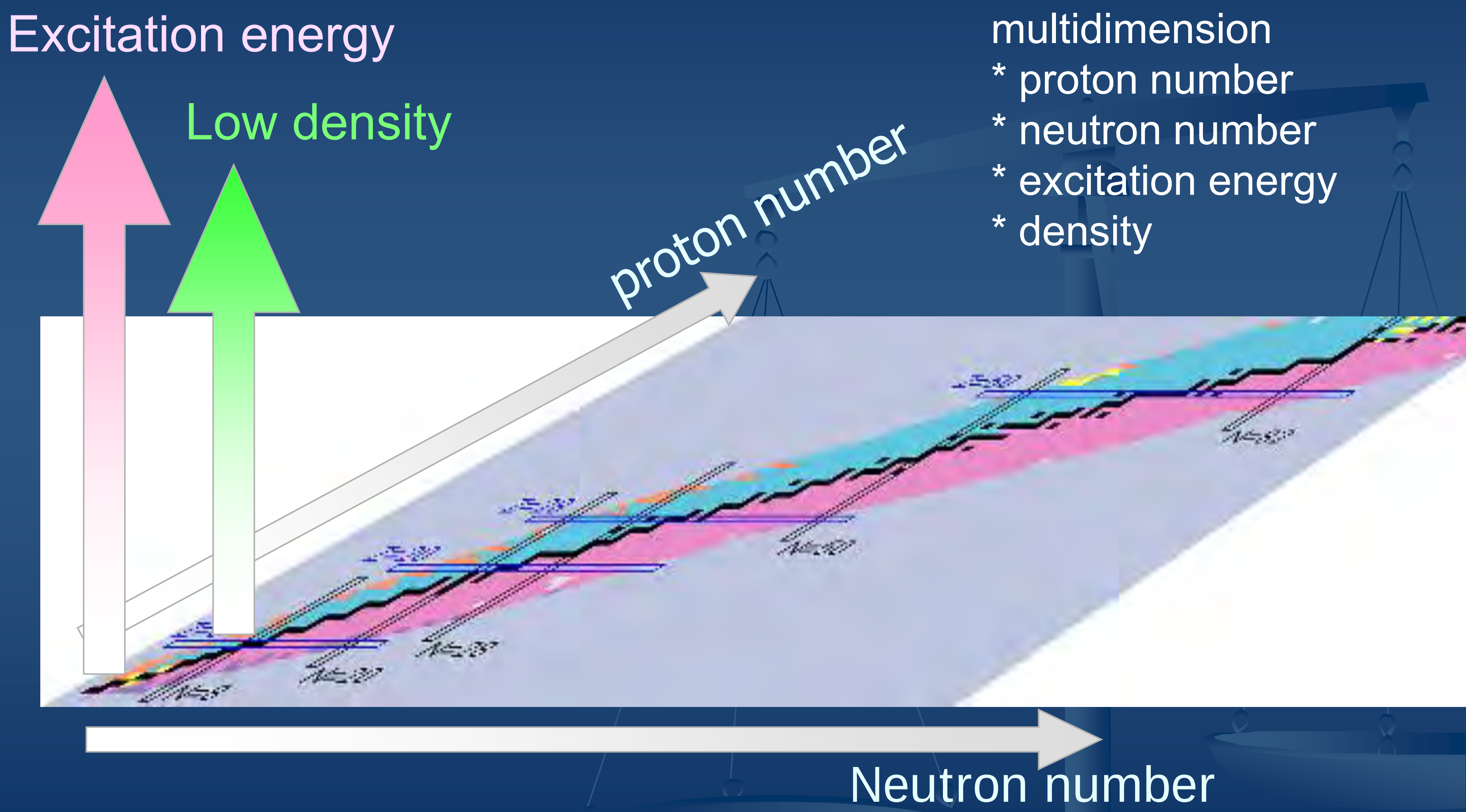
Summary

Rich cluster phenomena in n-rich nuclei
as function of proton and neutron numbers and excitation energy

- ✓ Cluster formation/breaking in low-lying states
- ✓ valence neutrons: MO Bond, new types of clusters
- ✓ Cluster excitation and resonances
- ✓ Many clusters : cluster gas, chain

Independent particle motion v.s. many-body correlations
single particle excitation(mode) v.s. cluster excitation

Systematic study in a wide region



multidimension
* proton number
* neutron number
* excitation energy
* density