Cluster and shape in stable and unstable nuclei

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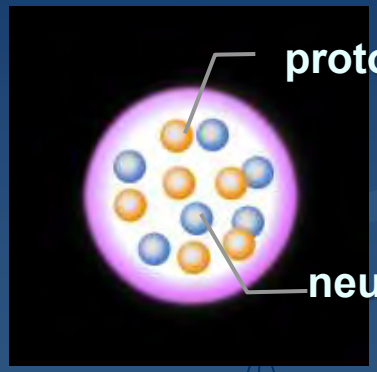
Y. Taniguchi (Tsukuba Univ.)

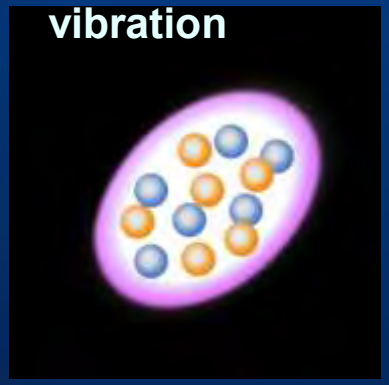
Introduction

Rich phenomena

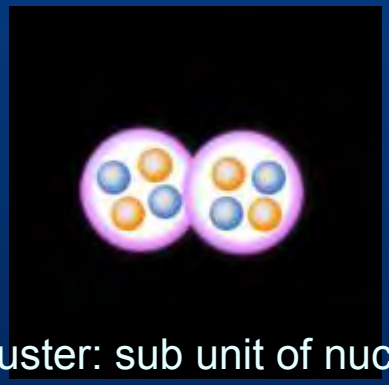


Neutron-rich

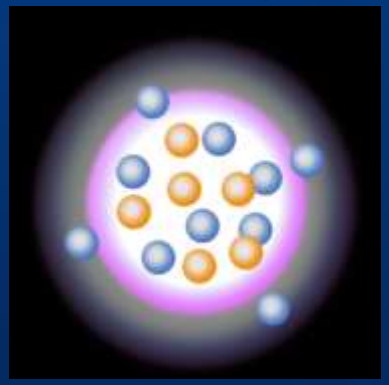
Deformation & vibration



Cluster structure



Neutron halo, skin

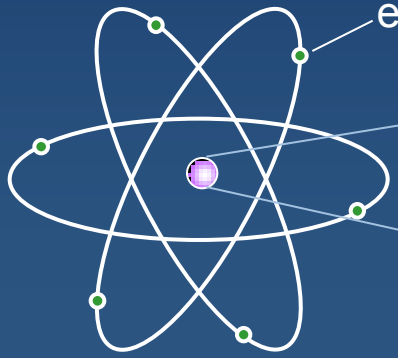


Cluster: sub unit of nucleons with spatial correlations

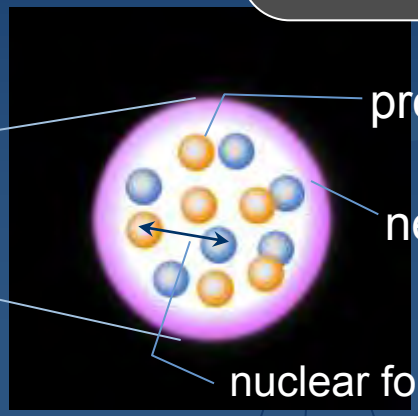
4He:p+p+n+n

Nuclear system

atom



nucleus

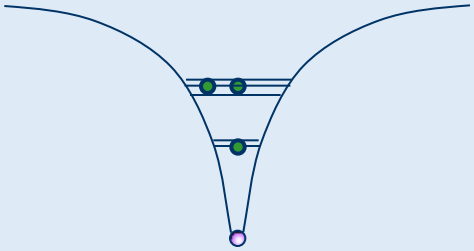


A finite quantum many-body system of protons and neutrons

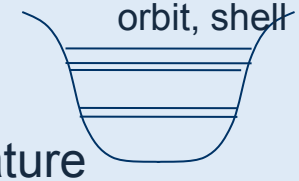
Analogy & Differences

Electron motion

Confined by the external field



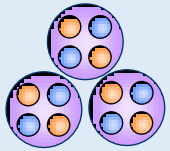
Nucleon motion



Self-bound

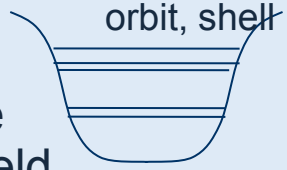
1. Independent-particle feature in self-consistent mean-field
2. Strong nucleon-nucleon correlations

cluster



Cluster

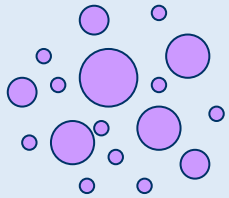
Nuclear system



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

3. Saturation properties

   Energy/nucleon～constant



Single-particle motion

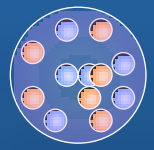
v.s.

Many-body correlation

Rich phenomena

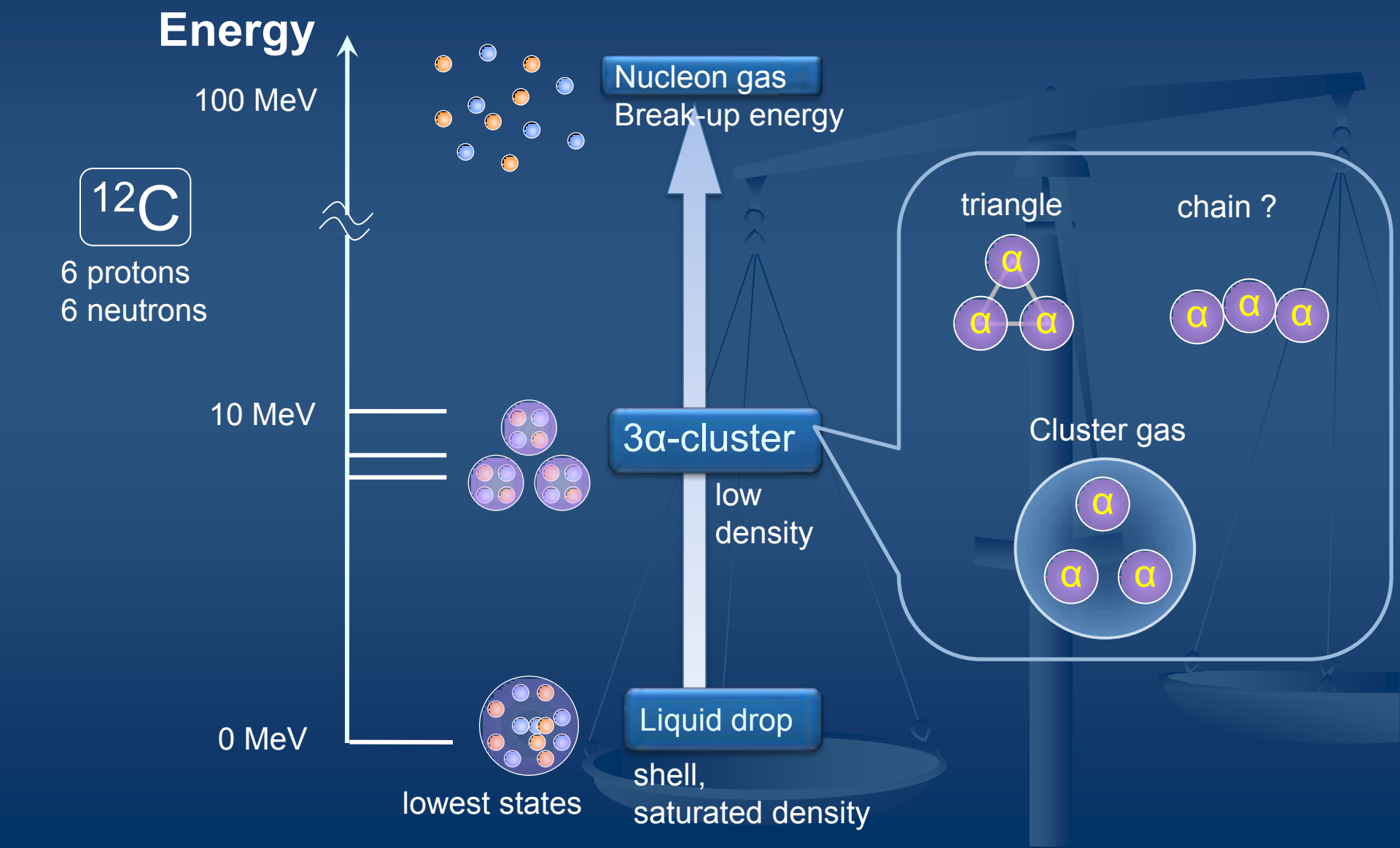
Cluster in low-lying excited states

Ground state

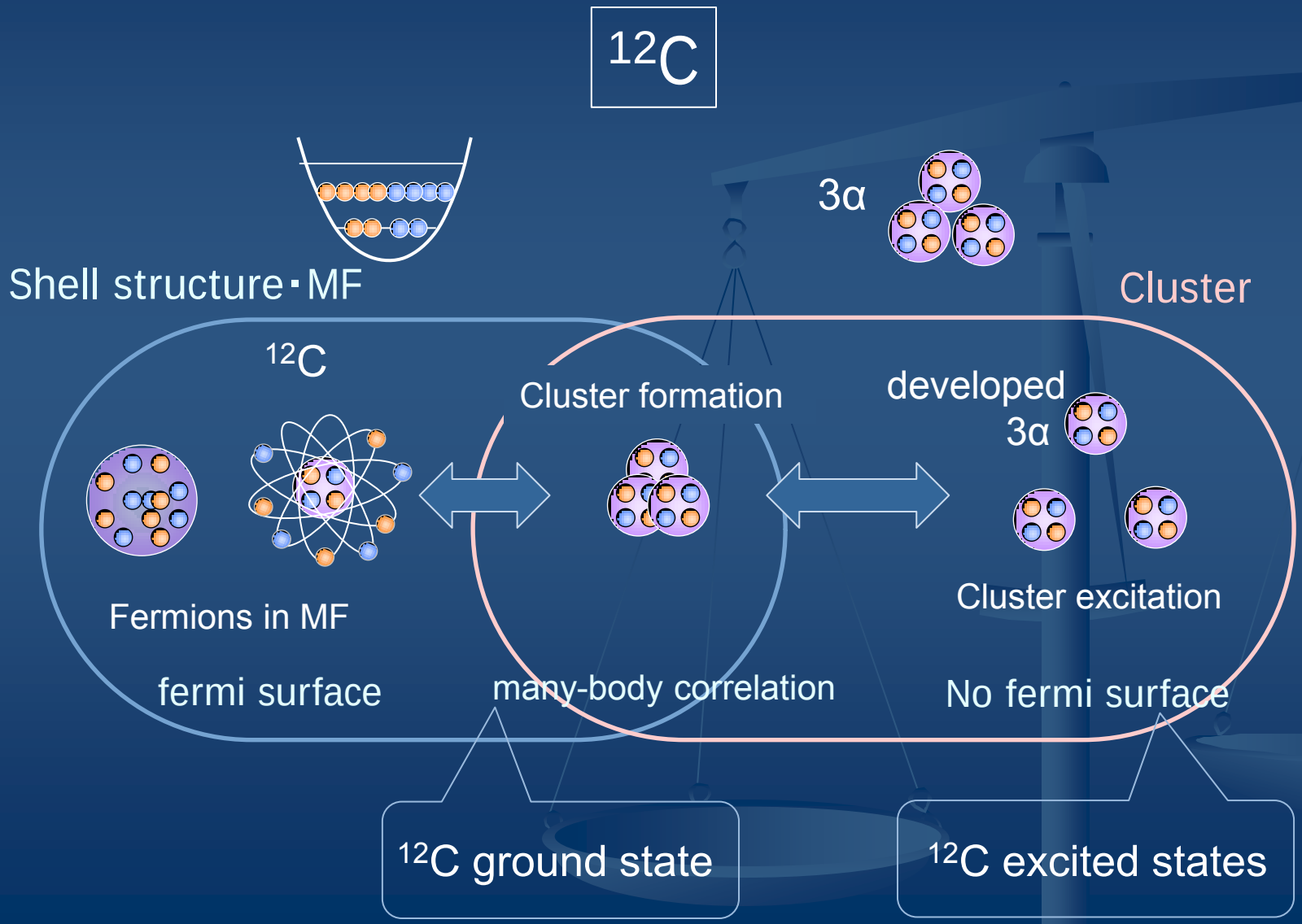


Excited state

Cluster states in low energy

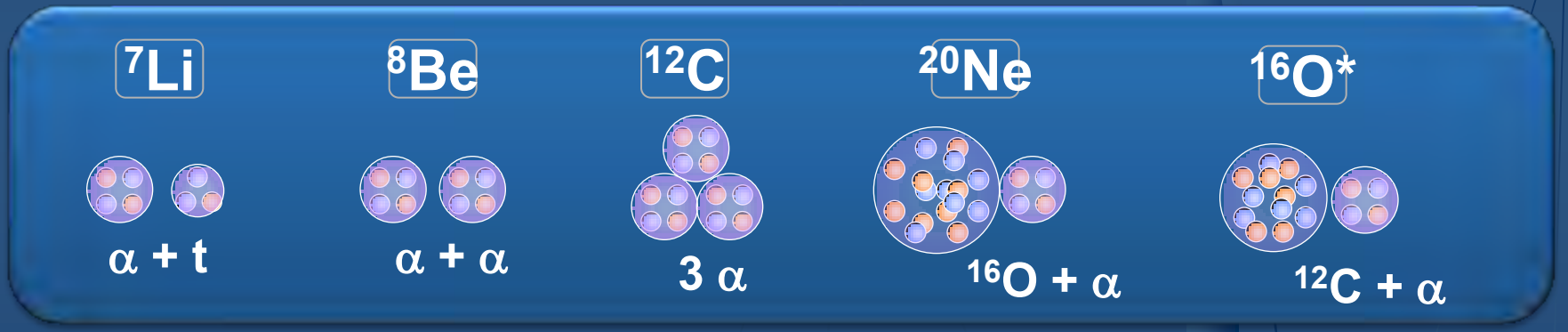


Coexistence of cluster and MF features



Typical Cluster structures

cluster structures known in light stable nuclei

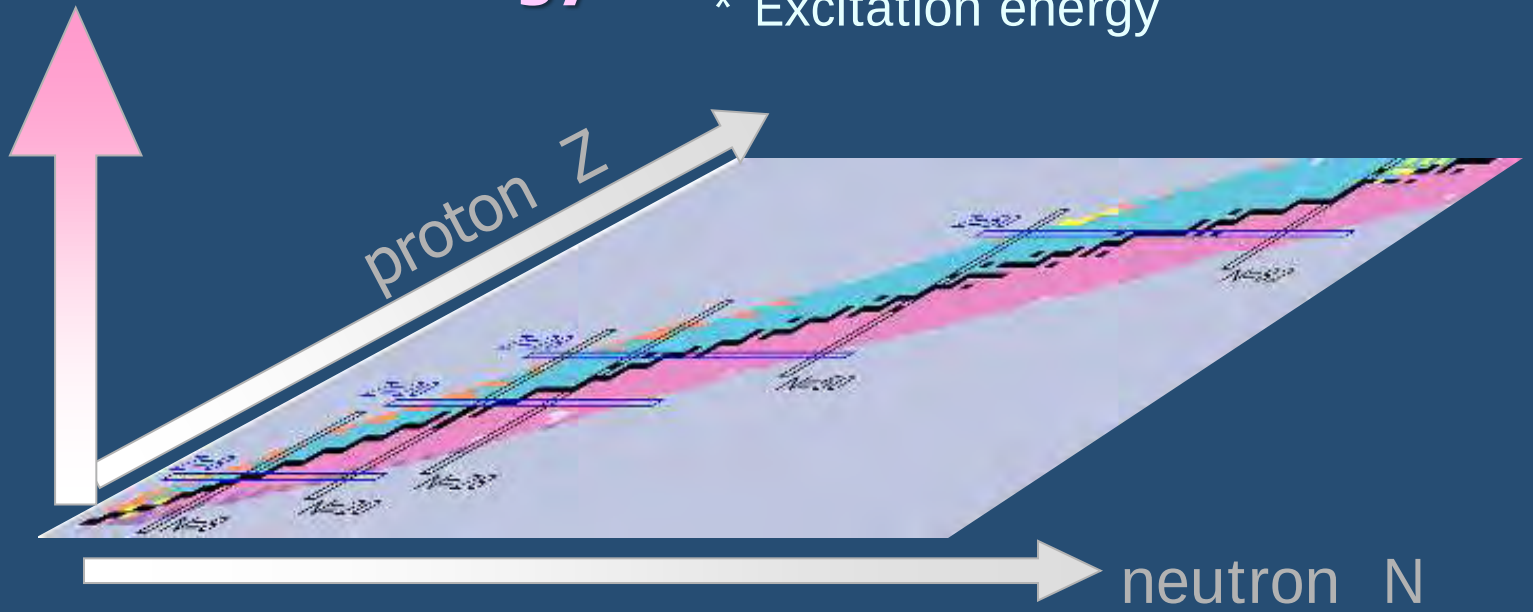


Rich phenomena in unstable nuclei

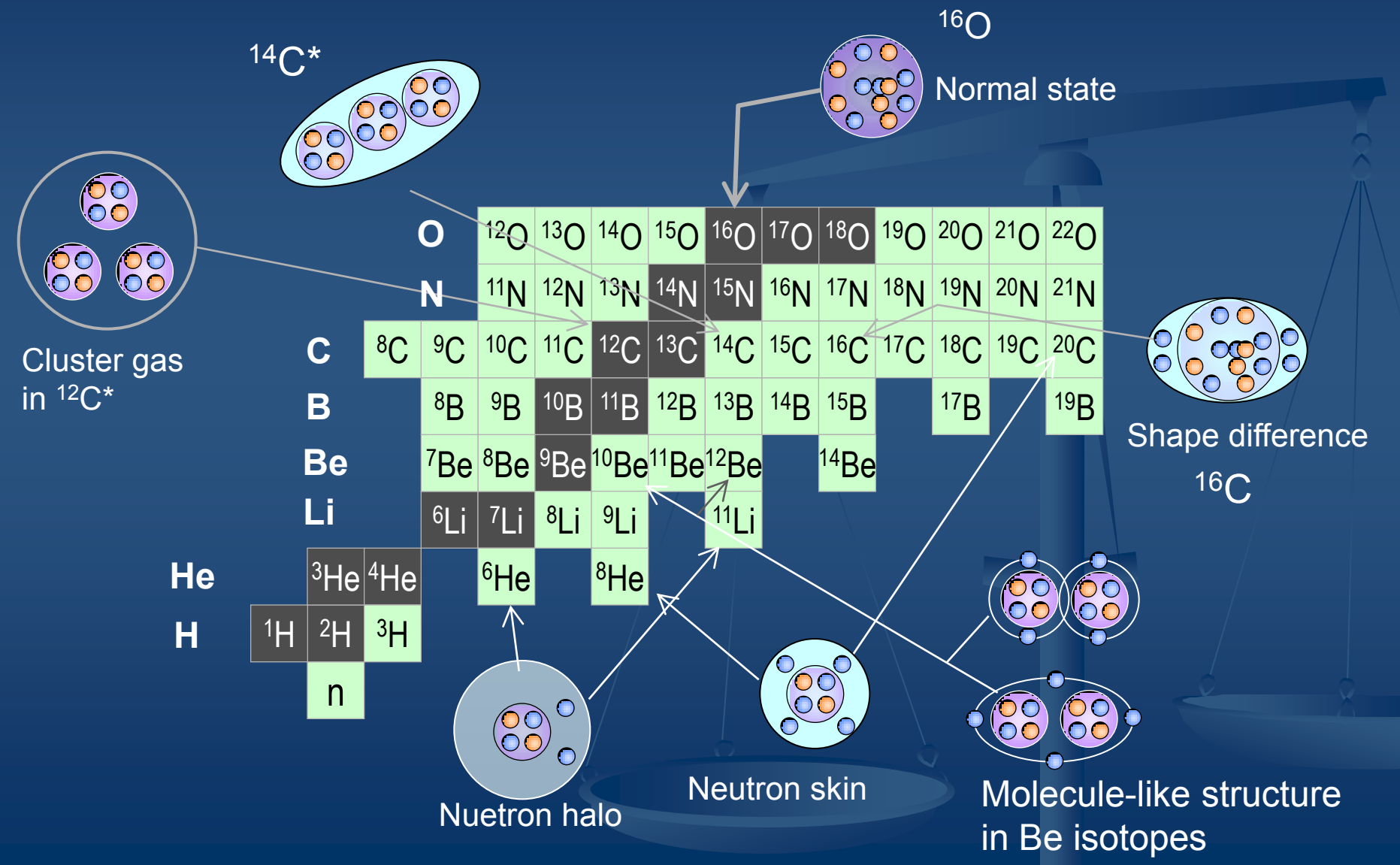
- New Facility (RIBF etc.)

Unbalanced proton-neutron ratio

* proton number
* neutron number
* Excitation energy



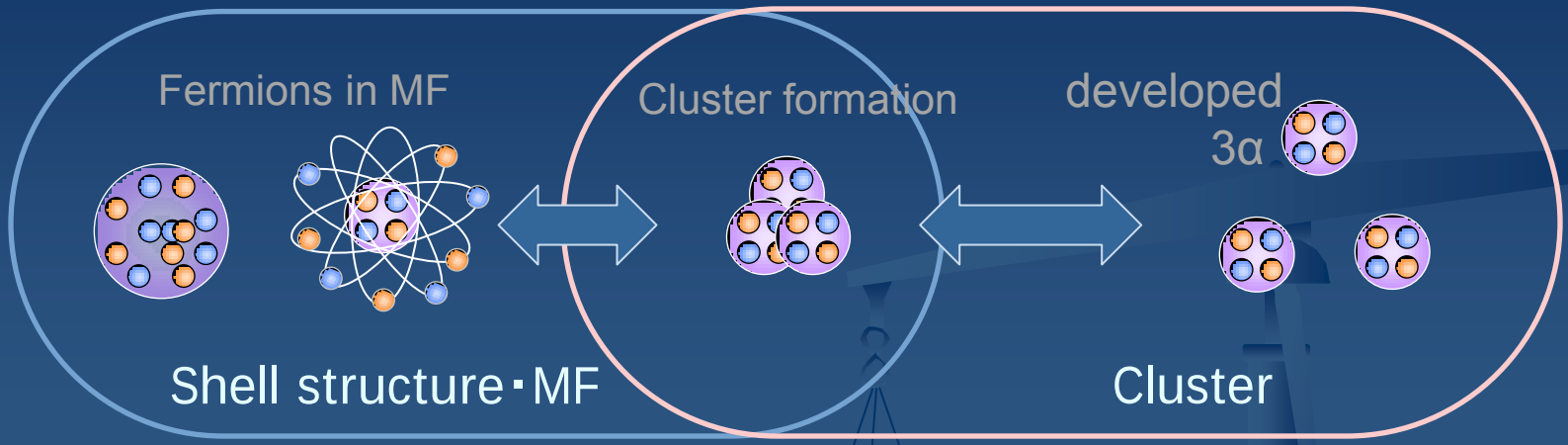
Rich phenomena in unstable nuclei



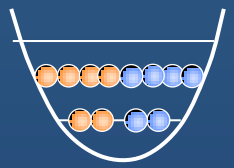
Theoretical Framework

Approach for nuclear structure to study coexistence of cluster and mean-field aspects

To study cluster and MF aspects

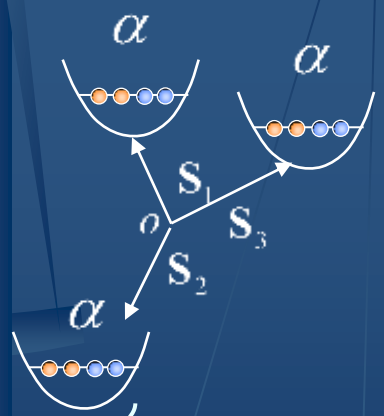


Shell-model, MF approaches



One-center basis expansion

Cluster models



Multi-center model:
Clusters a priori
assumed

AMD Antisymmetrized molecular dynamics

Cluster and MF aspects, stable/unstable nuclei, cluster formation/breaking

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

spatial

$$\varphi_i = \phi_{Z_i}\chi_i$$

$$\phi_{Z_i}(\mathbf{r}_j) \propto \exp\left[-\nu\left(\mathbf{r} - \frac{Z_i}{\sqrt{\nu}}\right)^2\right]$$

$$\chi_i = \begin{pmatrix} \frac{1}{2} + \xi_i \\ \frac{1}{2} - \xi_i \end{pmatrix} \times \quad p \text{ or } n$$

Intrinsic spins

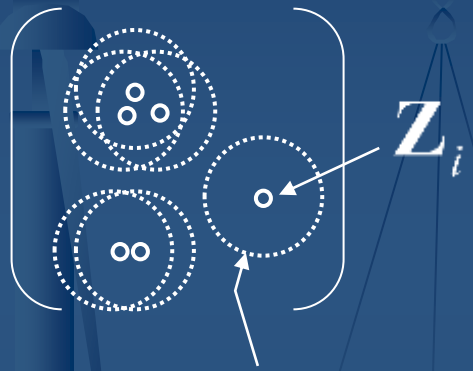
isospin

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

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

Variational parameters:
Gauss centers, spin orientations

det



Energy Variation

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

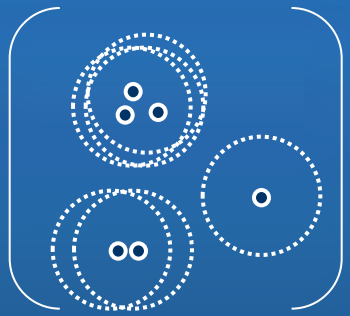
Model wave fn. Φ

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

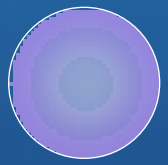
det

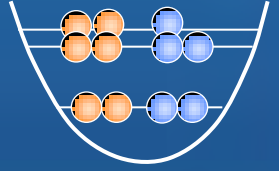


A variety of cluster st.

Cluster and MF formation/breaking

det

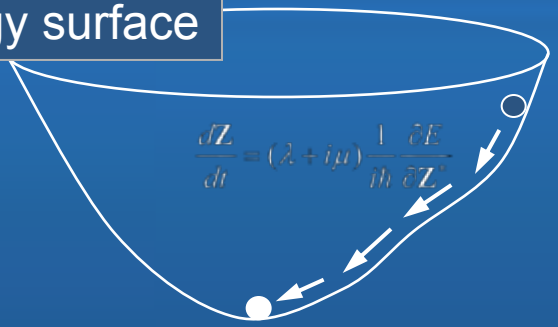




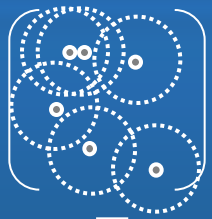
Shell structure

Energy variation

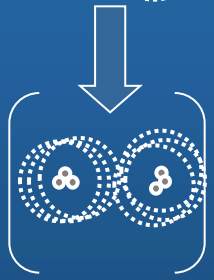
Energy surface



Model space (Z plane)

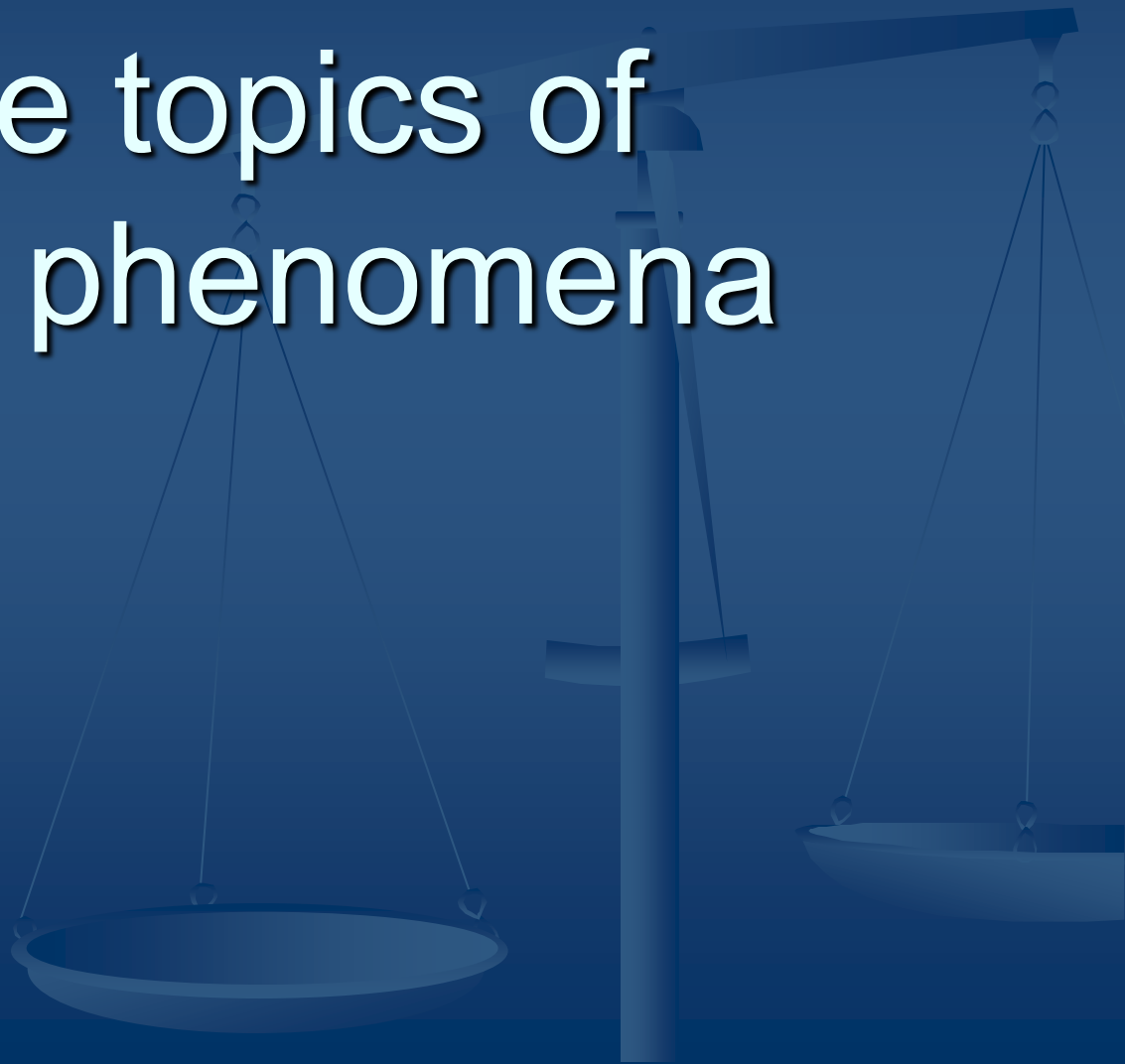


Randomly chosen Initial states



Energy minimum states

Some topics of cluster phenomena



Topics of cluster phenomena

- Cluster gas, Linear chain states in C isotopes
- Cluster structures in Be isotopes
- Cluster & shapes: symmetry breaking(SB) and restoration

Topics of cluster phenomena

- Cluster gas, Linear chain states in C isotopes
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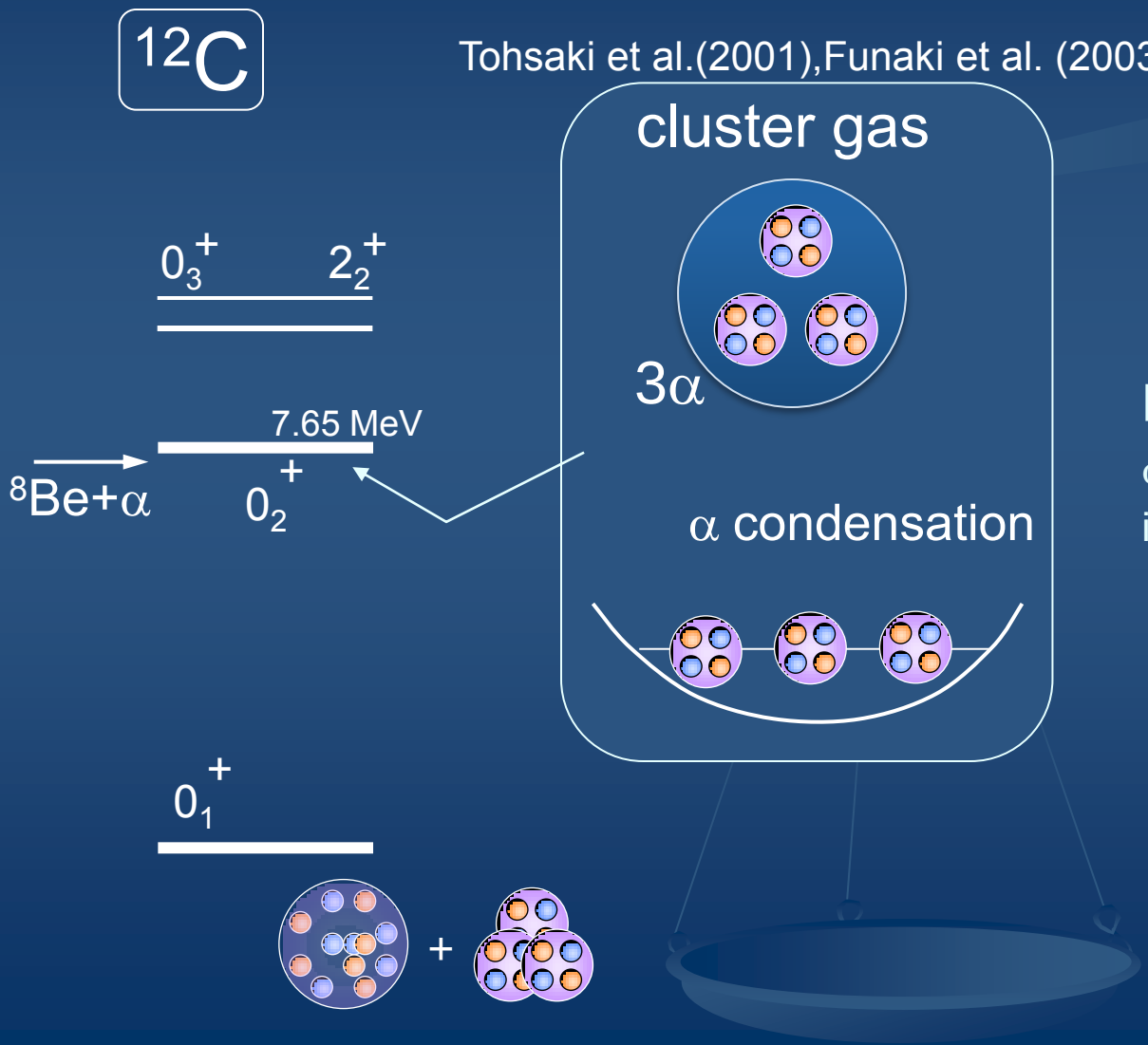
Cluster gas states in excited states

^{12}C

Tohsaki et al.(2001),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)

2α+t cluster in $^{11}B(3/2^-_3)$

AMD by Y.K-E., Suhara

^{12}C

similar cluster gas of 2α+t ?

^{11}B, ^{11}C

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

Cluster gas of 3α

0^+_2 7.65 MeV

^8Be+a

0^+_1

+

2α+t

2a+t

$3/2^-_4$

10.3

^7Li+a

$3/2^-_3$

8.5

$3/2^-_2$

$3/2^-_1$

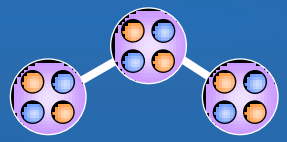
Strong E0 transition

Kawabata et al.
PLB646, 6 (2007)

Linear chain of 3α in C* ?

^{12}C

Linear chain of 3α ?

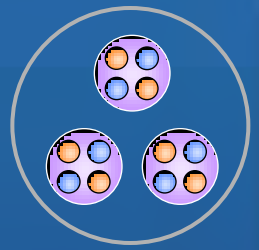


0_3^+ 2_2^+

7.65 MeV

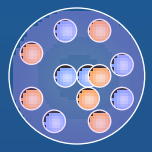
$^8Be+\alpha$

0_2^+



3α clustser gas

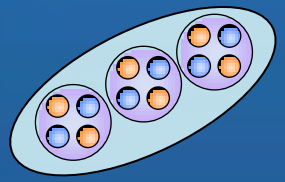
0_1^+



$^{14,16}C$

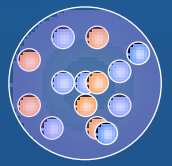
stabilized by excess neurons

Itagaki et al., Y.K-E.et al., Suhara et al.



Linear chain structure ?

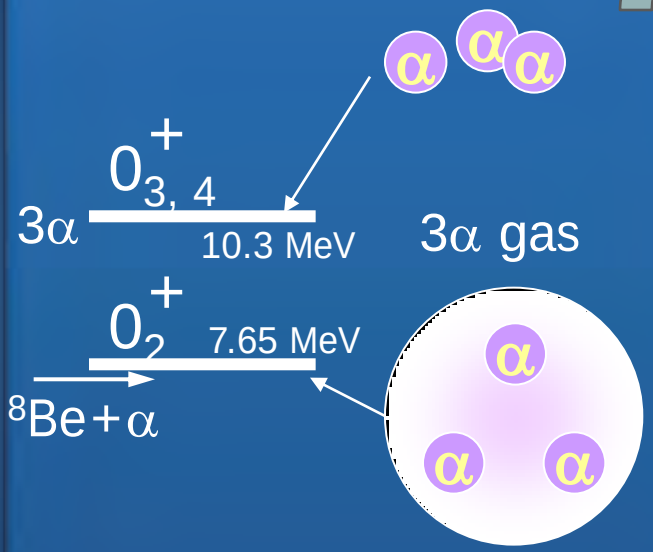
0_1^+



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

^{12}C

3α chain-like

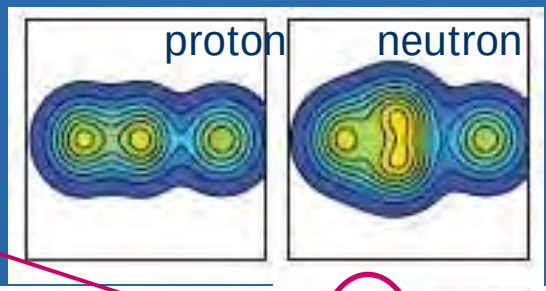


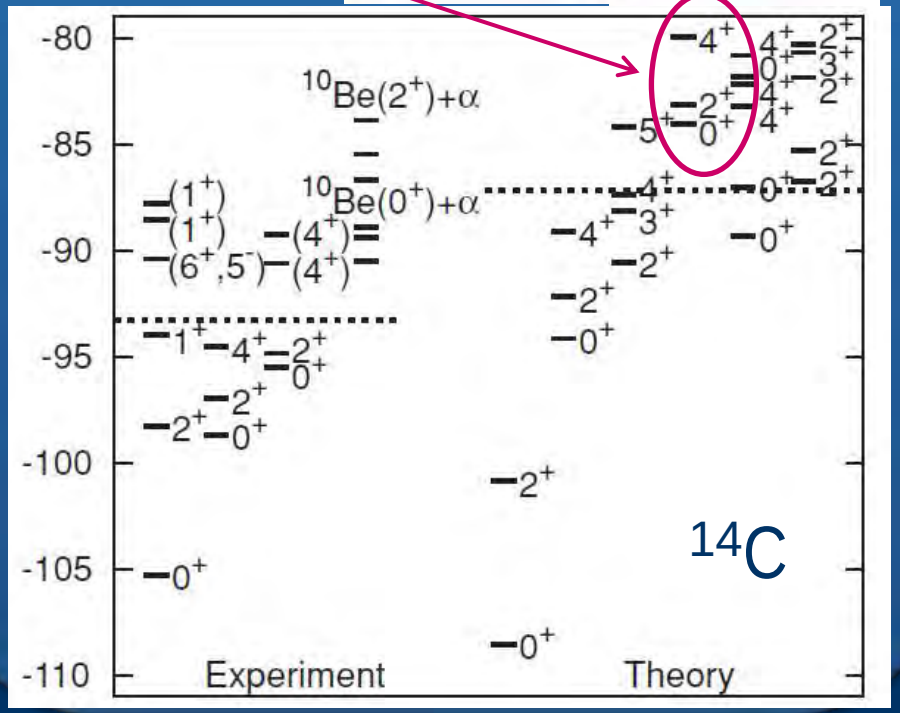
Add two neutrons

^{14}C

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

3α linear chain

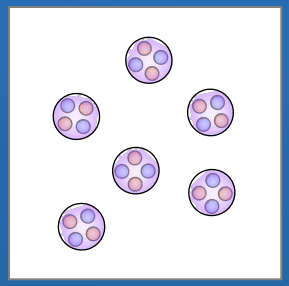




Many-body correlations at low density

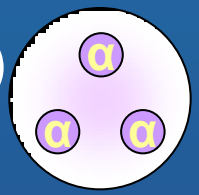
Cluster gas, chain ?

Nuclear matter



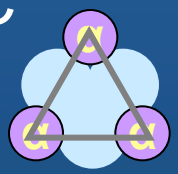
α-cond.
in low density

$^{12}C(0_2^+)$
$^{16}O^*$

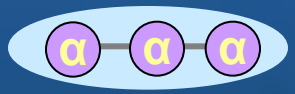


Dilute α-cluster gas

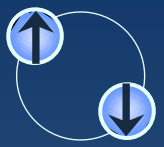
$^{14\text{-}16}C^*$



Geometric (crystal ?)

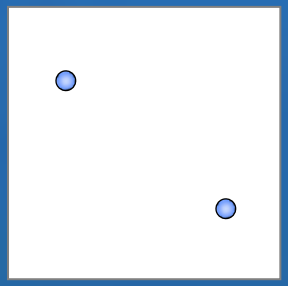


Dineutron correlation ?

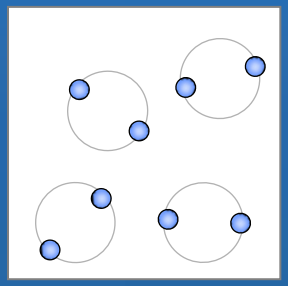


Neutron matter

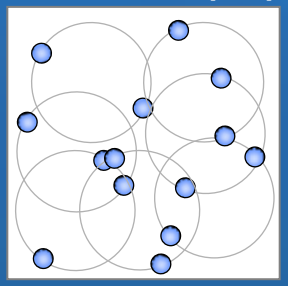
Matsuo et al. PRC73 044309 ('06)



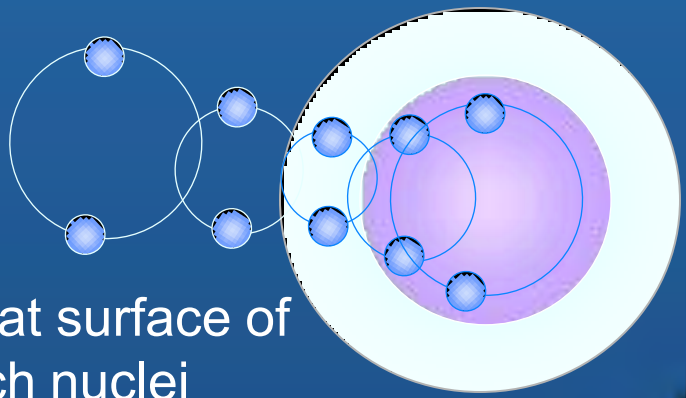
Unbound



BEC-BCS



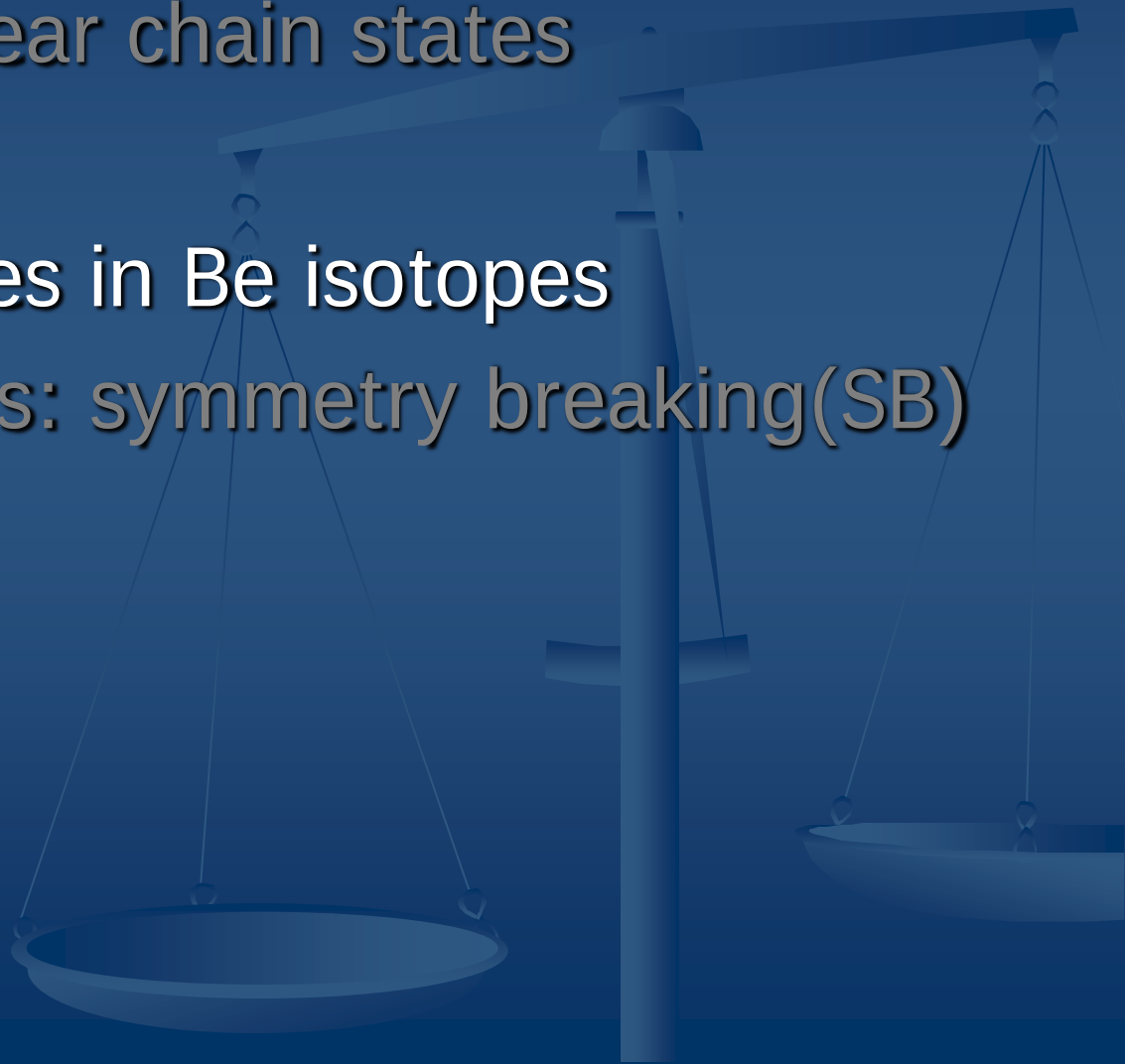
BCS



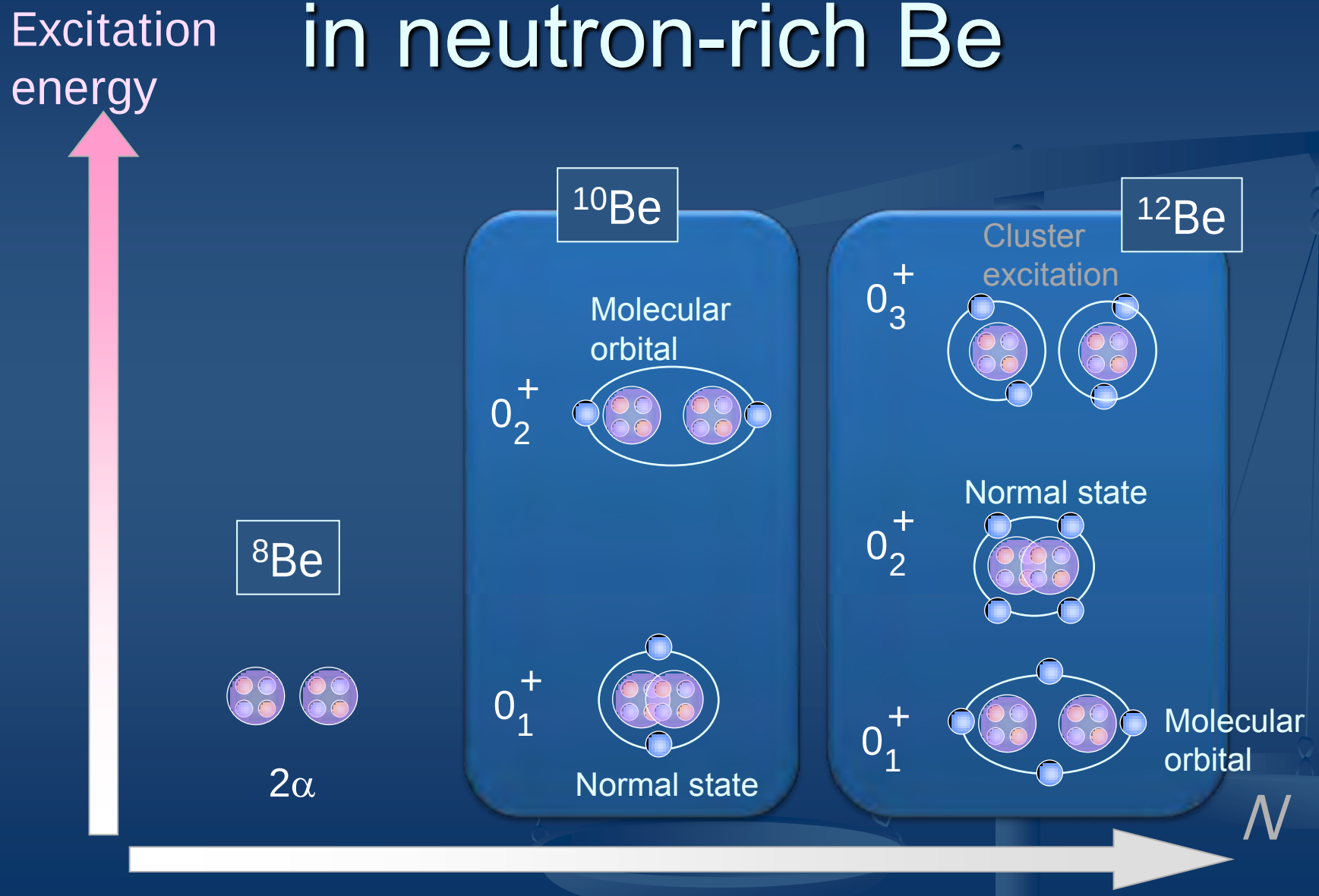
Dineutron at surface of neutron-rich nuclei
by F. Kobayashi PTP126, 457 (2011)

Topics of cluster phenomena

- Cluster gas, Linear chain states in C isotopes
- Cluster structures in Be isotopes
- Cluster & shapes: symmetry breaking(SB) and restoration

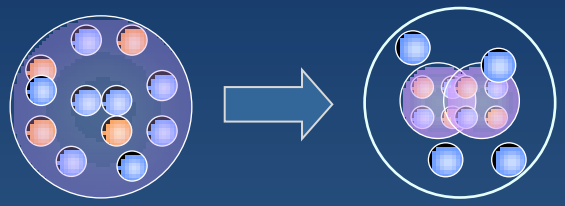


Cluster structure in neutron-rich Be



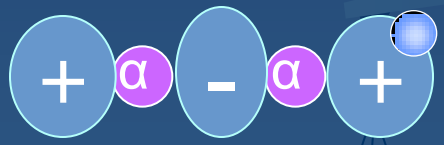
Molecular orbital(MO) structure in Be

2α-core formation



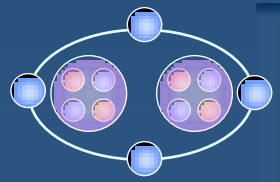
MO formation

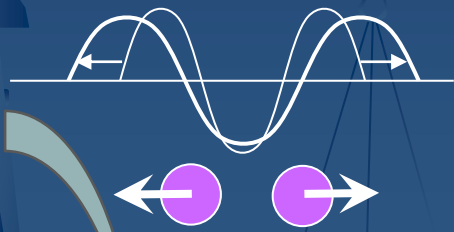
Von Oertzen et al., N. Itagaki et al., Y. K-E. et al.



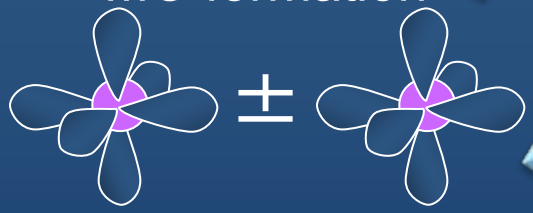
σ-orbital

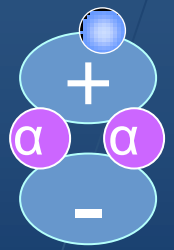
MO state





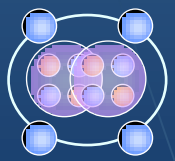
MO formation





π-orbital

Normal state



Gain kinetic energy in developed 2α system

Low-lying MO states

vanishing of magic number N=8 in ^{11}Be, ^{12}Be, ^{13}Be

Topics of cluster phenomena

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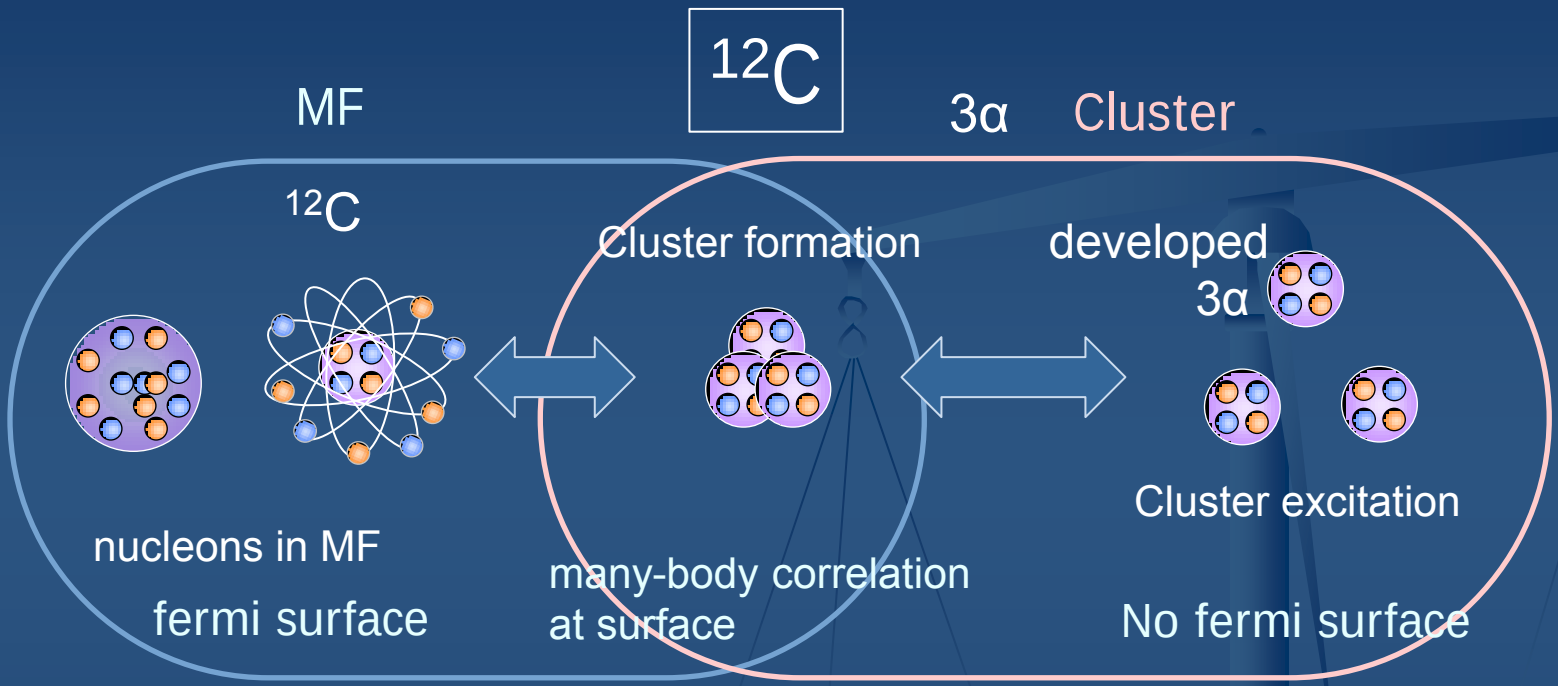
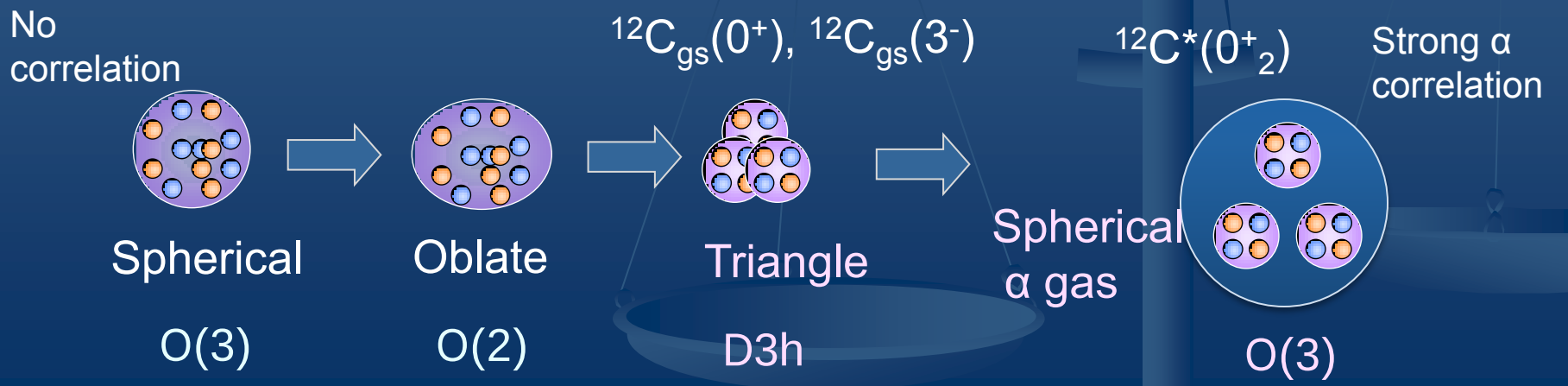
Exotic shapes from cluster correlation

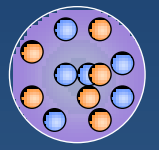




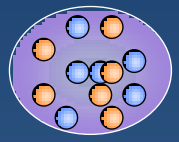
Cluster correlation and SB

Y. K-E. and Y. Hidaka, PRC84, 014313 (2011)

rotational/axial symmetry



Spherical



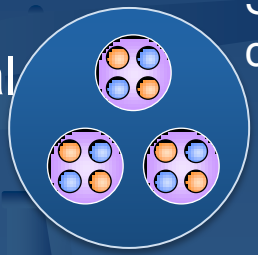
Oblate

broken

Triangle

restored

Spherical α gas



Strong α correlation

Angular DW (Edge DW)

$$\left\langle a^{+}_{L_z+1} a_{-L_z} \right\rangle \neq 0$$

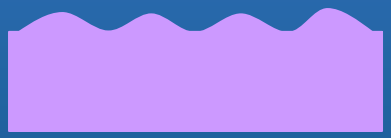
$2L_z+1$ periodicity

Infinite matter

Translational symmetry

Fermi gas

broken phase



Density wave(DW)

restored

BEC: alpha cond.

$$\left\langle a^{+}_{k} a_{-k} \right\rangle \neq 0$$

2k periodicity

Summary

- Coexistence of cluster and MF aspects brings variety of structures.
- Topics of cluster phenomena in stable and unstable nuclei:

  Cluster gas, Linear chain, molecular orbital etc.

  Cluster and symmetry breaking
- In studies of unstable nuclei, further rich phenomena will be discovered as functions of proton/neutron numbers and excitation energy.
- Analogy with other quantum many-fermion systems (cold atoms, quark systems)

Acknowledgments

- Thank to members of the nuclear theory group
- Thank to GCOE program for a chance to start new collaborations