cluster states and their rotation in light nuclei

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Collaborators:
  Y. Hidaka(RIKEN), T. Ichikawa(YITP),
  M. Kimura(Hokkaido), F. Kobayashi(Kyoto),
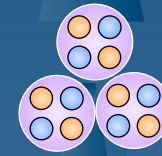 T. Suhara (Matsue) ,Y. Taniguchi(NIMS), Y. Yoshida (Kyoto)

1.Introduction

Cluster & Mean field

Mean field, shell structure
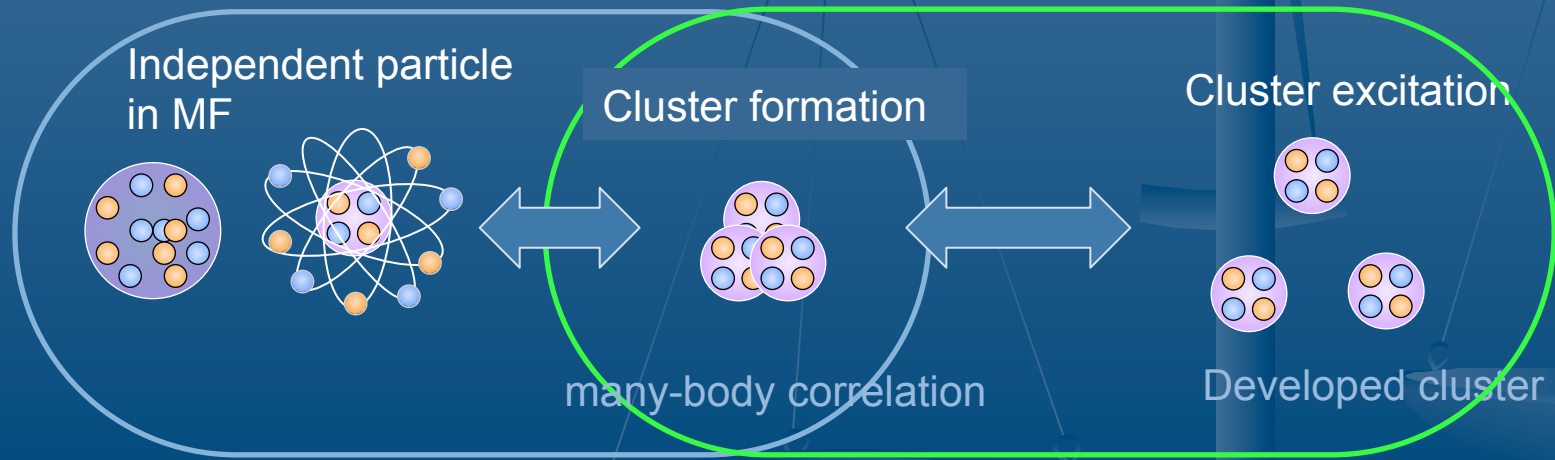Independent single-particle

Cluster:
Many-body correlation

Shell structure・MF   v.s.   Cluster
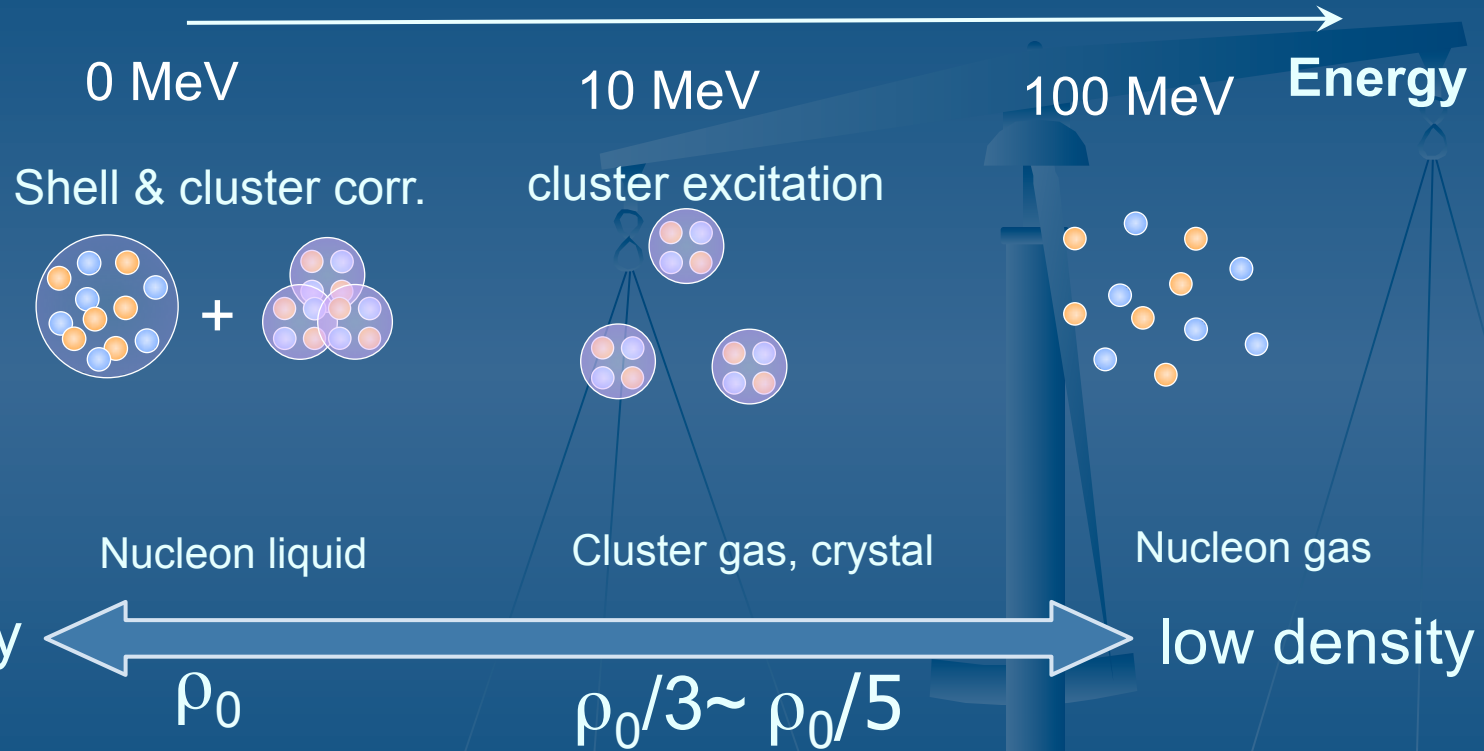
Independent particle
in MF

Cluster formation

Cluster excitation

many-body correlation

Developed cluster

no correlation   g.s. correlation   excited states

Cluster structures

Energy

0 MeV   10 MeV   100 MeV

^{12}C

Shell & cluster corr.   cluster excitation

+

Nucleon liquid   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

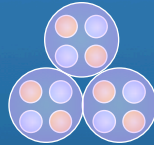## Typical cluster structures known in stable nuclei

^{7}Li

$\alpha + t$

^{8}Be

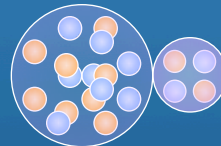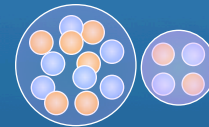$\alpha + \alpha$

^{12}C

3α

^{20}Ne

^{16}O $+ \alpha$

^{16}O*

^{12}C $+ \alpha$

Heavier nuclei

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

α

α-cluster

^{36}Ar-α, ^{24}Mg-α, ^{28}Si-α
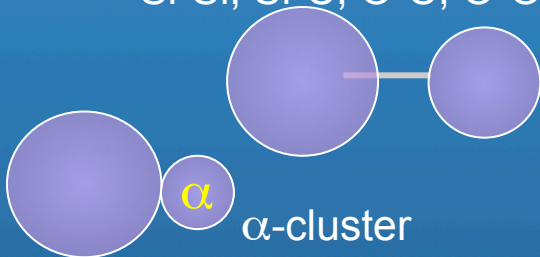
^{40}Ca*, ^{28}Si*, ^{32}S*

Unstable nuclei

α-cluster excitation

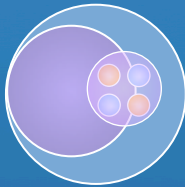3α linear chain

^{14}C*
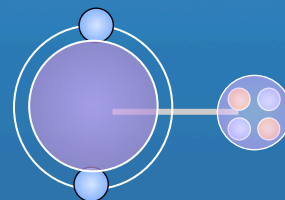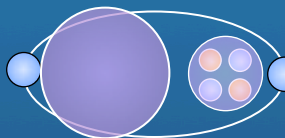
Molecular orbital
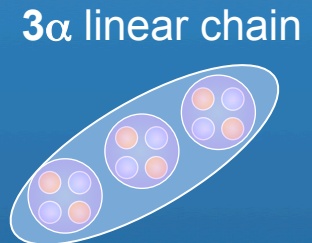
Be, C, O, Ne, F

Cluster structures in n-rich nuclei

gs cluster correlation
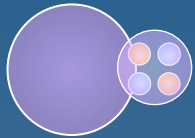
cluster weakening/ melting

Clustering in deformed Neutron density

n-rich Be, F, Ne

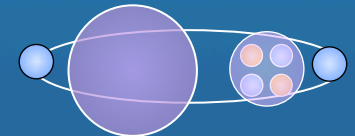α-cluster excitation

stable nuclei
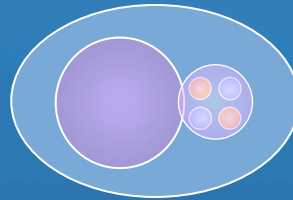
n-rich nuclei

- ✓ n-skin suppression
- ✓ large deformation
- ✓ breaking of magic number N=8, N=20
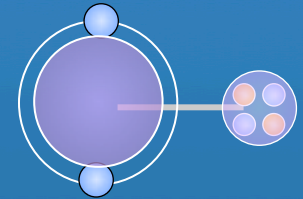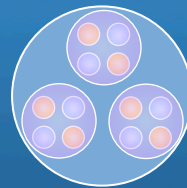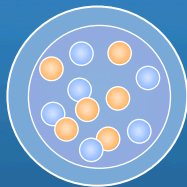
Molecular orbital

cluster gas
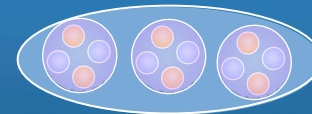
n-rich C

linear chain

in C*

Roles of excess neutrons in cluster structures of n-rich nuclei

^{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

^{18}O+α

α ---- α

^{16}O ---- α
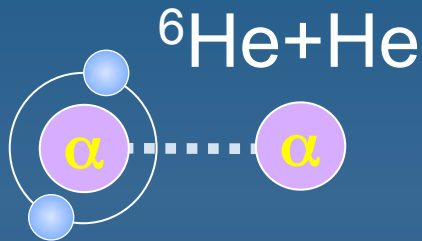
Atomic:
Cluster resonance

Weak coupling

α α

^{16}O α
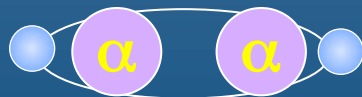
Molecular Orbital:
bonded clusters
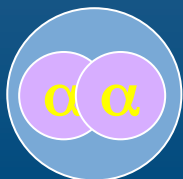
Strong coupling

α α

Normal states
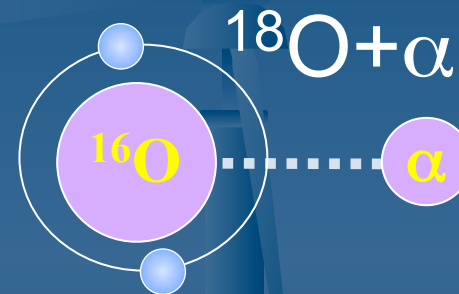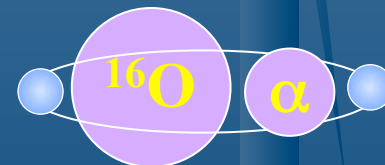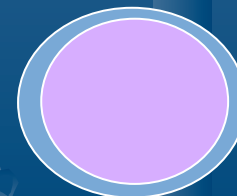
shell model-like

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,

AMD study by Kimura, PRC75 (2007)

^{22}Ne

^{18}O+α

^{16}O α **Cluster res.**

^{16}O α **MO-bond**

^{22}Ne α cluster bands

α+^{18}O molecular bands

molecular orbital bands

α+^{18}O threshold

ground band

$K^{\pi}=0^-_4$
$K^{\pi}=0^+_3$
$K^{\pi}=1^-$
$K^{\pi}=0^-_1$
$K^{\pi}=0^+_2$
$K^{\pi}=0^+_1$

EXP (ve-parity) (ive-parity)
AMD (positive-parity) (negative-parity)

excitation energy [MeV]

J

(f) neutron orbital No. 6

y [fm]

z [fm]

^{22}Ne   (+ - + + -)

1s0d-orbital around ^{16}O   0p-orbital around α

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,
Theor: Suhara '10

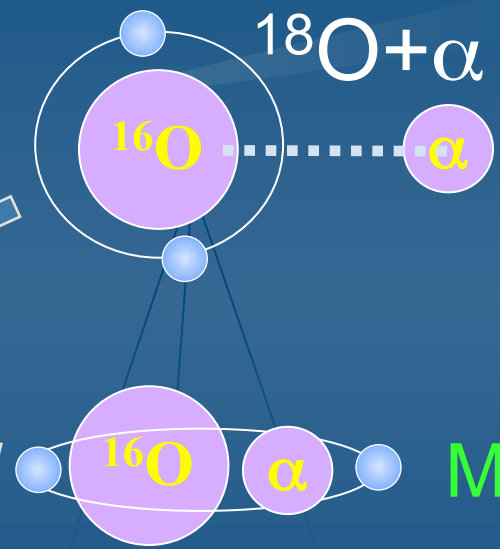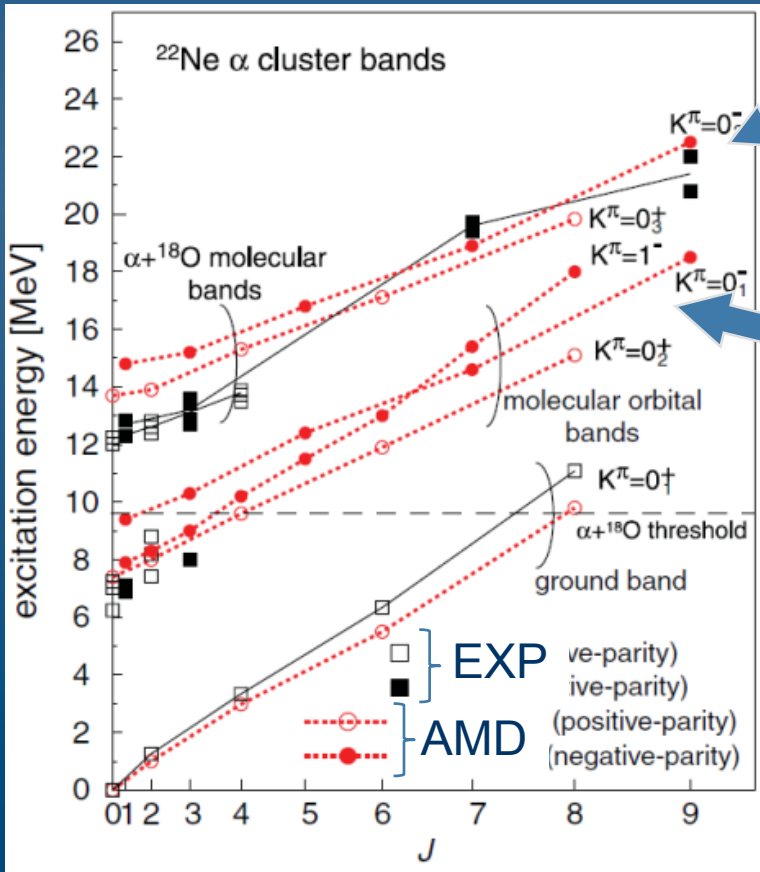^{14}C+α in ^{18}O*   Exp Scholz et al., Rogachev et al., Goldberg et al.,Ashwood et al., Yildiz et al.,
Theor: Descouvemont, Kimura,

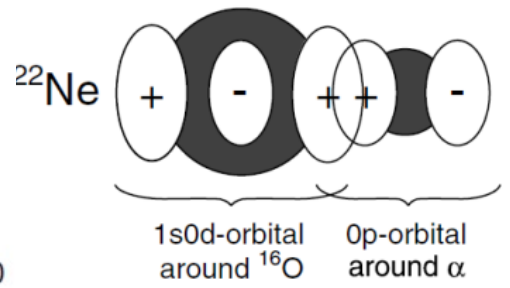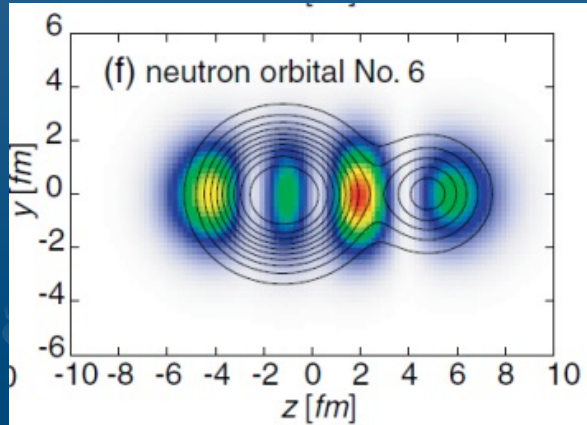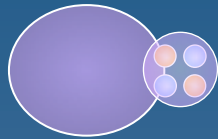^{18}O+α in ^{22}Ne*   Exp Scholz '72, Rogachev '01, Goldberg '04, Ashwood '06, Yildiz et al.,
Theor: Descouvemont '88, Kimura '07

-> information of nucleus-nucleus potential and valence neutron effects there.
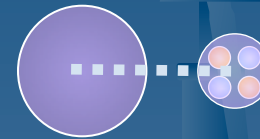
Two kinds of cluster structure

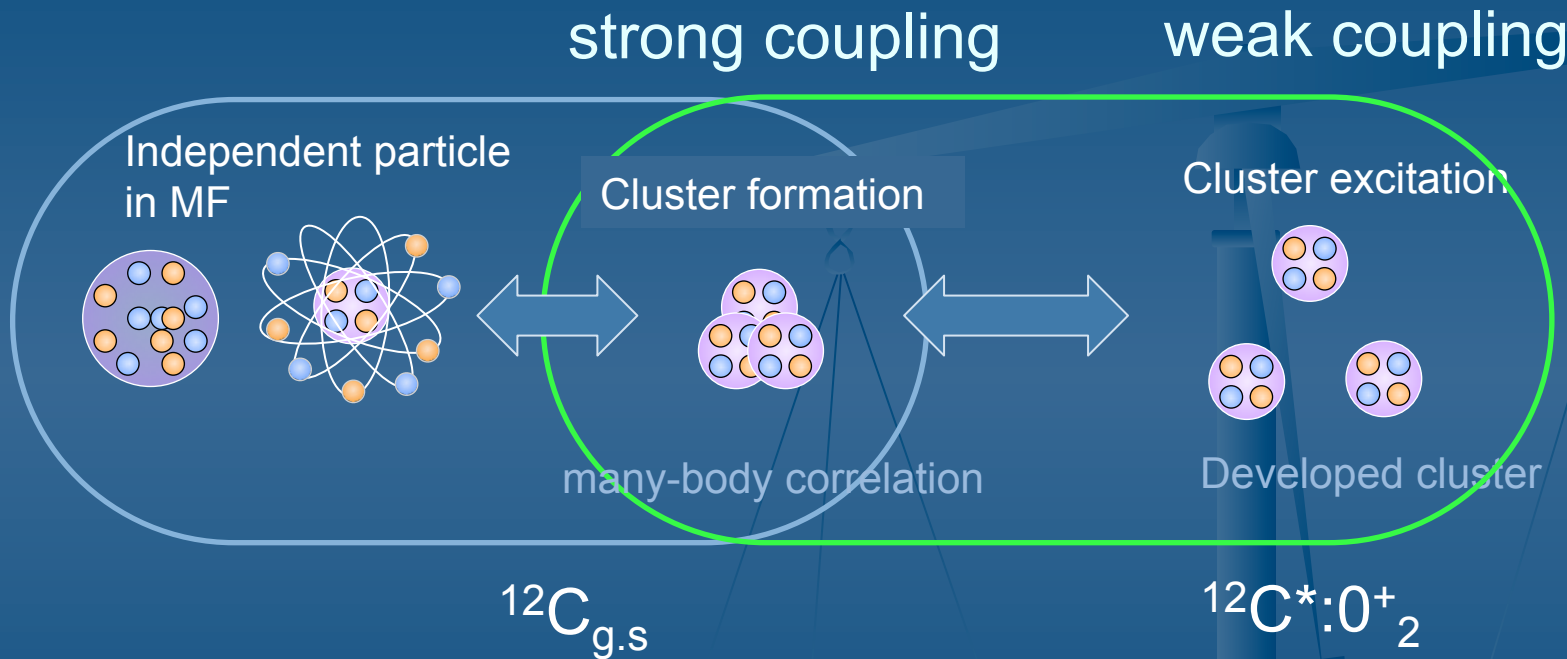strong coupling cluster   V.S. weak coupling cluster

- Cluster core at surface
- Clusters are overlapping
- Usually bound state
- Indirect evidence
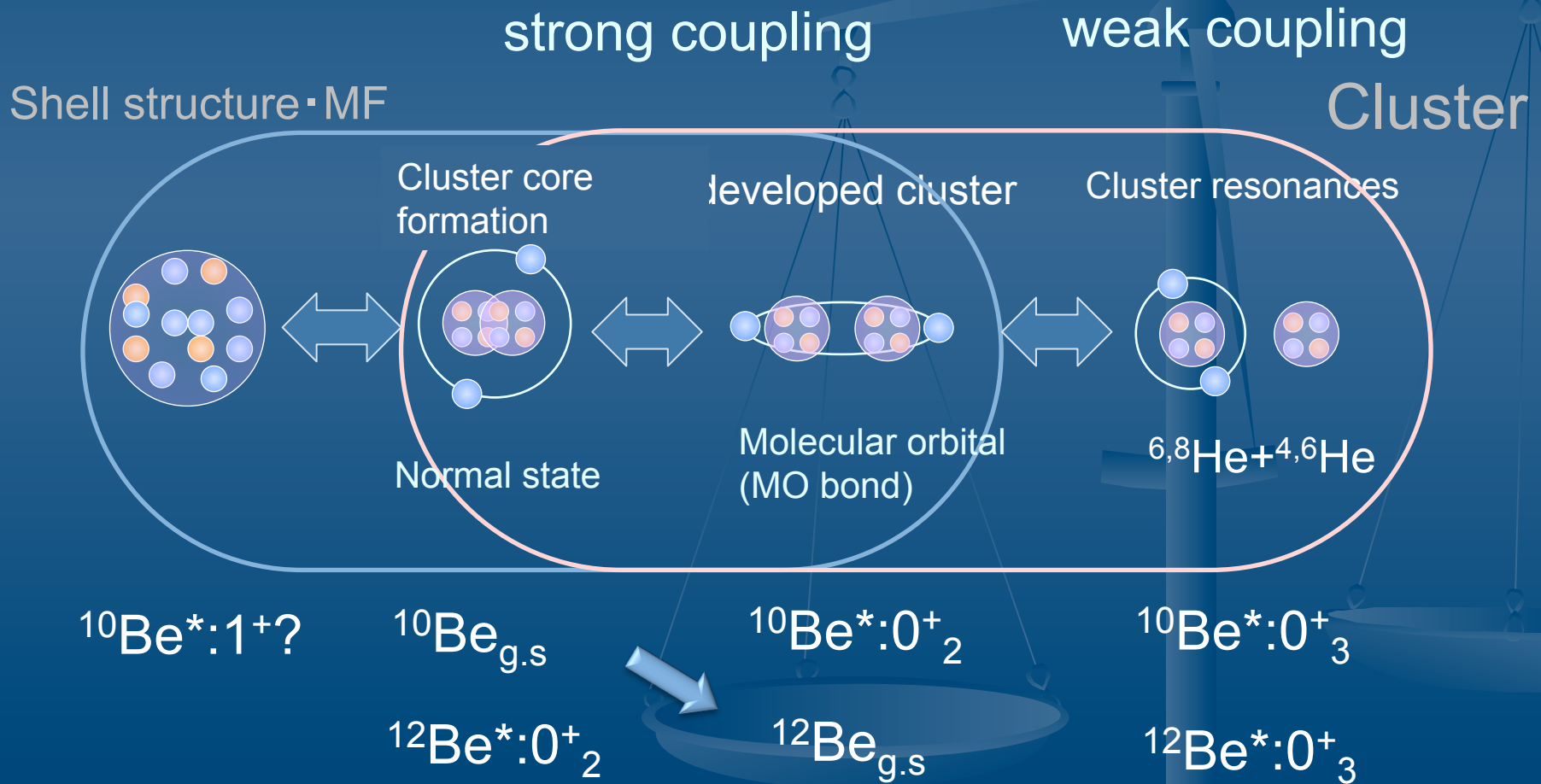deformation, trancitions, charge radii, s.p. config.

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

ex) when knock-out the deeply bound cluster, the residual may not be the pure ground state but contain g.s. and excited configurations.

Cluster & Mean field

strong coupling

weak coupling

Independent particle in MF

Cluster formation

Cluster excitation

many-body correlation

Developed cluster

$^{12}C_{g.s}$

$^{12}C^*{:}0^+_2$

Cluster phenomena in n-rich Be

$^{10,11,12,..}$Be

strong coupling   weak coupling

Shell structure・MF   Cluster

Cluster core formation   developed cluster   Cluster resonances

Normal state   Molecular orbital (MO bond) ^{6,8}He+^{4,6}He

^{10}Be*:1^+? ^{10}Be$_{g.s}$ ^{10}Be*:0^+_2 ^{10}Be*:0^+_3

^{12}Be*:0^+_2 ^{12}Be$_{g.s}$ ^{12}Be*:0^+_3

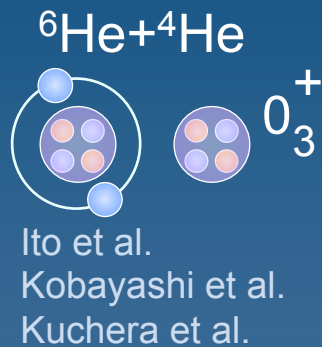# 3. Some topics of cluster phenomena
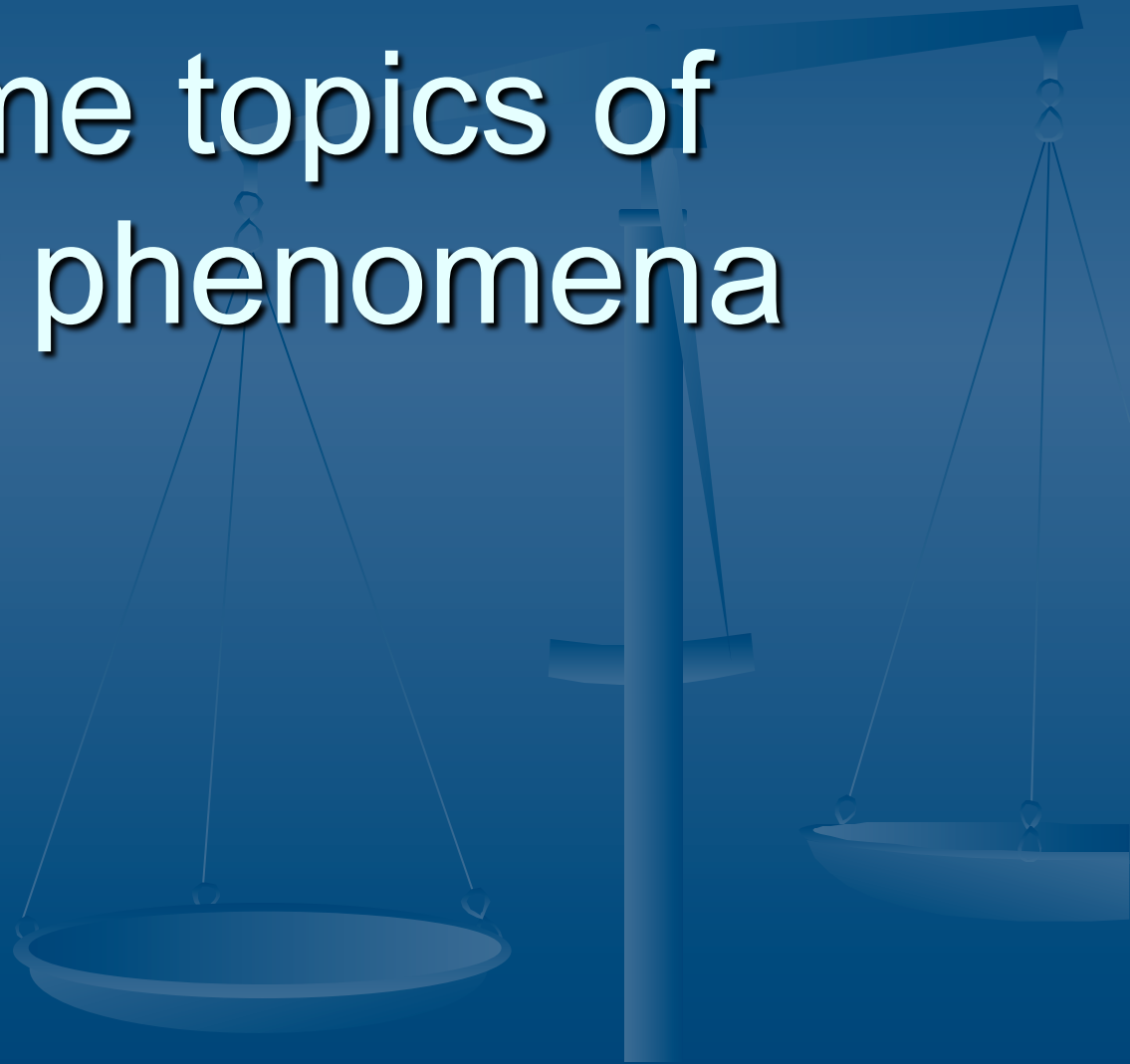
3-1. MO bond in n-rich Be
     & vanishing of magic number

3-2. Cluster resonances

3-3. Linear chain in n-rich C
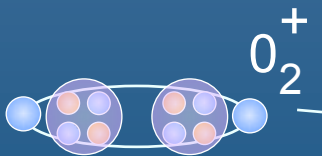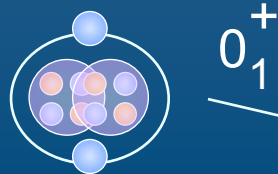
Cluster structures in neutron-rich Be

cluster res.
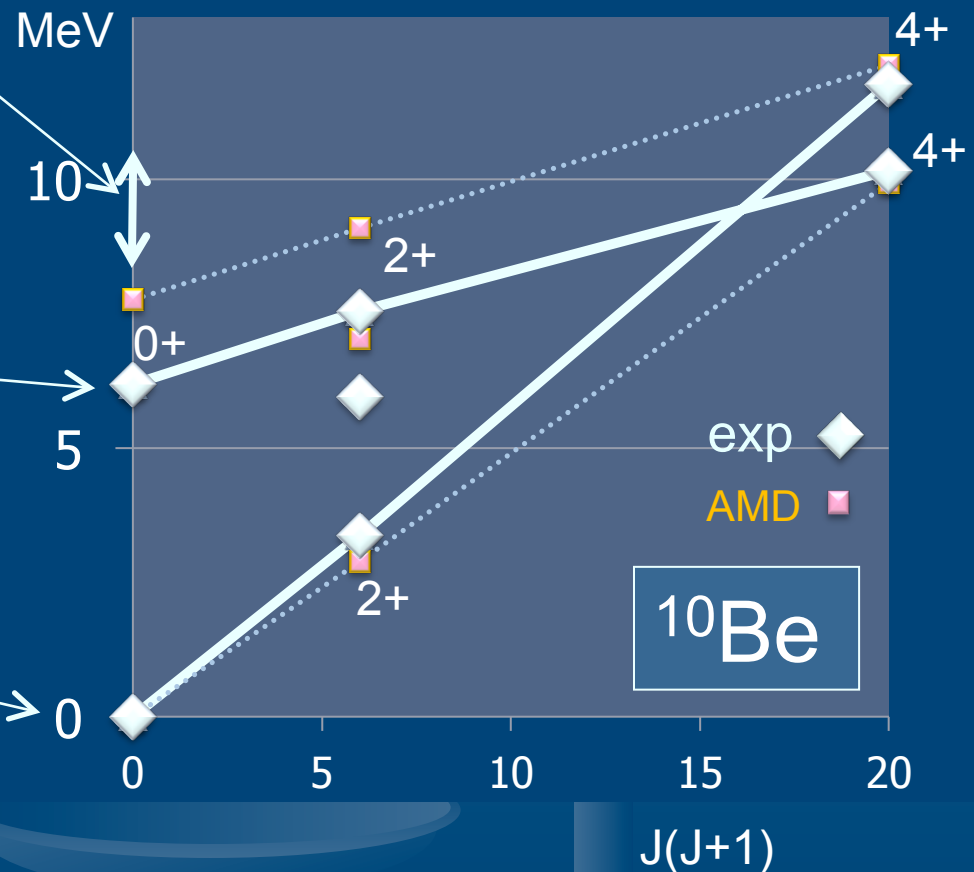
^{6}He+^{4}He

0^+_3

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

MO bond

0^+_2

Normal

0^+_1

^{10}Be: energy levels

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

MeV

10

5

0

4+

4+

2+

0+

2+

exp

AMD

^{10}Be

0   5   10   15   20

J(J+1)

Energy levels of ^{12}Be

VAP calculation with AMD method
positive parity states with
normal spins

^{12}Be

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

0_3^+ cluster resonances

0_2^+

strong coupling MO picture

0_1^+
intruder
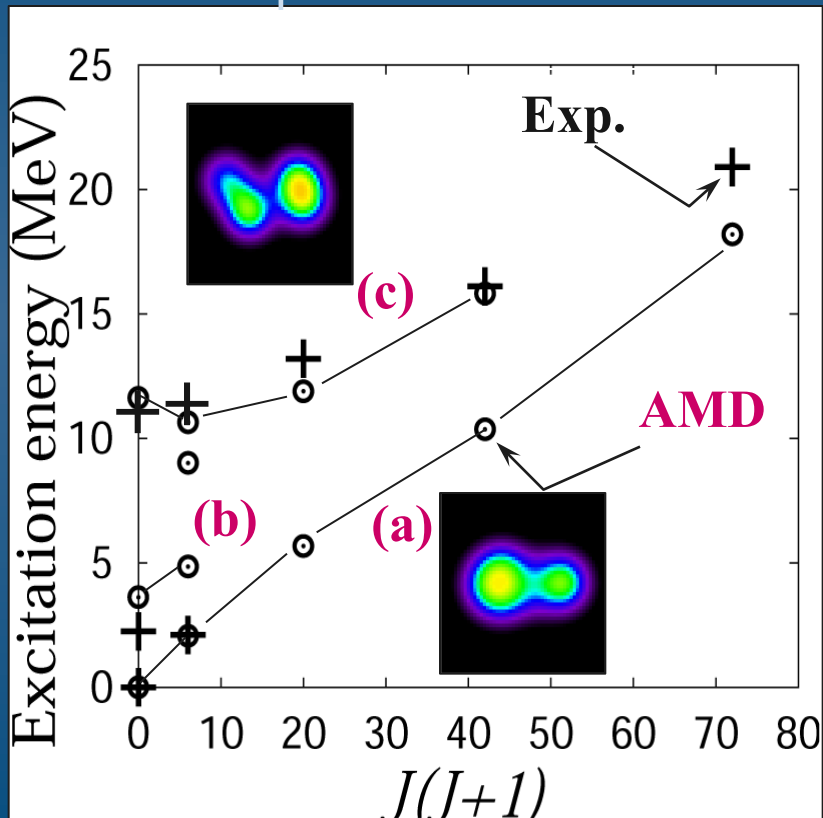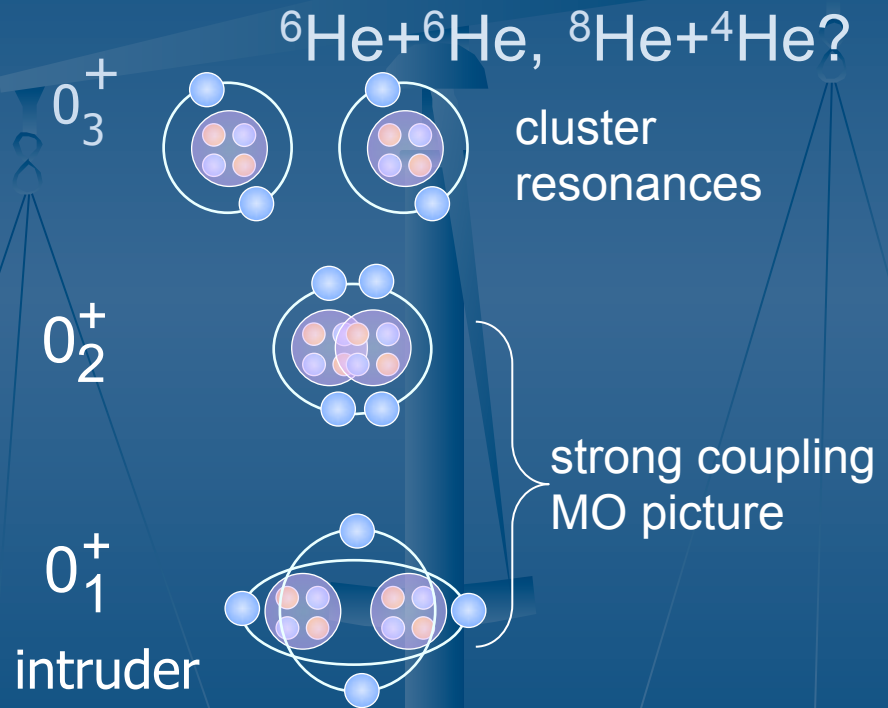
Breaking of N=8 magicity
Formation of 2a+molecular orbitals

Molecular orbital(MO) structure in Be

2α-core formation

MO formation

σ-orbital

MO formation

$\pm$

π-orbital
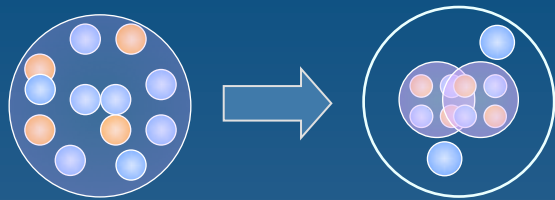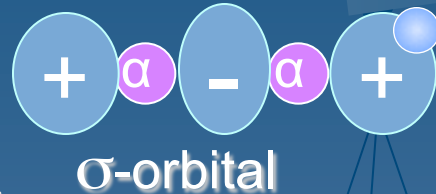
MO state
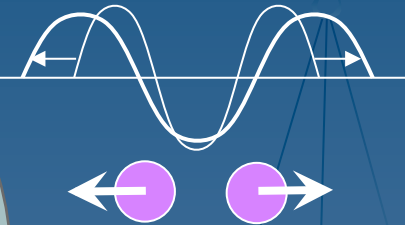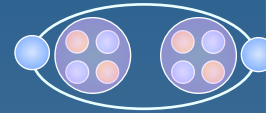
Normal state
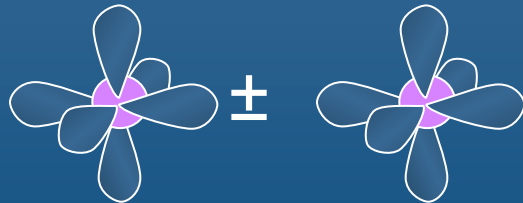
Gain kinetic energy
in developed 2α system
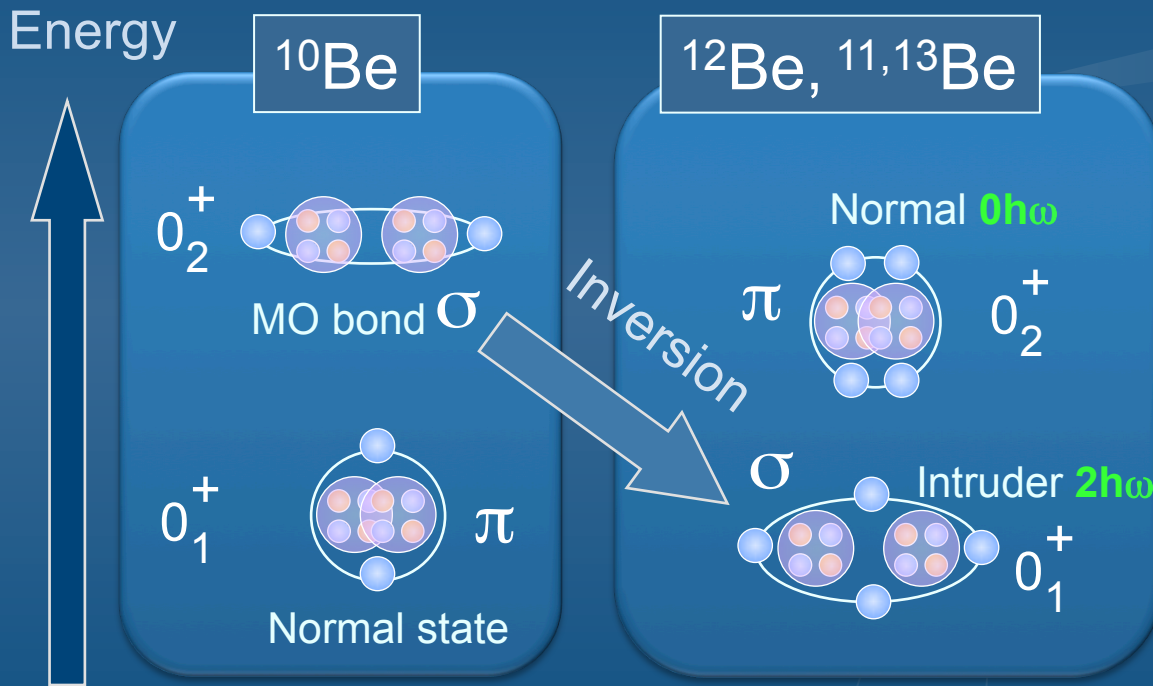
Level inversion
in ^{11,12,13}Be

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

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

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

Energy

^{10}Be

^{12}Be, ^{11,13}Be

0_2^+

MO bond σ

0_1^+ π

Normal state

Inversion

Normal $0\hbar\omega$

π 0_2^+

σ Intruder $2\hbar\omega$

0_1^+

n-rich

^{12}Be g.s. 0+ ^{13}Be g.s. 1/2-

➤ deformation in ^{12}Be(gs)

Inelastic scat. life time:
Iwasaki PLB481(00),
Imai PLB673(09)

➤ intruder config. in ^{12}Be(gs)
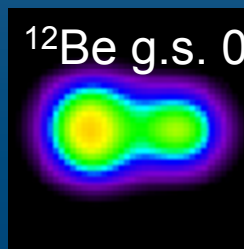
1n-knockout reac.:
Navin PRL85(00),
Pain PRL96(06)

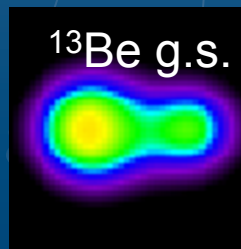➤ ^{12}Be(0_2^+) with p-shell config.

Shimoura PLB654 (07)

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

➤ abnormal parity of ^{13}Be(gs)

Kondo et al. PLB690 (10)

Cluster phenomena in n-rich Be

$^{10,11,12,..}Be$

strong coupling   weak coupling

Shell structure・MF   Cluster

Cluster core formation   developed cluster   Cluster resonances

Normal state   Molecular orbital (MO bond) $^{6,8}He+^{4,6}He$

$^{10}Be*:1^+$? $^{10}Be_{g.s}$ $^{10}Be*:0^+_2$ $^{10}Be*:0^+_3$

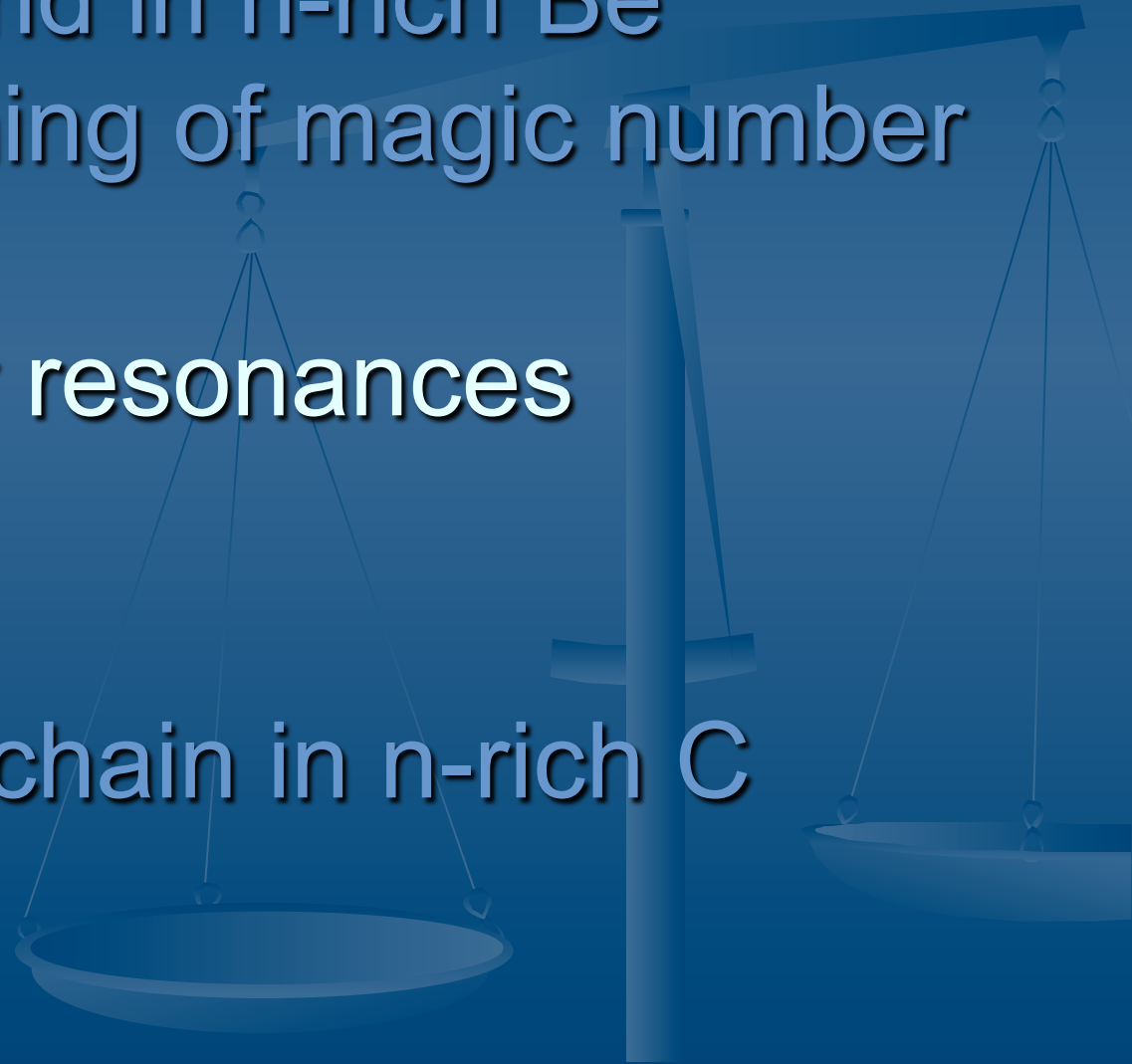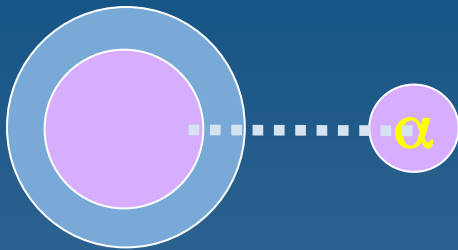$^{12}Be*:0^+_2$ $^{12}Be_{g.s}$ $^{12}Be*:0^+_3$

3-1. MO bond in n-rich Be
    & vanishing of magic number

3-2. Cluster resonances

3-3. Linear chain in n-rich C

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$+\alpha$ 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$+\alpha$ in ^{14}C*

Exp Soic 04, von Oertzen '04, Price 07, Haigh 08, Theor: Suhara '10

^{14}C$+\alpha$ in ^{18}O*

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

^{18}O$+\alpha$ in ^{22}Ne*

Exp Scholz '72, Rogachev '01, Goldberg '04, Ashwood '06, Yildiz et al., Theor: Descouvemont '88, Kimura '07

-> information of nucleus-nucleus potential and valence neutron effects there.

Cluster resonances
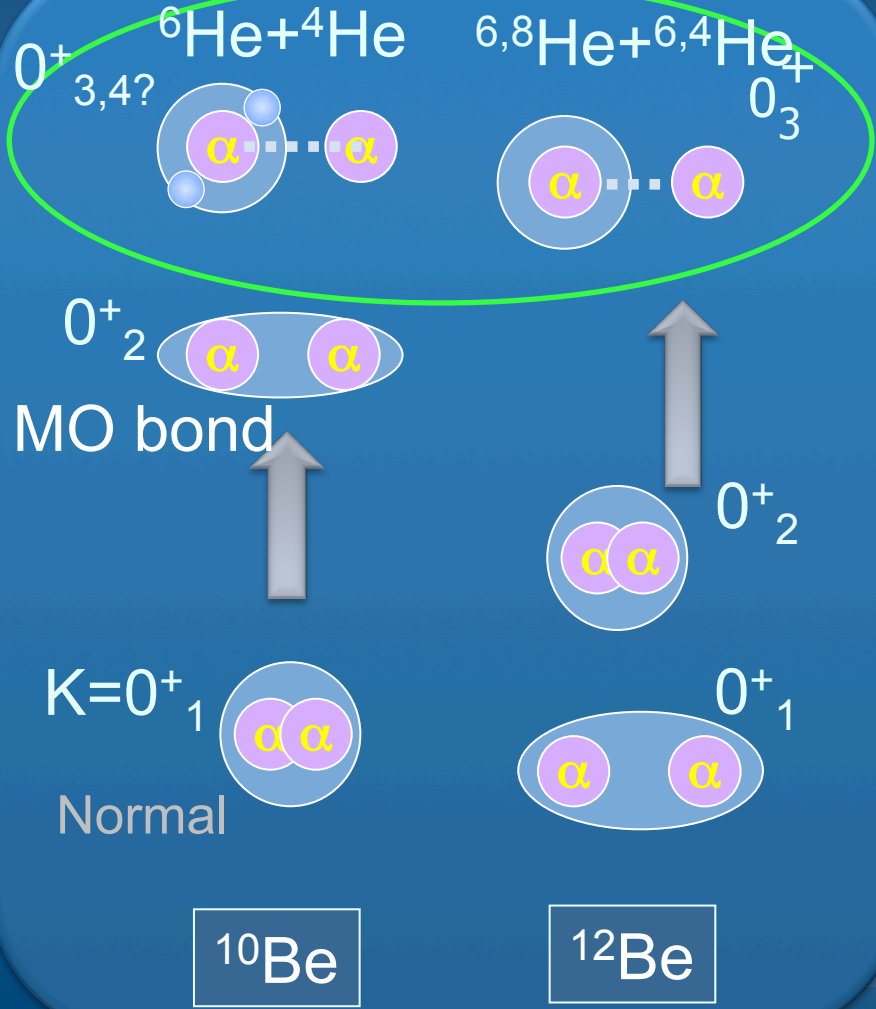
Question: Is triton cluster general?

^{7}Li α+t

^{9}Li* ^{6}He+t

^{11}B*   2α+t gas
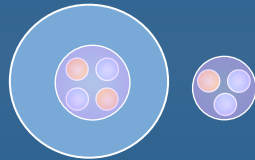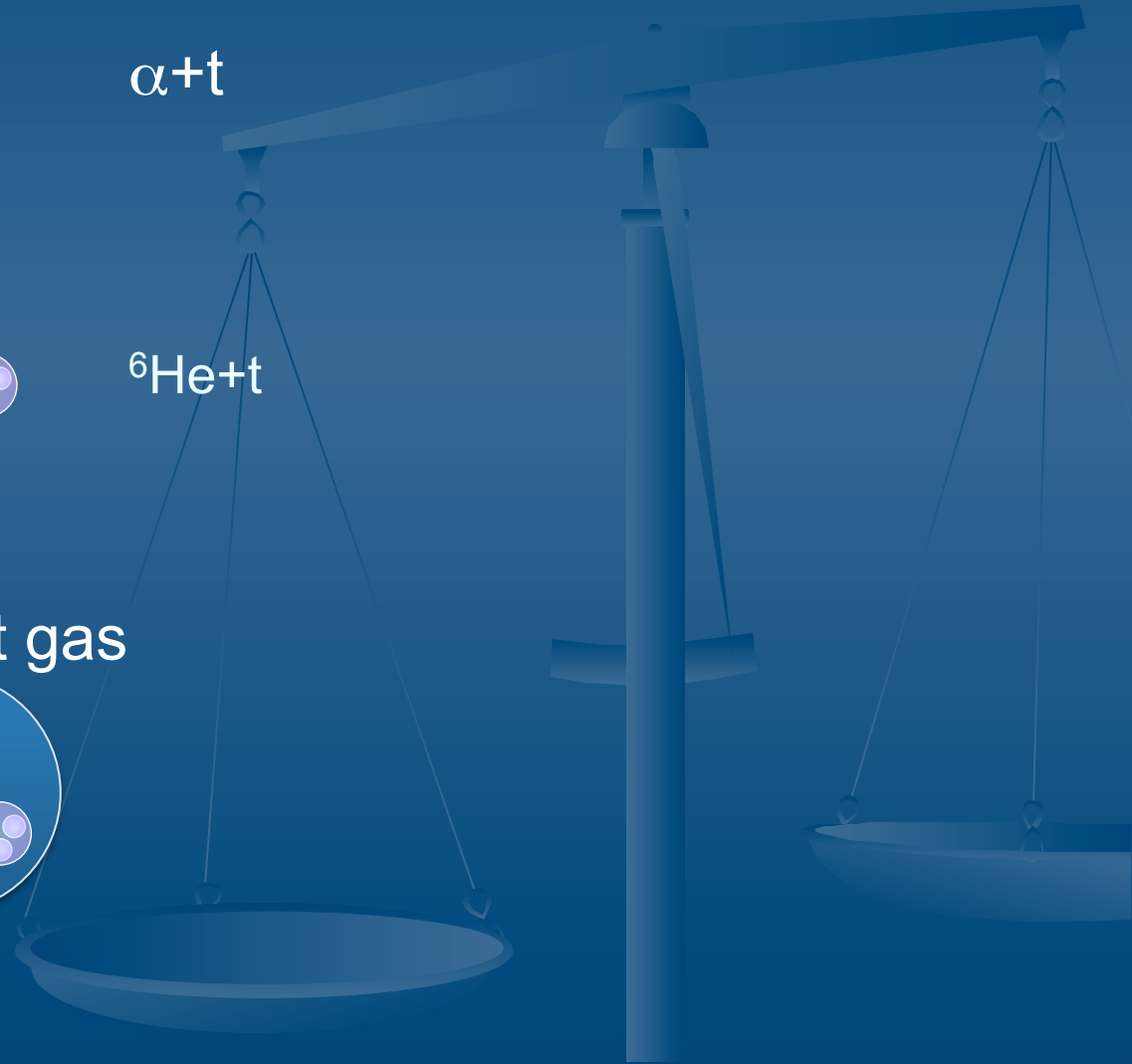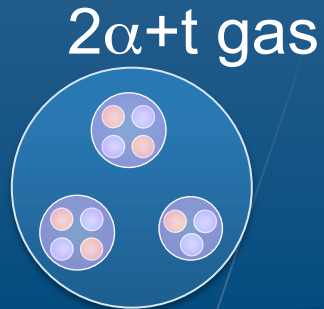
$^6\text{He}+^3\text{H}$ cluster resonances in ^9Li
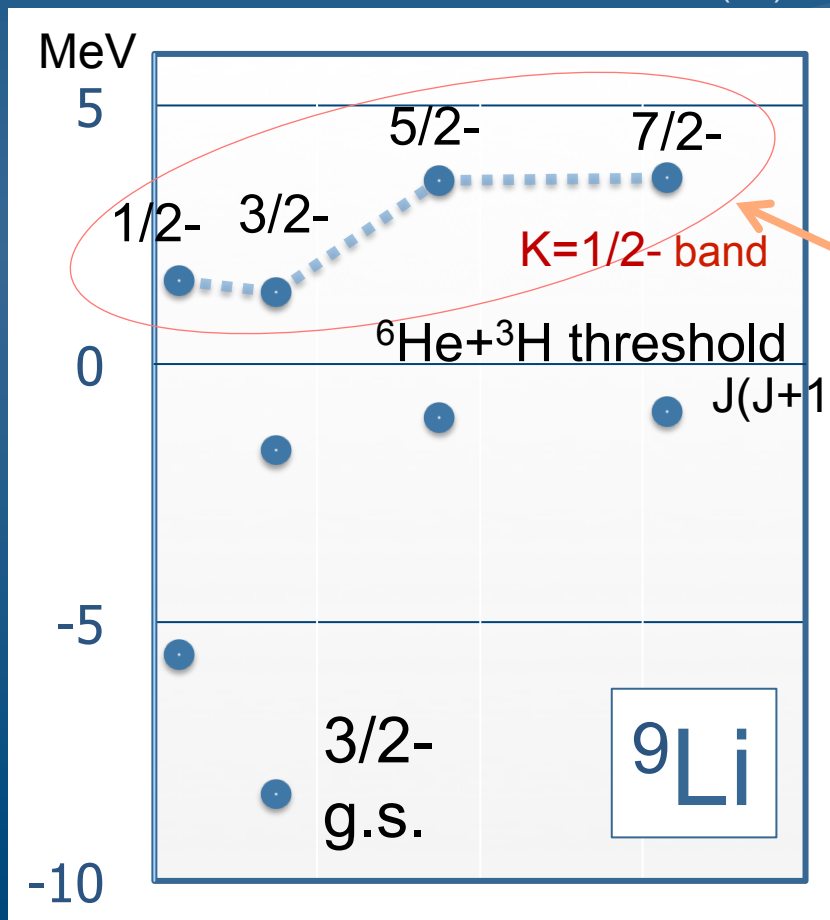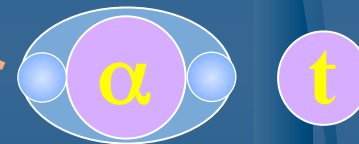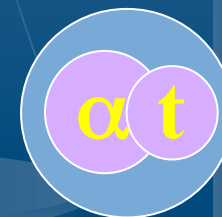
Summary

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

- ✓ Cluster formation/breaking in low-lying states

- ✓ Cluster excitation and resonances

- ✓ valence neutrons: MO Bond, new types of clusters

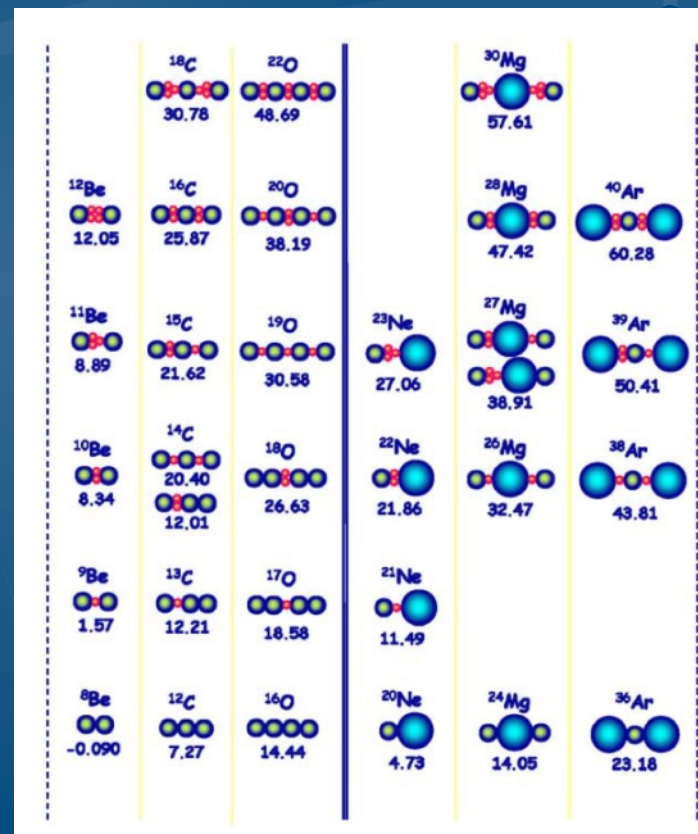- ✓ Many clusters : cluster gas, chain

strong coupling cluster   V.S. weak coupling cluster

Law of cluster states in n-rich nuclei: Extended Ikeda diagram?

Ikeda diagram
Ikeda et al.PTP464-S (1968)
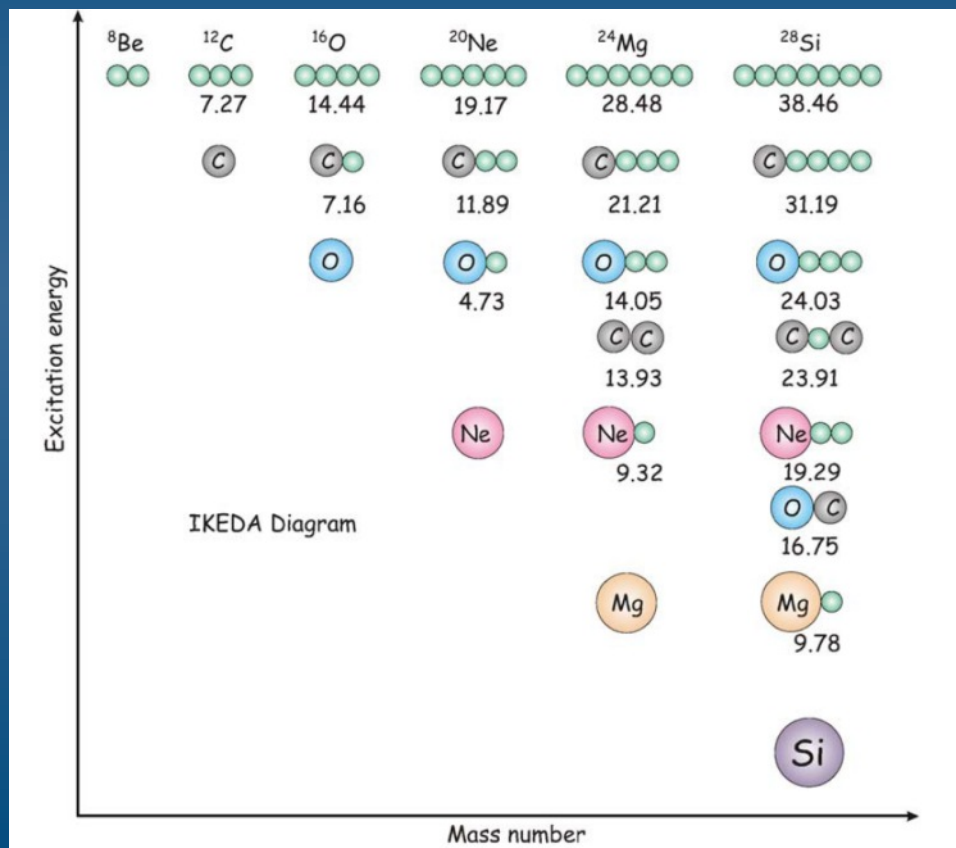
Extended Ikeda diagram
von Oertzen et al (2006)

Taken from Phys. Report 432 (2006)