Cluster phenomena in nuclear systems

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Lesson1: Introduction (overview)

Lesson2: what is correlation?

Lesson3: pn correlation

Lesson4: clustering in neutron-rich Be

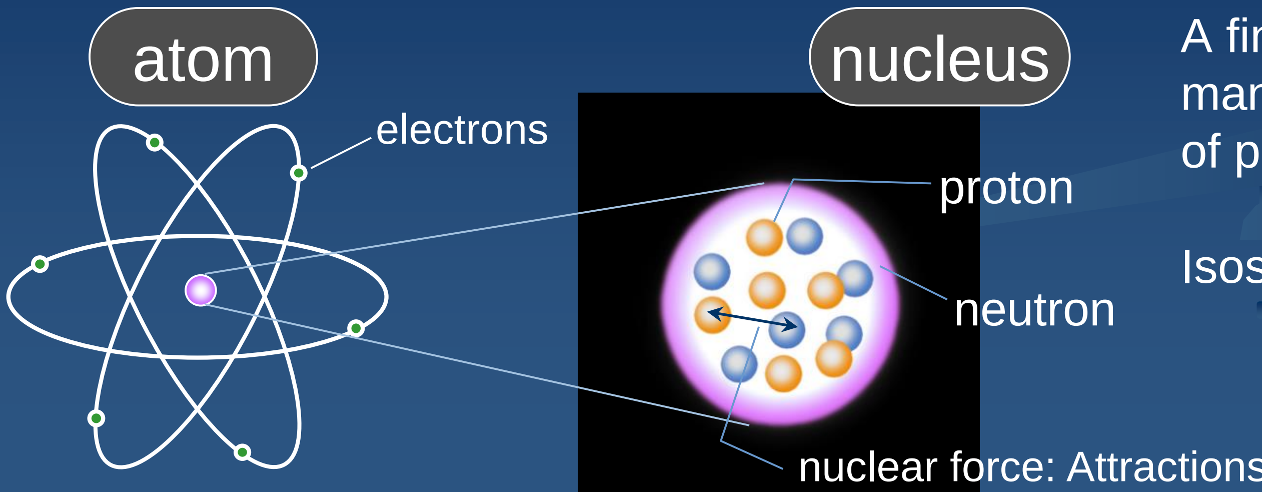
Lesson5: Monopole & Dipole excitations in light nuclei

Lesson6: Analogy to other systems

Lesson 1. Overview

cluster phenomena
in nuclear systems
(Personal opinion)

Nuclear system



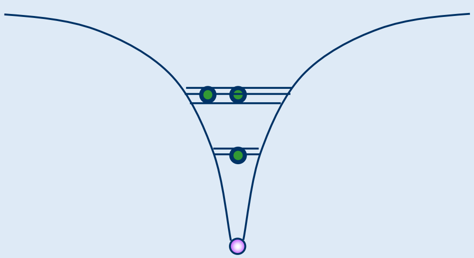
A finite quantum many-fermion system of protons and neutrons

Isospin x spin : SU(4)

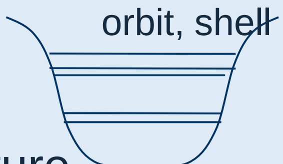
Analogy & Differences

Electron motion

Confined by the external field



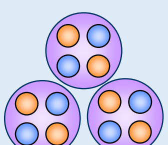
Nucleon motion



Self-bound

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

cluster

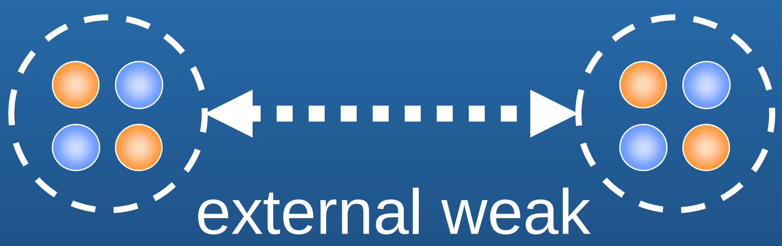


correlations

- general phenomena in interacting many-particle systems
- cluster=strongly correlated subsystems
- cluster limit: internal-strong & external-weak

by H. Tanaka, K. Ikeda

Internal strong



energy & length scale

E_x(Internal) >> E_r(inter-cluster)

$\xi \ll \rho$ -1/3

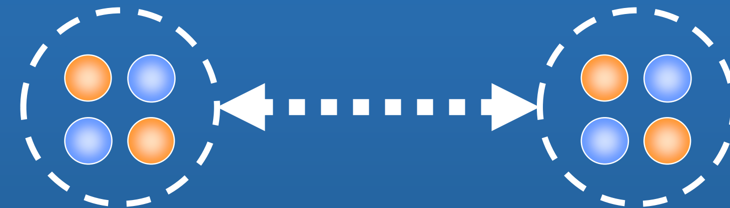
→decoupling of scale(DOF) → Hierarcy

- Dependences on density and energy

analogy to other systems

- [n↑n↓], [n↑n↓p↑p↓], [qqq], FF
  SU(2), SU(4), SU(3) <u>singlet</u> ⇒ screening
  robust cluster unit

"Internal strong & external weak"

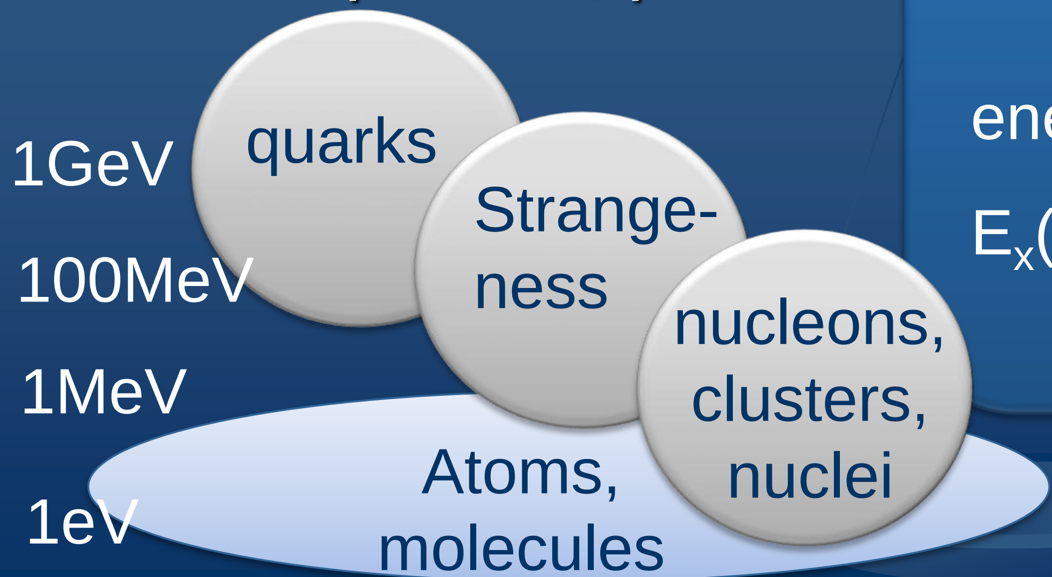


energy & length scale

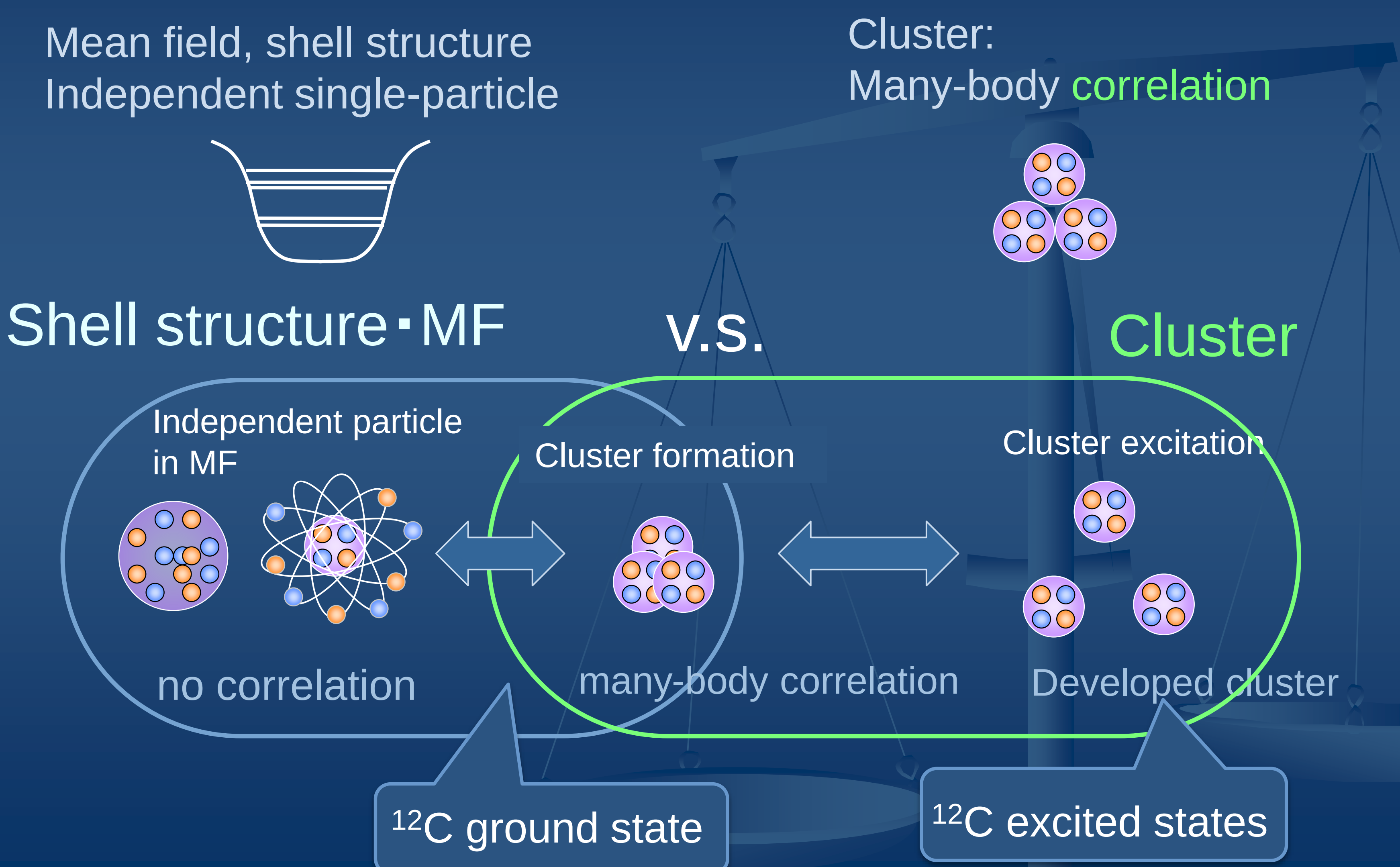
E_x(Internal) >> E_r(inter-cluster)

$\xi << \rho^{-1/3}$

- flavor: pn→ud, pnY→uds



Cluster & Mean field



Cluster structures

Nuclear structure

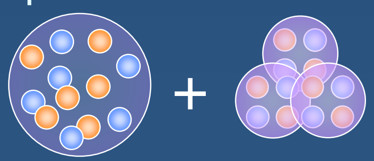
^{12}C

Z=N=6

Energy →

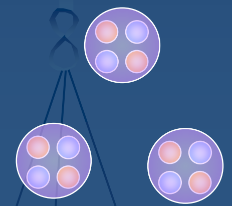
0 MeV

Shell & cluster corr.
p3/2-closed & 3α

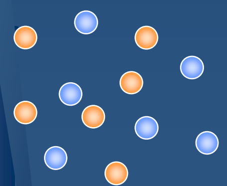


10 MeV

cluster excitation



100 MeV



Nucleon liquid
Fermi gas, BCS

Cluster gas, crystal

Nucleon gas

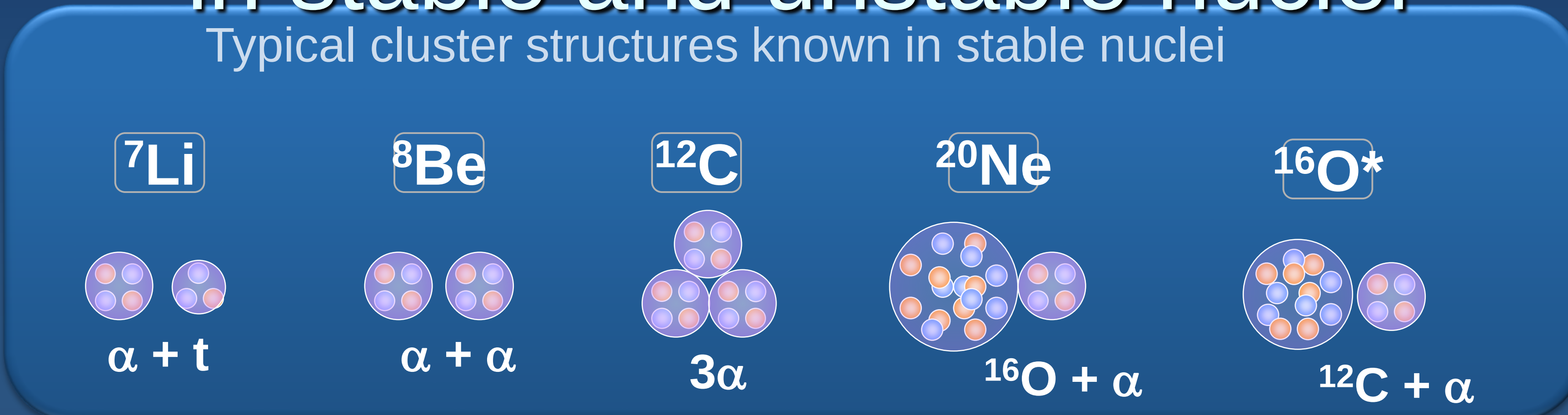
high density ⟷ low density

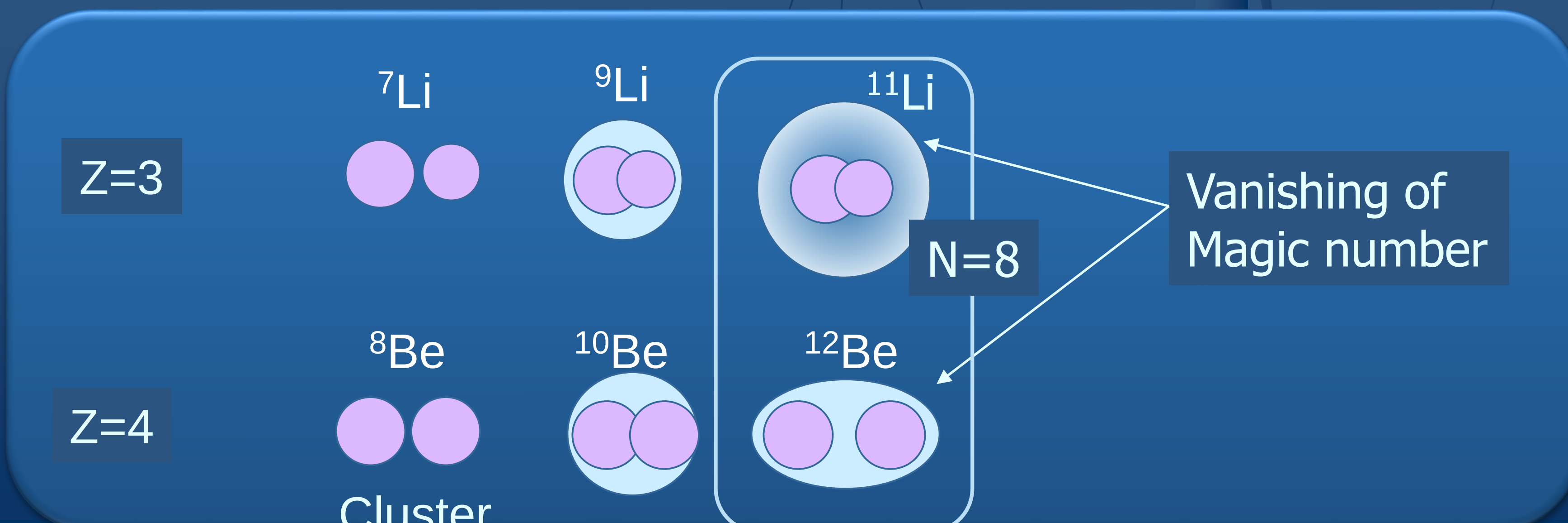
ρ_0 $\rho_0/3 \sim \rho_0/5$

Cluster enhancement at low density

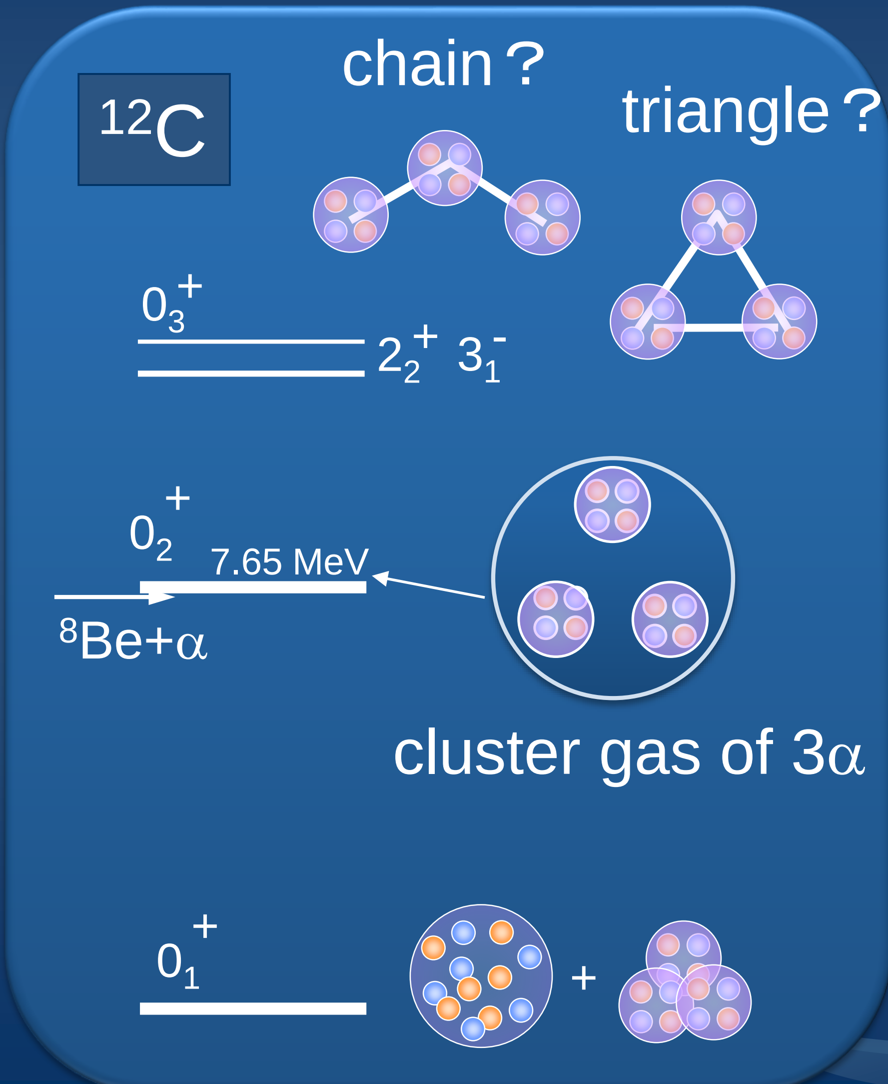
Nuclear surface
Light-mass nuclei
Excited states
Heavy ion collision

Typical examples of cluster structures in stable and unstable nuclei



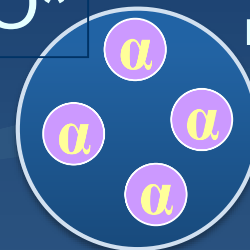


multi-cluster: gas, triangle, linear chain



^{16}O*

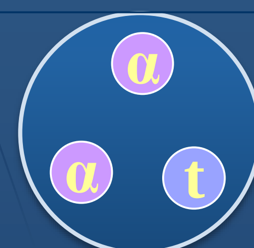
Tohsaki et al., Yamada et al., Funaki et al. Wakasa et al.,



4α gas

^{11}C*, ^{11}B*

K-E. , Kawabata et



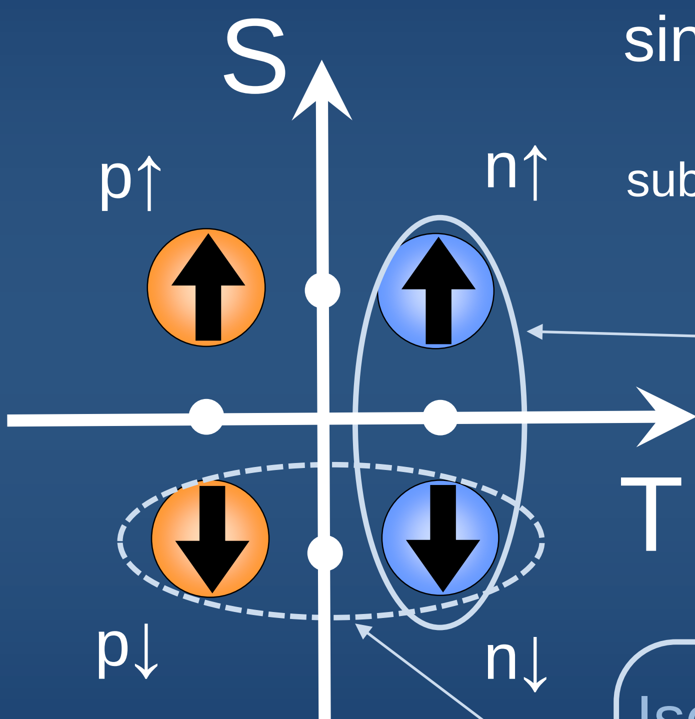
2α+t gas

^{14}C*

Itagaki, Suhara

Triangle, linear α-hain

α cluster: 4 species of fermions



SU(4): SU(2)xSU(2) 4 species of fermions

singlet: T=0,S=0 ^{4}He, α clusters ffff=b

subspace SU(2) NN Pairs: ff=b

Iso-vector (“”), spin-scalar (S=0)

Isospin active → unstable nuclei

weak(β) -decay

Iso-scalar (T=0), spin-vector (“S=1”)

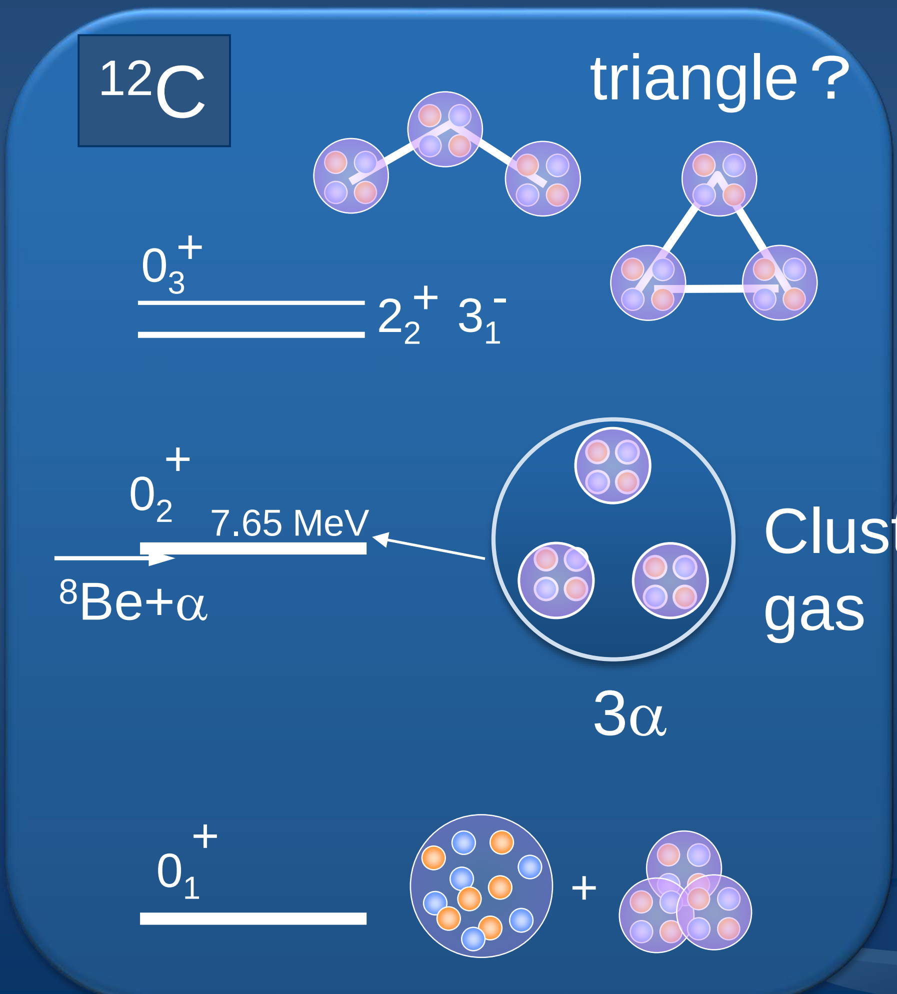
spin active → nuclear spintoronics

non-central (ls, tensor), EM (M1), β(GT)

1. S=0,T=0 world Z=N=even nuclei

Excitations in Coordinates(r,L) space

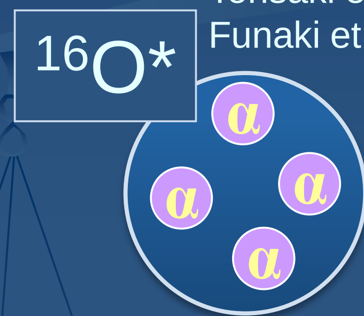
multi-cluster: gas, triangle, linear chain



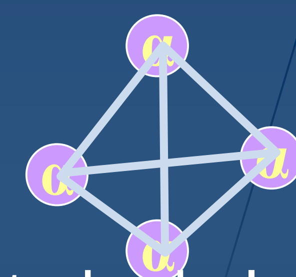
Cluster (boson) gas

Tohsaki et al., Funaki et al

Yamada et al.,

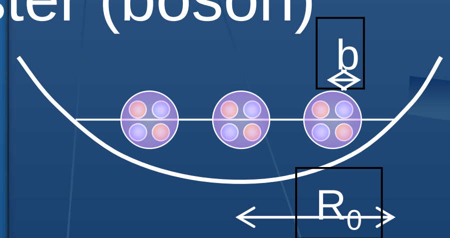


4α gas



tetrahedral

Y. K-E PRC96 (2017) 034306
Y. K-E. PRC89 (2014)

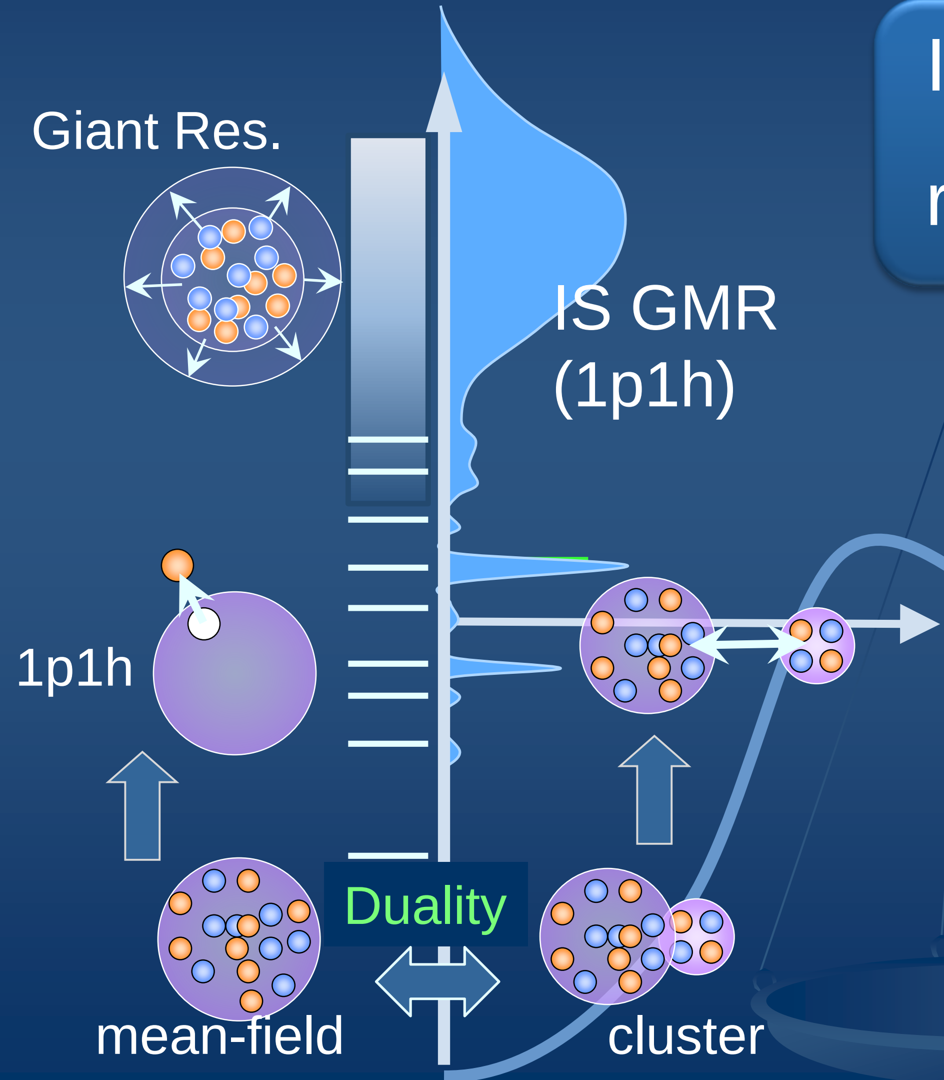


Analogy to

BEC in nuclear matter

1. S=0,T=0 world Z=N=even nuclei

Excitations in Coordinates(r,L) space



Isoscalar Monopole (ISM)

r^2-excitation (L=0)

single-particle vs cluster

Low-energy ISM for cluster states

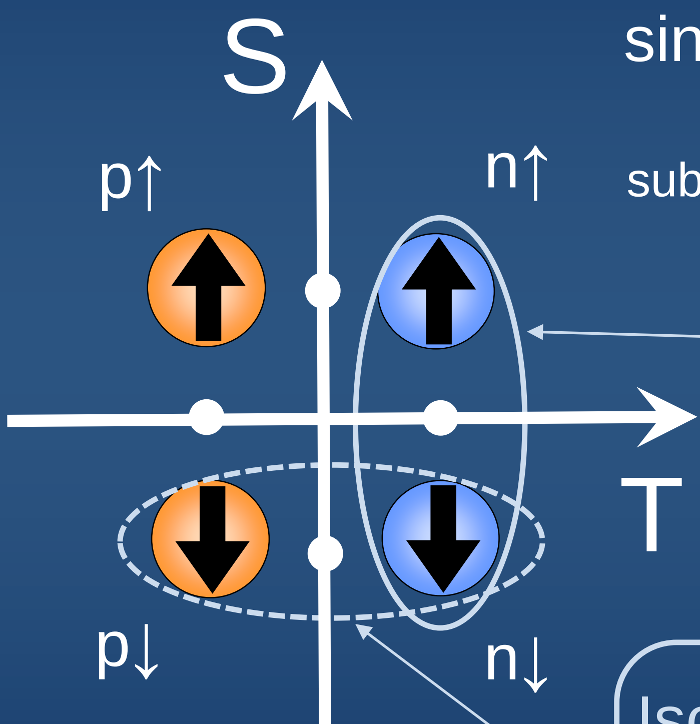
Kawabata et al.
Yamada et al.

Y. K-E. PRC89 (2014)
Y. K-E. PRC94 (2016)
Y. Yoshida and Y. K-E. PTEP2016 (2016)
Y. K-E. PRC93 (2016)
H. Matsuno,.. Y. K-E. et al. PTEP2014 (2014)

Species of particles

SU(4): SU(2)xSU(2) 4 species of fermions

singlet: T=0,S=0 ^{4}He, α clusters ffff=b



subspace SU(2) NN Pairs: ff=b

Iso-vector ("T=1"), spin-scalar (S=0)

Isospin active → unstable nuclei

weak(β) -decay

Iso-scalar (T=0), spin-vector ("S=1")

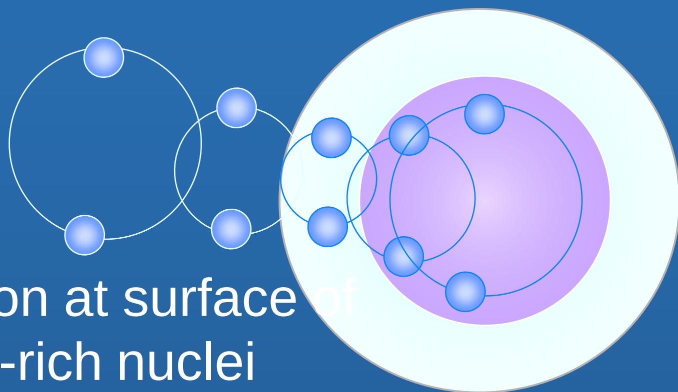
spin active → nuclear spintoronics

non-central (ls, tensor), EM (M1), β(GT)

Isospin T≠0 world

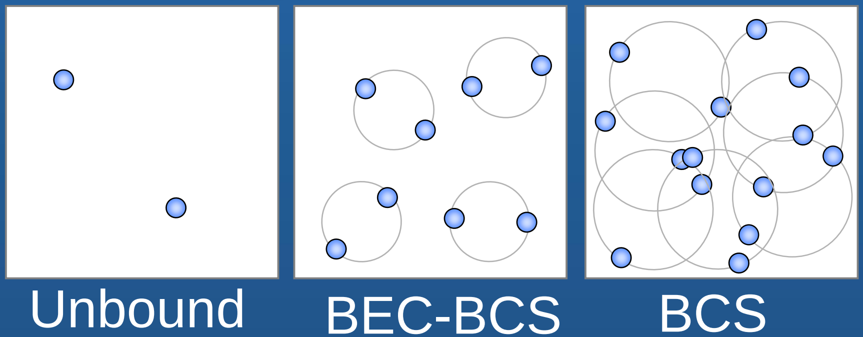
$core_{T=0}$+nn.. dynamics

Neutron skin,halo,matter



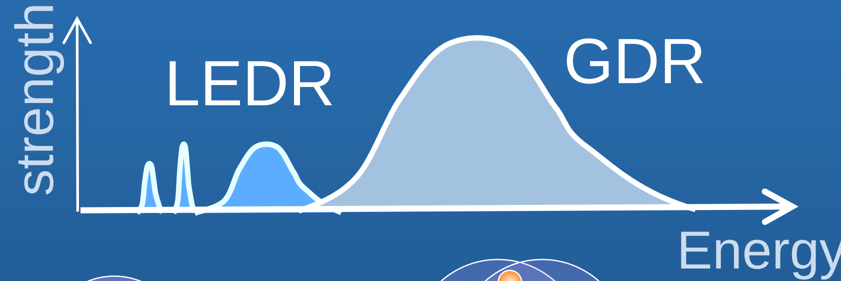
Dineutron at surface of neutron-rich nuclei

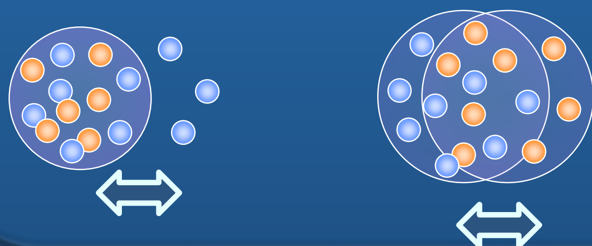
Neutron matter Matsuo et al. PRC73 044309 (‘06)



Different from alpha matter !

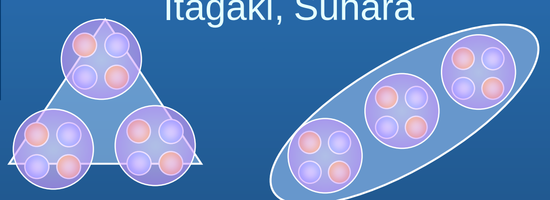
Isovector(E1) excitations





$^{14}C^*$

Itagaki, Suhara



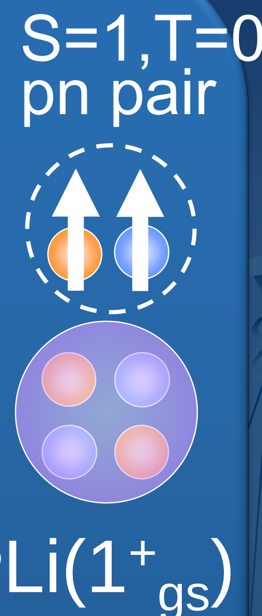
Triangle, linear α-hain

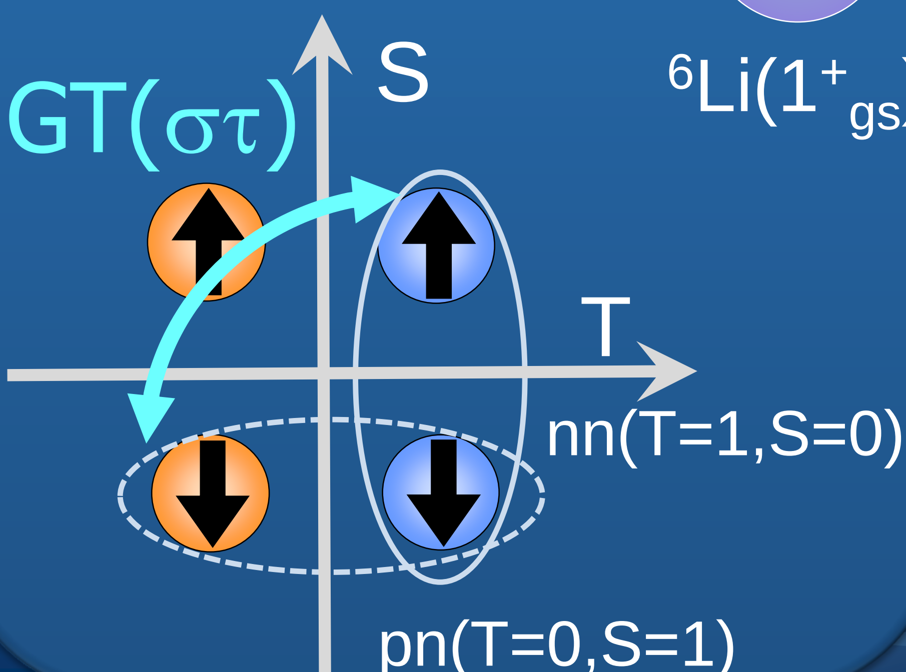
Spin S≠0 world pn pair in Z=N=odd nuclei

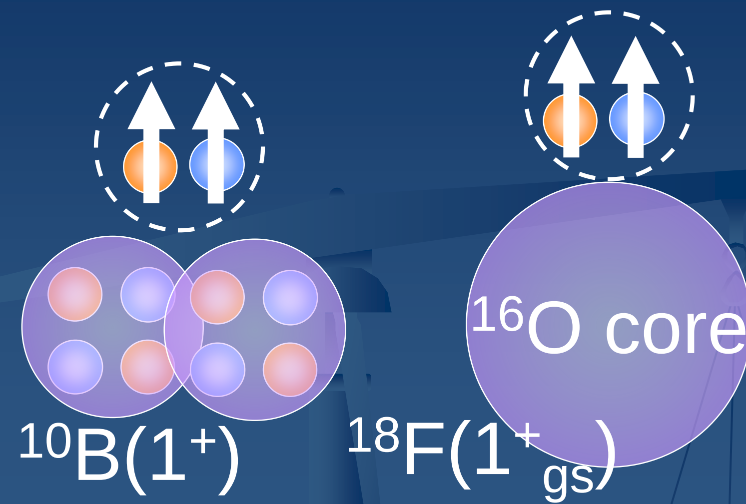
nn→pn GT(στ)

Gamov-Teller transition
Rotation in SU(2)xSU(2) space
Strong GT in SU(4) symmetry

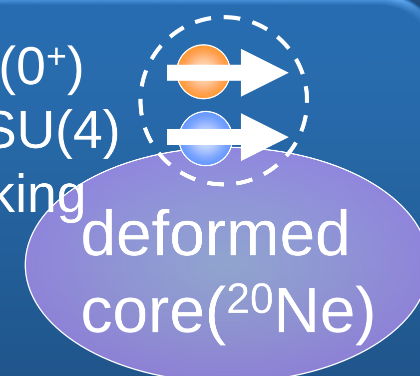
Super-allowed GT by SU(4) symmetry







^{22}Na(1^{+})← ^{22}Ne(0^{+})
GT splitting by SU(4)
Symmetry breaking in spin space
(defo. ls force)



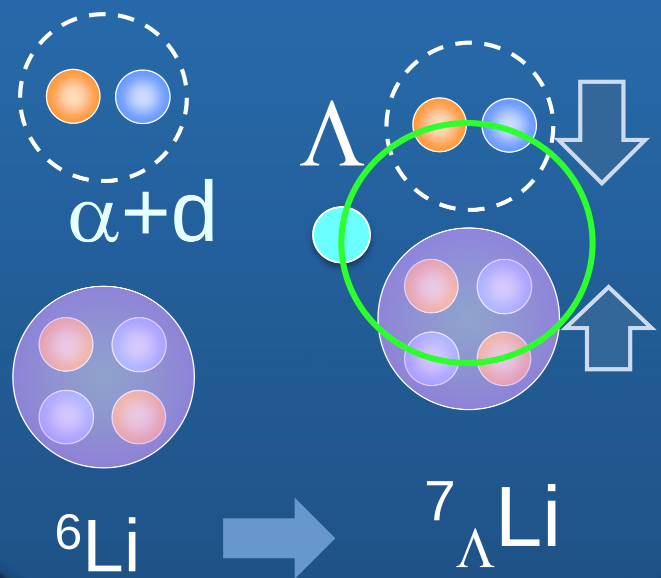
Isospin-Strangeness world SU(6)

- Λ T=0, Σ T=1

spin-independent Λ-N
Dynamical effect in r-space

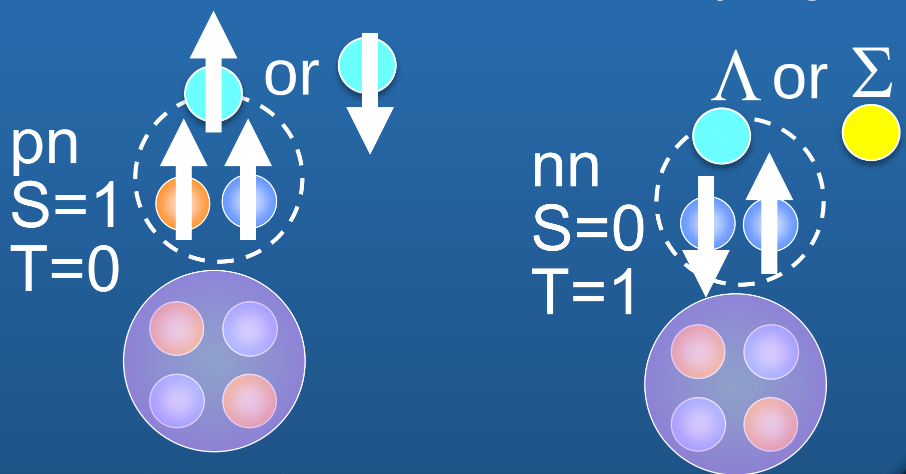
spin- and isospin-dependence: Λ-N
spin S≠0 nuclei & isospin T≠0 nuclei

Glue-like role $^{7}_{\Lambda}$Li, $^{13}_{\Lambda}$C
Motoba et al., Hiyama et al., Tanida et al.



$_{\Lambda}{}^{7}$Li(3/2^{+},1/2^{+})

Λ–Σ coupling



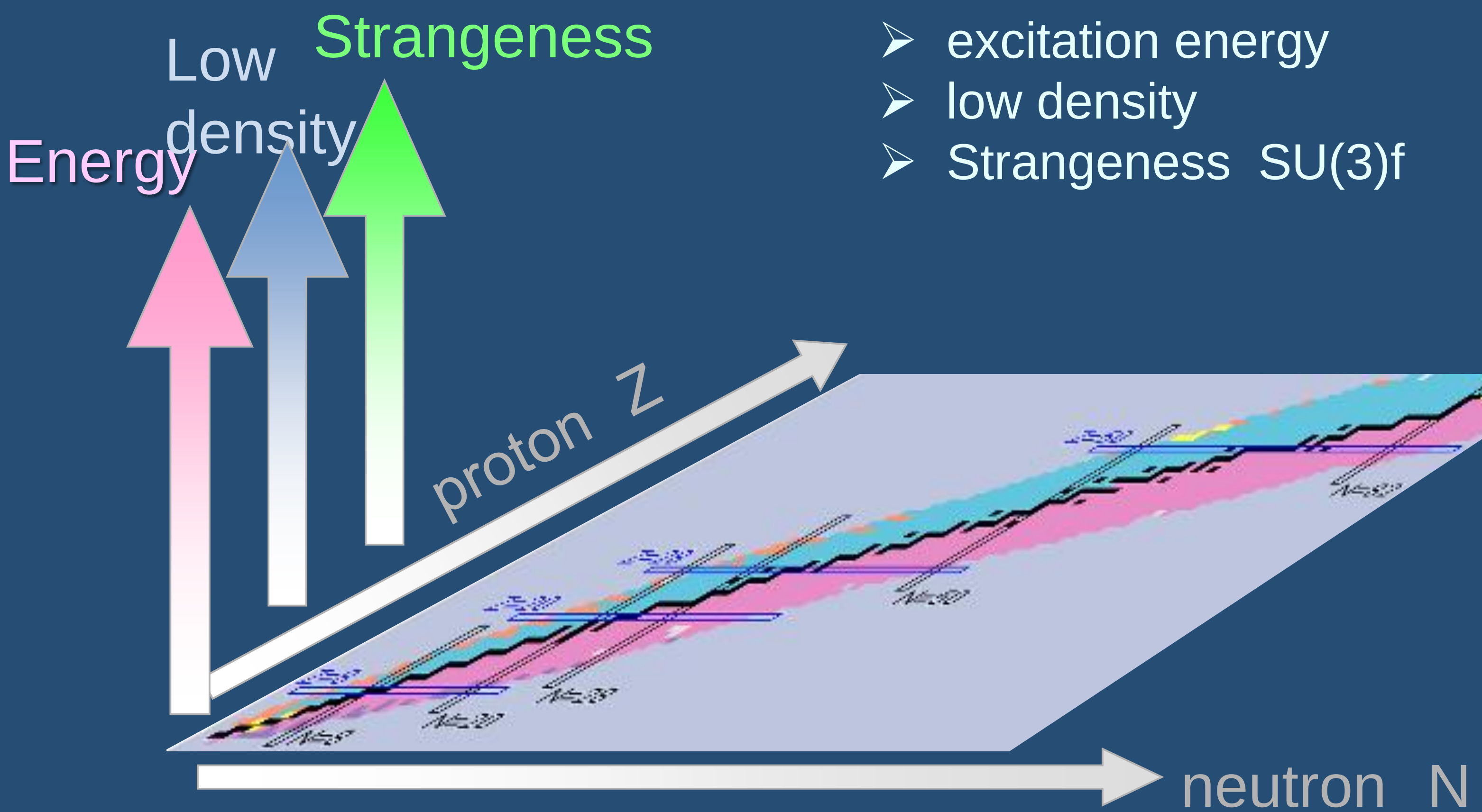
^{6}Li, ^{10}B, ^{18}F(1+)

^{6}He, ^{6}Li

Y. K-E. PRC97 (2018)
Y. K-E. PRC97 (2018)
Y. K-E. M. Isaka, T. Motoba, arXiv:1803.04089

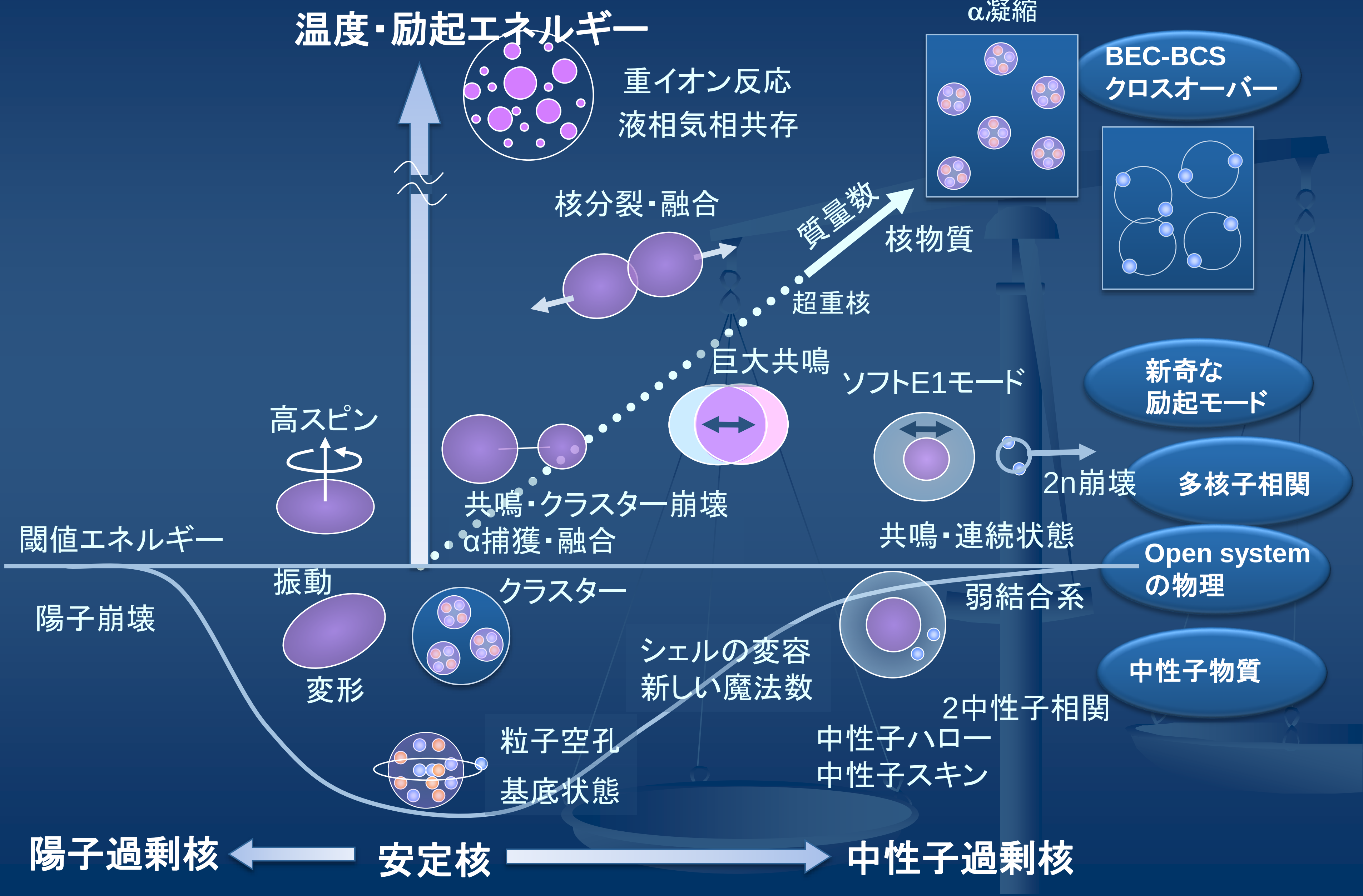
Active flavor(isospin) world

- New Facilities



- isospin asymmetry
- mass number
- excitation energy
- low density
- Strangeness SU(3)f

核子多体系の多様な現象



近年の進展、課題と展望

新奇な現象発見 従来の常識・模型の破綻 → **新たな理論的枠組みの発展**
基礎（核力）から構築する理論

予言 ←

→ **新しい物理の発展**

（近年の大発見の例）

- ★魔法数の消滅
- ★異常に大きな半径（中性子ハロー・スキン）
- ★核融合・分裂
- ★奇妙な励起モード（変形、E1励起、GT）
- ★対相関・クラスター
- ★^{12}C励起状態の謎

第一原理計算の発展
大規模シェル模型計算
テンソル力、3体力

少数系計算
弱結合系・連続状態

反応理論の進展

平均場理論(DFT)の発展
二核子(対)相関

クラスター現象記述の発展
アルファ凝縮

原子核の統一的理解
新魔法数、新モード、多体相関

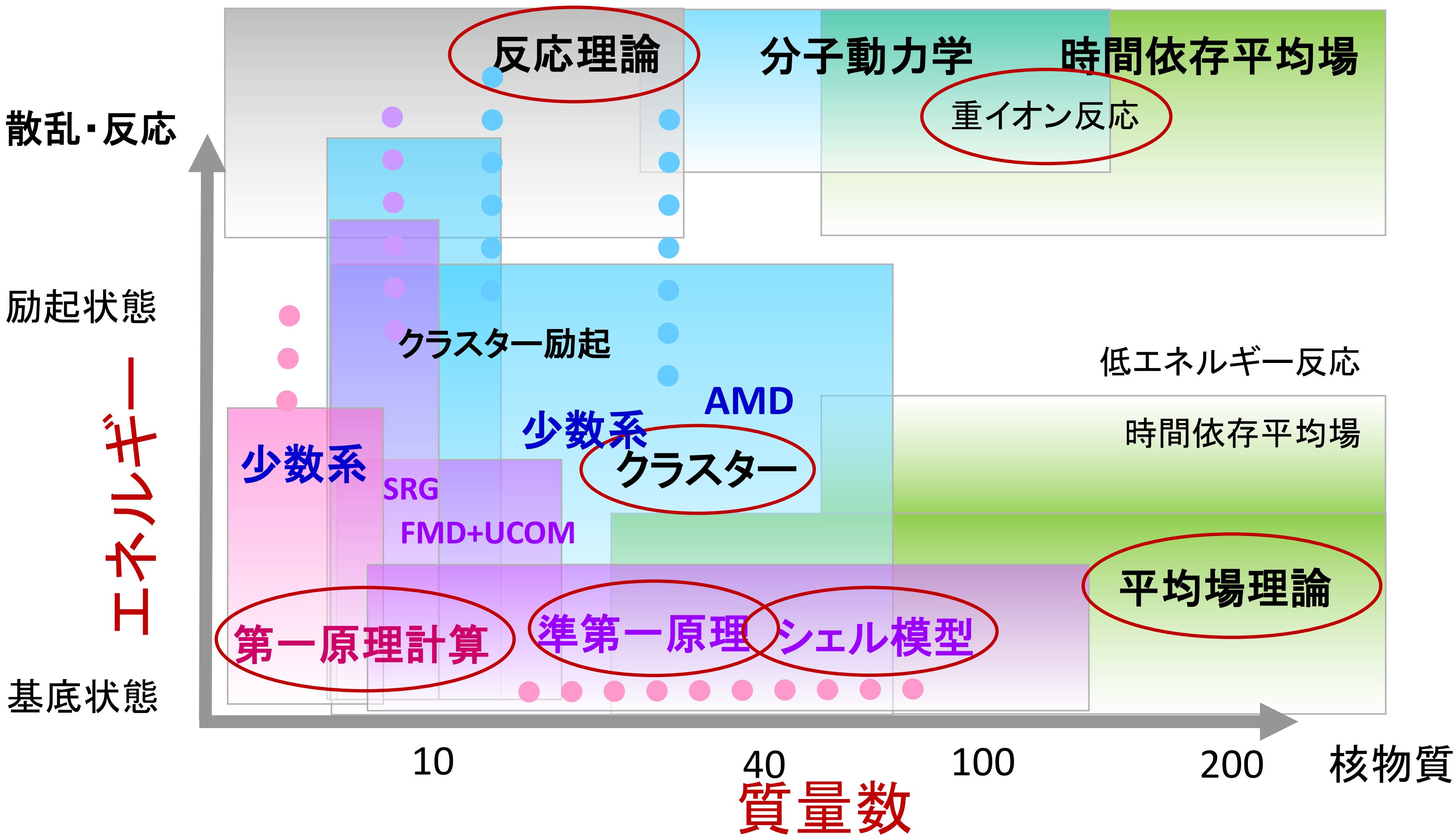
核物質の状態方程式
対称エネルギー,圧縮率

元素合成・中性子星の性質などの解明
→ 天体核物理への貢献

多体系の新しい存在様式
量子多体系の新現象、普遍性、新理論
→ 物性物理との関連

系統的研究：広範な質量数領域、エネルギー領域をカバー
予言力：核力に基づく理論（テンソル、3体力）

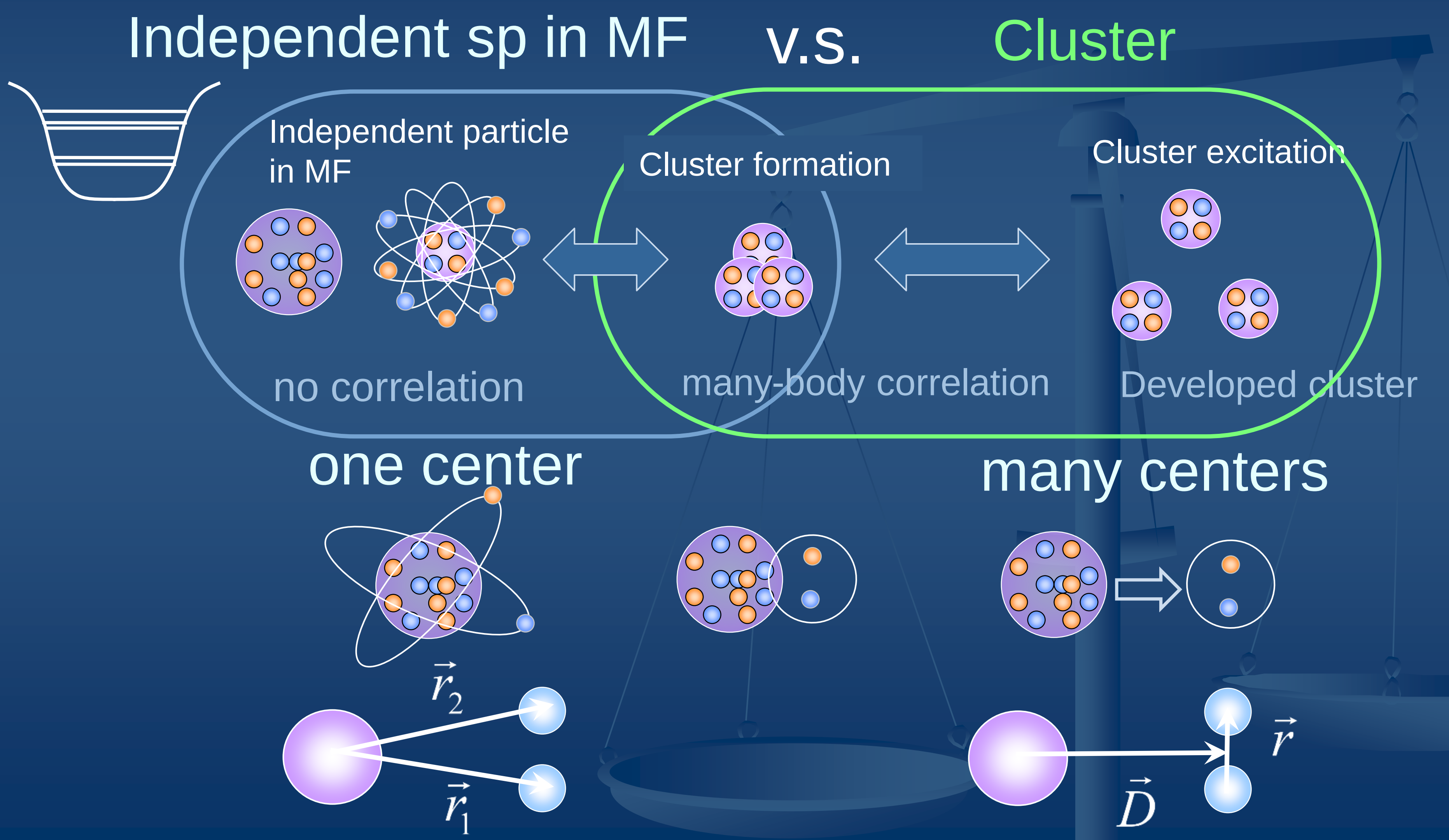
広範な領域をカバーした系統的研究、核力に基づく予言力のある研究



Lesson 2.
What is cluster?
(case of spatial correlations)

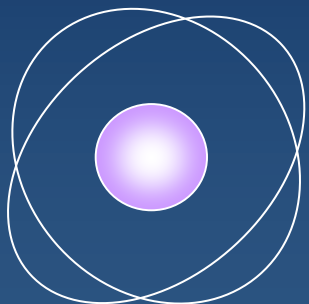
theoretical description

Cluster formation & development
one center & many centers

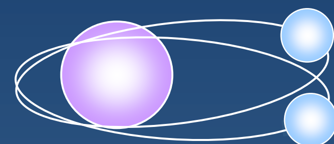


How to measure correlations?

座標

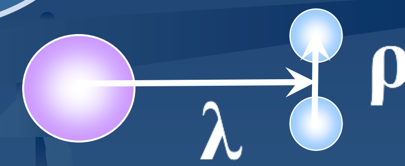


cluster size
≈system size

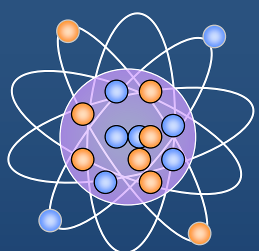


cluster size
>system size

duality

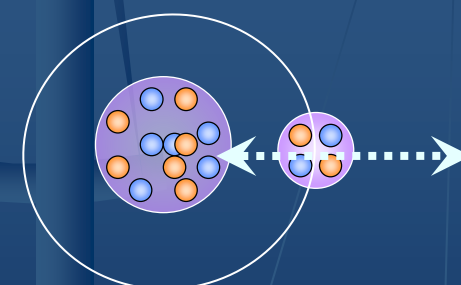


cluster size
>>system size



核子”非”局在

核子局在
クラスター局在

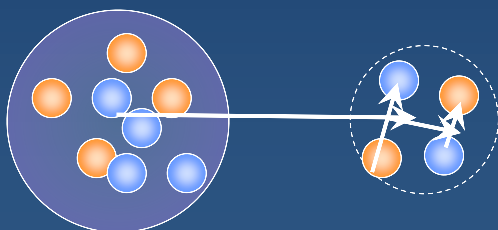


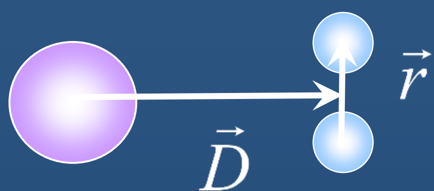
核子局在
クラスター”非”局在

1体密度(演算子)では区別できない→2体以上の相関

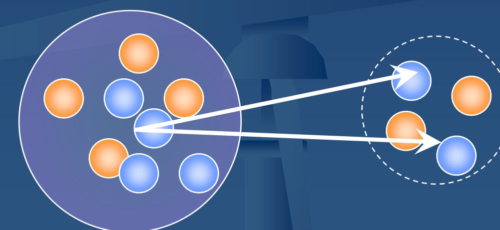
Cluster: strongly correlated state

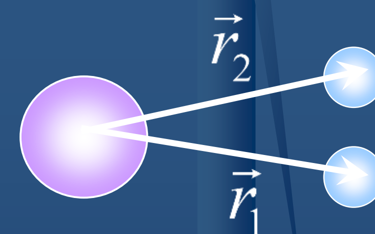
Strongly correlated state





Basis expansion from a center





$$\Delta r \Delta p \geq \hbar$$

$$l \approx D \times \frac{\Delta p}{\hbar} \geq \frac{D}{\Delta r}$$

Large D
Small Δr

⇒ Large l

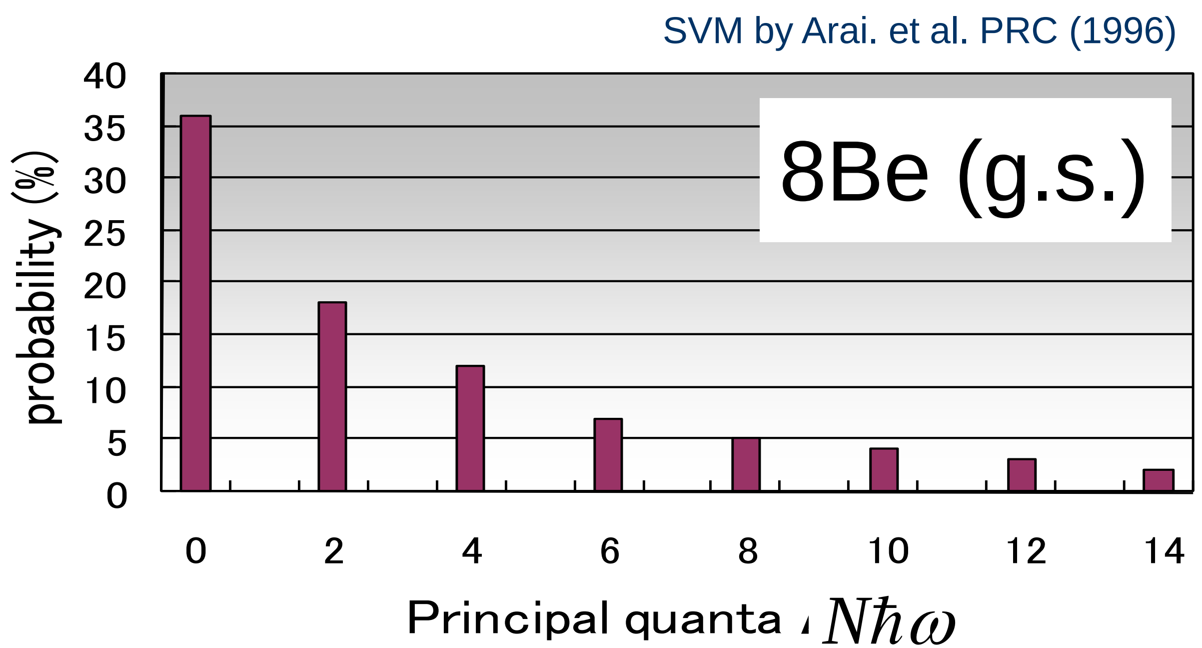
Mixing of high angler momentum components

$$l_1 \otimes l_2$$

8Be (g.s.)

Developed 2α

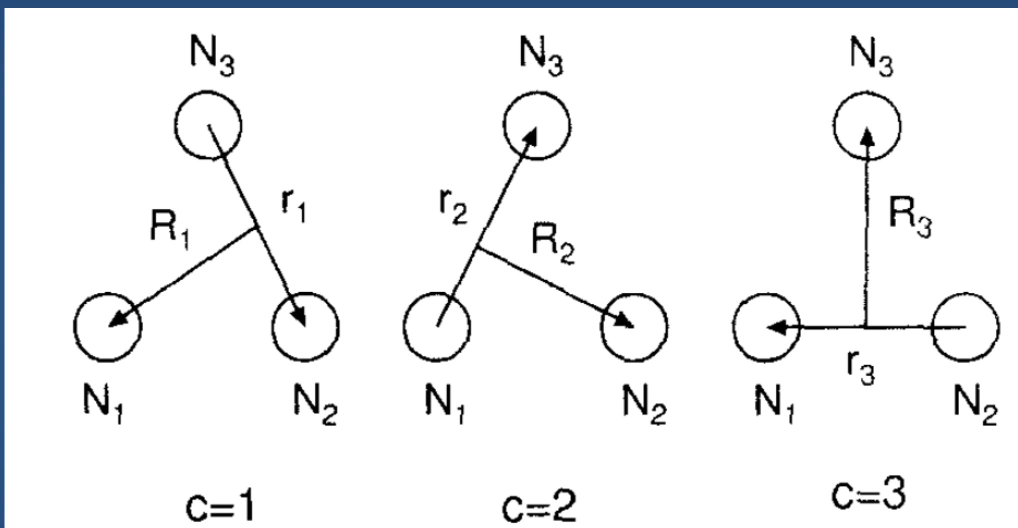
Strong spatial correlation involves higher-shell components.

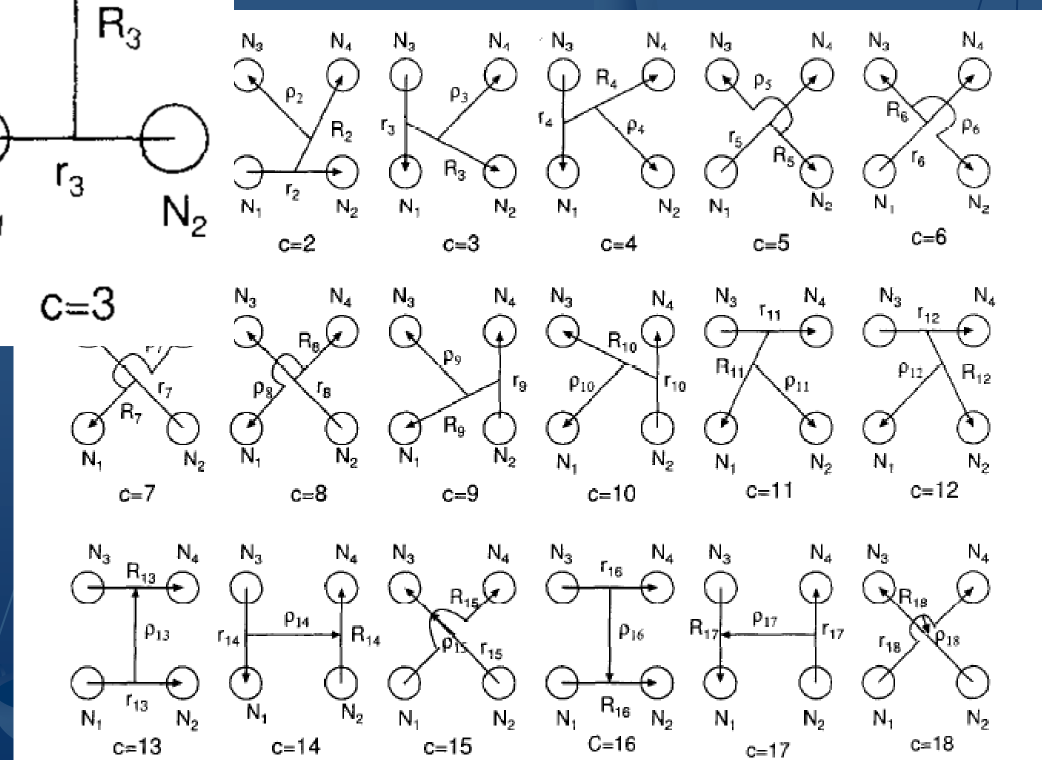


Developed cluster states are usually beyond mean-field

Jacobi coordinates

Hiyama, Kamimura
PPNP, 2003

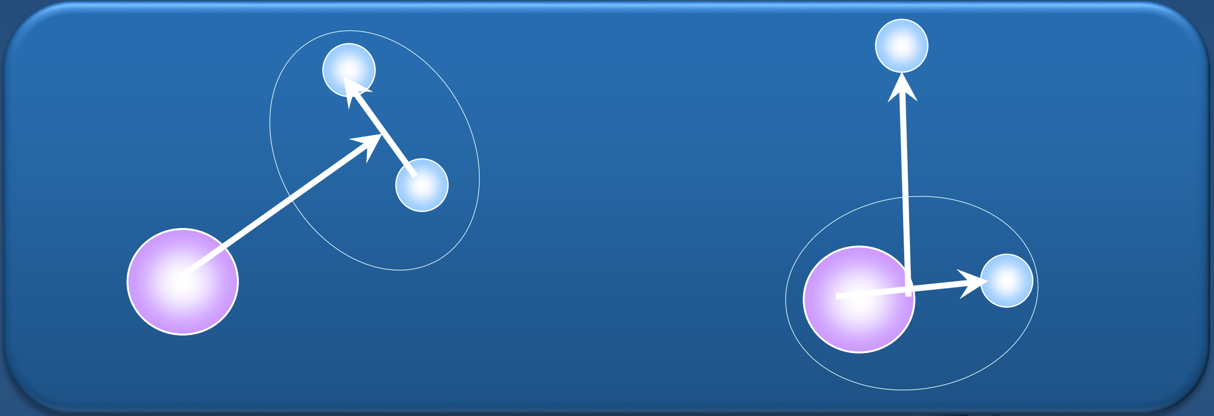




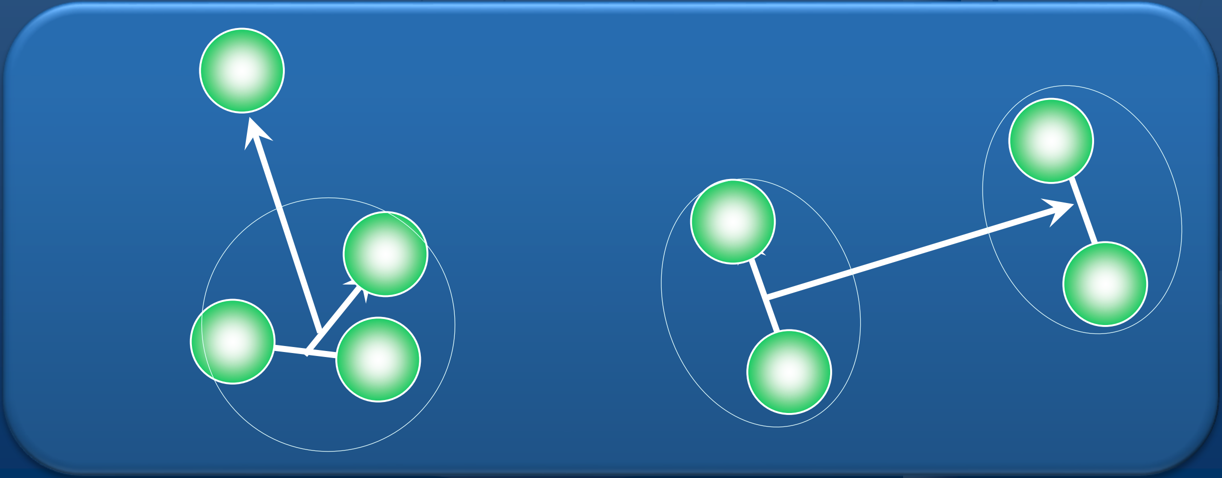
Jacobi coordinates
~coupling and decoupling of scale(DOF)

散乱問題なら当たり前

3-body



4-body



A model: AMD

Antisymmetrized molecular dynamics

AMD wave fn.

Similar to FMD wave fn.

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

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

$$\varphi_{\rm i} = \phi_{\mathbf{Z}_{\rm i}}\chi_{\rm i} \begin{cases} \phi_{\mathbf{Z}_{\rm i}}(\mathbf{r}_{\rm j}) \propto \exp\left[-\nu\left(\mathbf{r} - \dfrac{\mathbf{Z}_{\rm i}}{\sqrt{\nu}}\right)^2\right] \\ \chi_{\rm i} = \begin{pmatrix} \frac{1}{2} + \xi_{\rm i} \\ \frac{1}{2} - \xi_{\rm i} \end{pmatrix} \times \quad p \text{ or } n \end{cases}$$

Intrinsic spins

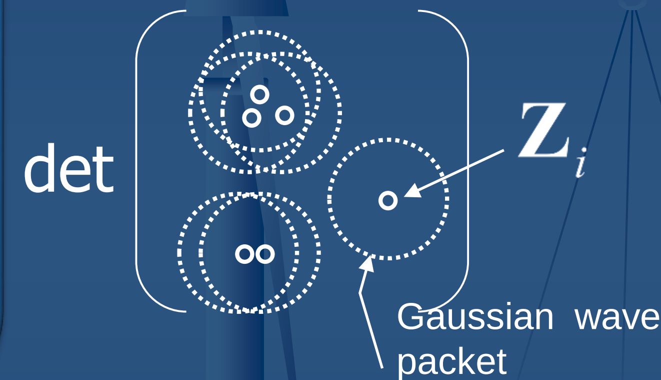
isospin

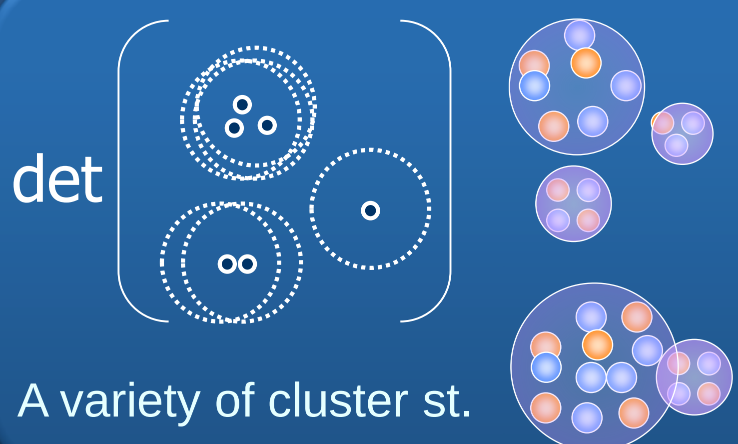
$$\Phi_{\rm AMD}(\mathbf{Z})$$

Variational parameters:

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

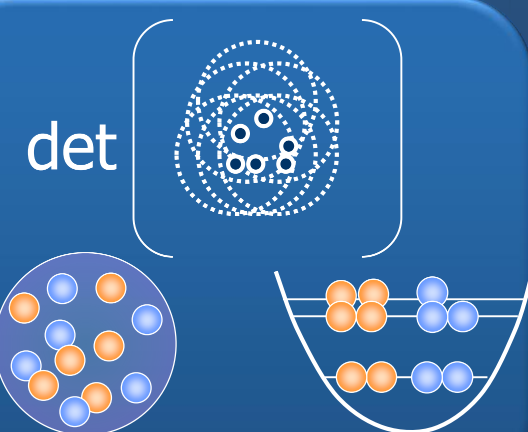
Gauss centers, spin orientations





A variety of cluster st.

Cluster and MF formation/breaking



Shell-model states

Energy variation

Model wave fn. $\Phi(\mathbf{Z})$

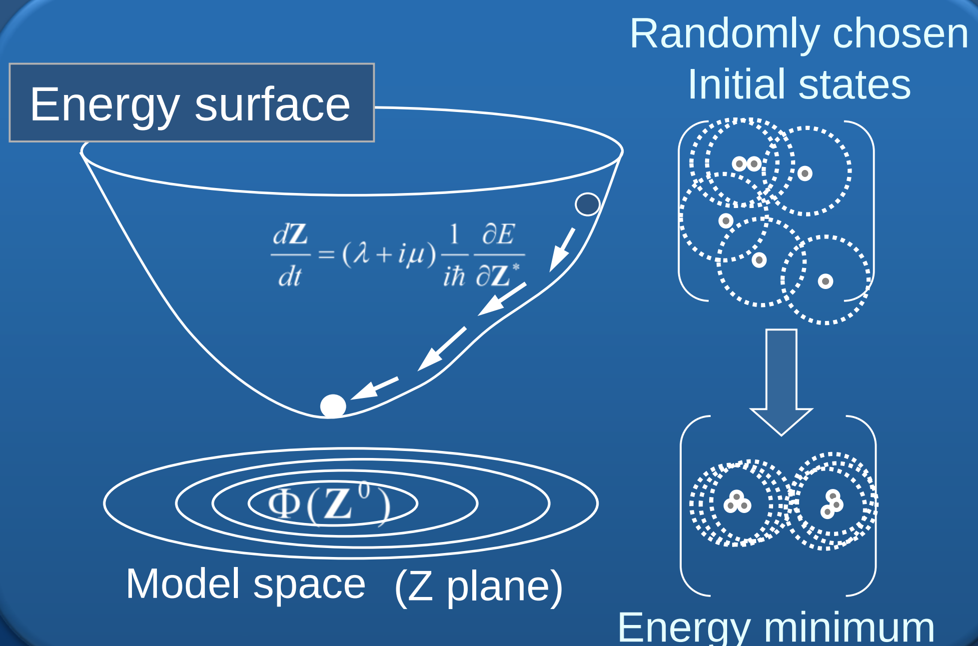
$$\delta \frac{\langle \Phi(\mathbf{Z}) | H | (\mathbf{Z}) \rangle}{\langle \Phi(\mathbf{Z}) | \Phi(\mathbf{Z}) \rangle} = 0$$

For $\delta \mathbf{Z}$

Phenomenological effective nuclear force

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

Volkov, MV1, Gogny etc.



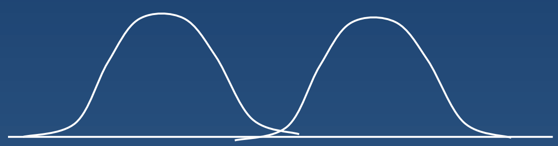
Variation, J^π -projection

- Variation after/before J^π–projection (VAP/VBP)
- Constraint AMD+GCM

Cluster limit v.s. Shell-model limit of AMD functions

Identical 2 fermions

$\phi_1(r_1) \qquad \phi_2(r_2)$



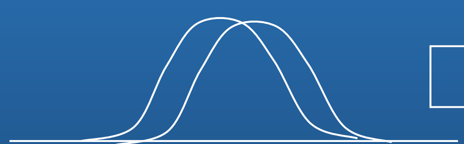
Anti-Symm.

$$\det\begin{bmatrix}\phi_1(r_1) & \phi_2(r_1)\\ \phi_1(r_2) & \phi_2(r_2)\end{bmatrix} = \det\begin{bmatrix}\phi_1'(r_1) & \phi_2'(r_1)\\ \phi_1'(r_2) & \phi_2'(r_2)\end{bmatrix}$$

with $\phi_1' \propto \phi_1 + \phi_2$

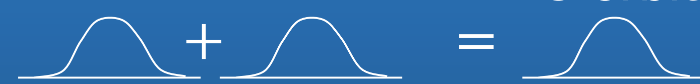
$\phi_2' \propto \phi_1 - \phi_2$

2 Gaussians at short distance



$\phi_1 \qquad \phi_2$

s-orbit

$\phi_1' =$ 

p-orbit

$\phi_2' =$ 

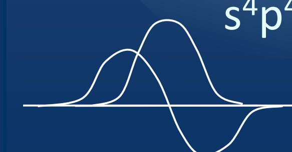
(0s)(0p) config.

2α system

Developed 2α

Strongly correlated

d→0 limit



$(0s)^4(0p)^4$

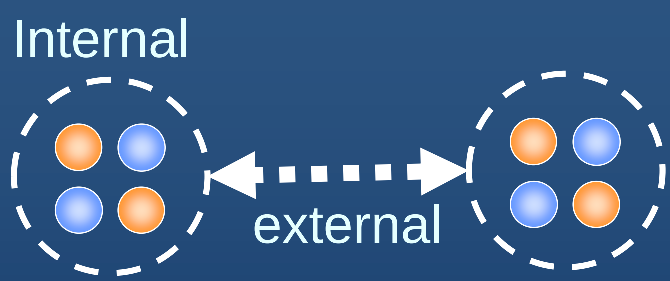
Lesson 3.
NN(pn,nn) correlation probed by Gamov-Tellar transition

clustering~correlations

- cluster=strongly correlated "sub"systems
- decoupling of "DOF" (scale)
- cluster limit: "internal"-strong & "external"-weak

by H. Tanaka, K. Ikeda

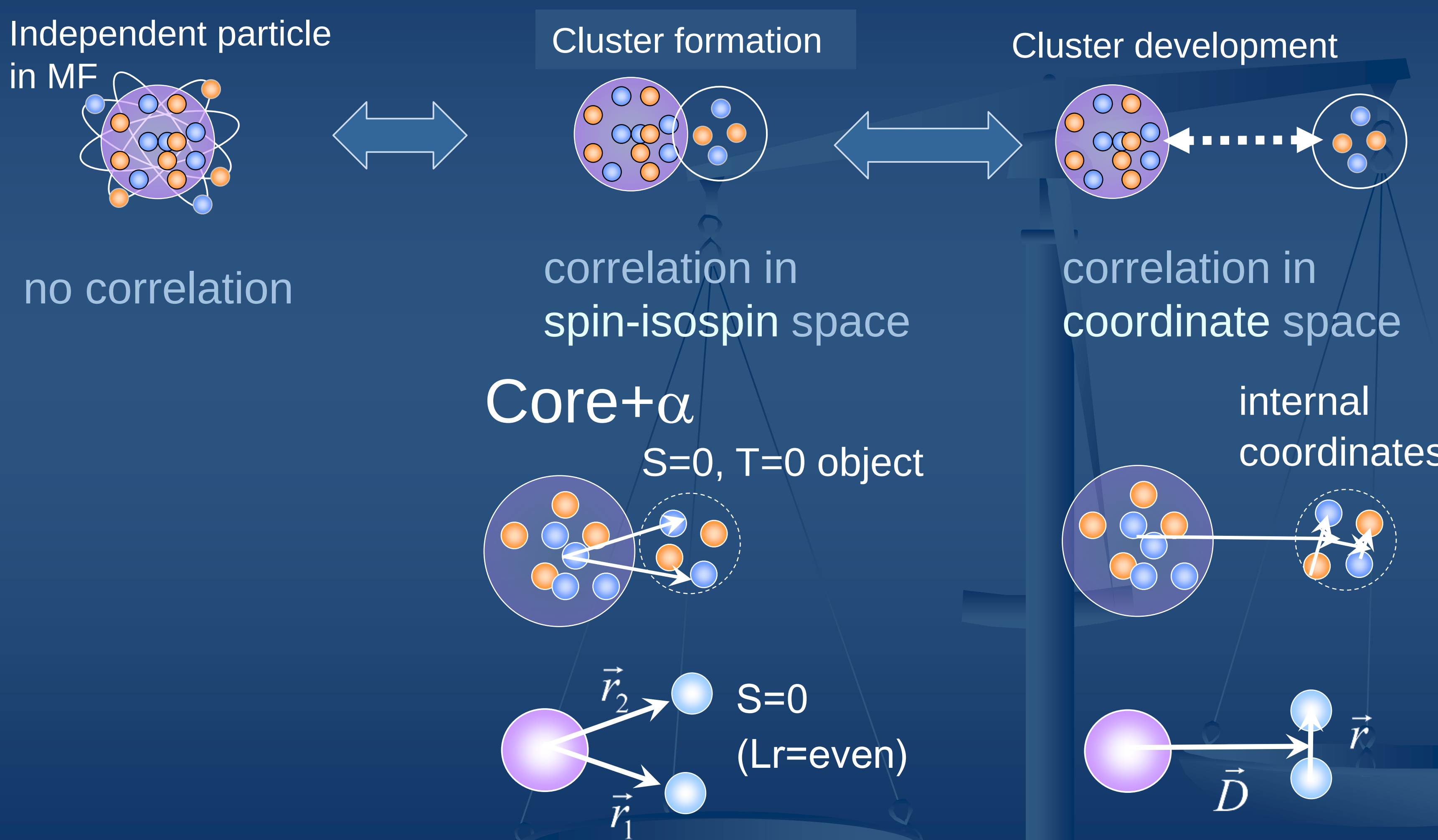
case 1)
spatial correlation



$$\psi(r_i, \sigma_i, \tau_i)$$

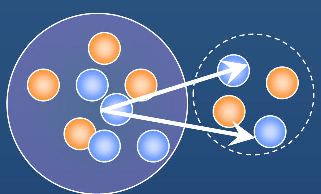
$$SO(3) \otimes SU(2) \otimes SU(2)$$

Cluster formation & development



4N, 2N correlations at nuclear surface

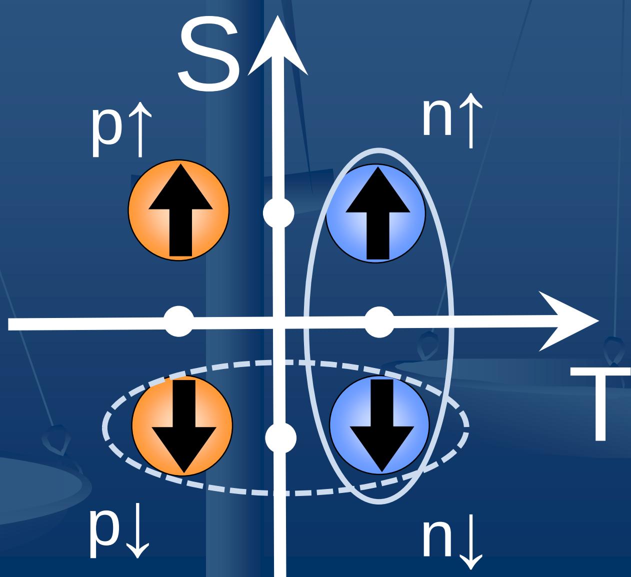
- Formation of S=0 (and T=0) subsystem
- decoupling of spin-isospin space
- Core+α(s), core+NN-pair(s)
- with and without spatial development



(ST)=(00) 4N: α-cluster

(ST)=(01) 2N: nn (dineutron)

(ST)=(10) 2N: pn (deuteron)



Cluster: decoupling in spin-isospin(flavor) and/or coordinate space

- 2n-halo nuclei: nn-cluster

  decoupling in spin-SU(2)&coordinate space

- heavy-quark symmetry in hadrons:qq-cluster

  decoupling in spin-flavor space

- quarkyonic phase -> hadronization

  decoupling in color-SU(3) space

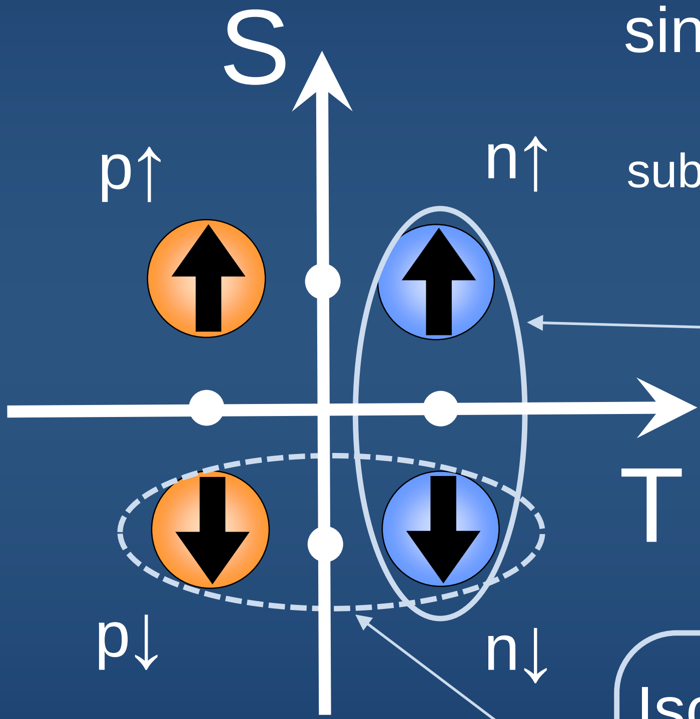
  but not in coordinate space (like BCS->BEC)

- hadron molecules: qqq(qqbar)-clusters

  decoupling in color&coordinate space

4 species of particles

SU(4): SU(2)xSU(2) 4 species of fermions
singlet: T=0,S=0 ^{4}He, α clusters ffff=b



subspace SU(2) NN Pairs: ff=b

Iso-vector (“T=1”), spin-scalar (S=0)

Isospin active → unstable nuclei

weak(β) -decay

Iso-scalar (T=0), spin-vector (“S=1”)

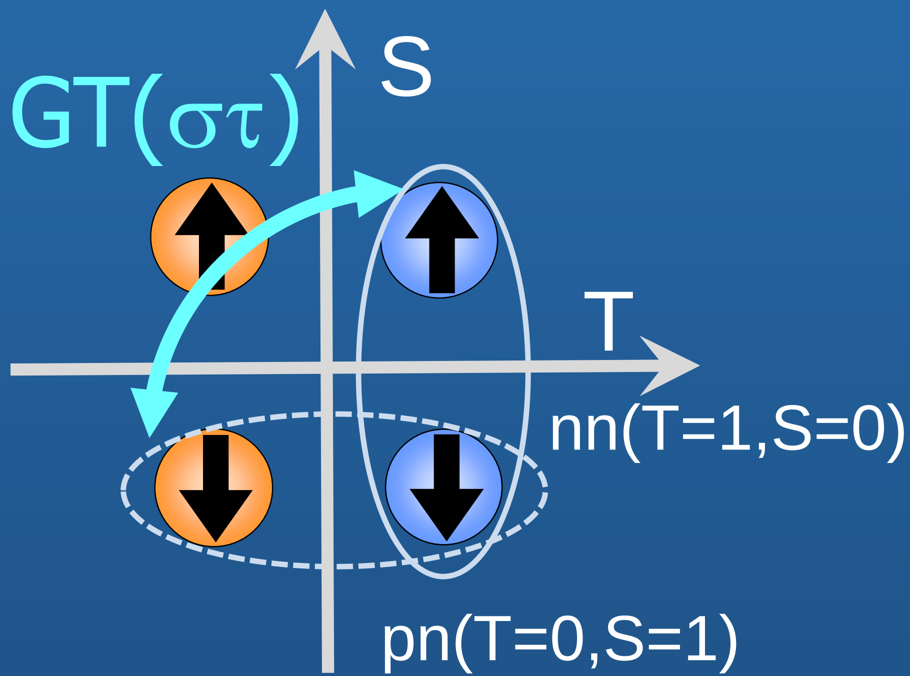
spin active → nuclear spintoronics

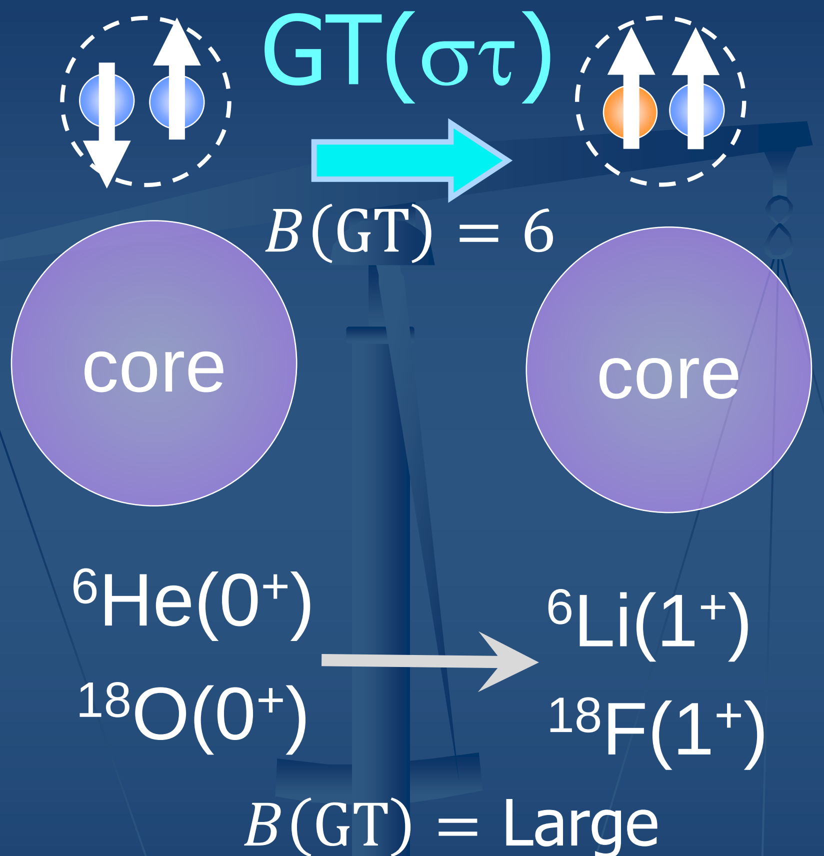
non-central (ls, tensor), EM (M1), β(GT)

GT transition of pn pair in Z=N=odd nuclei

nn→pn GT(στ)

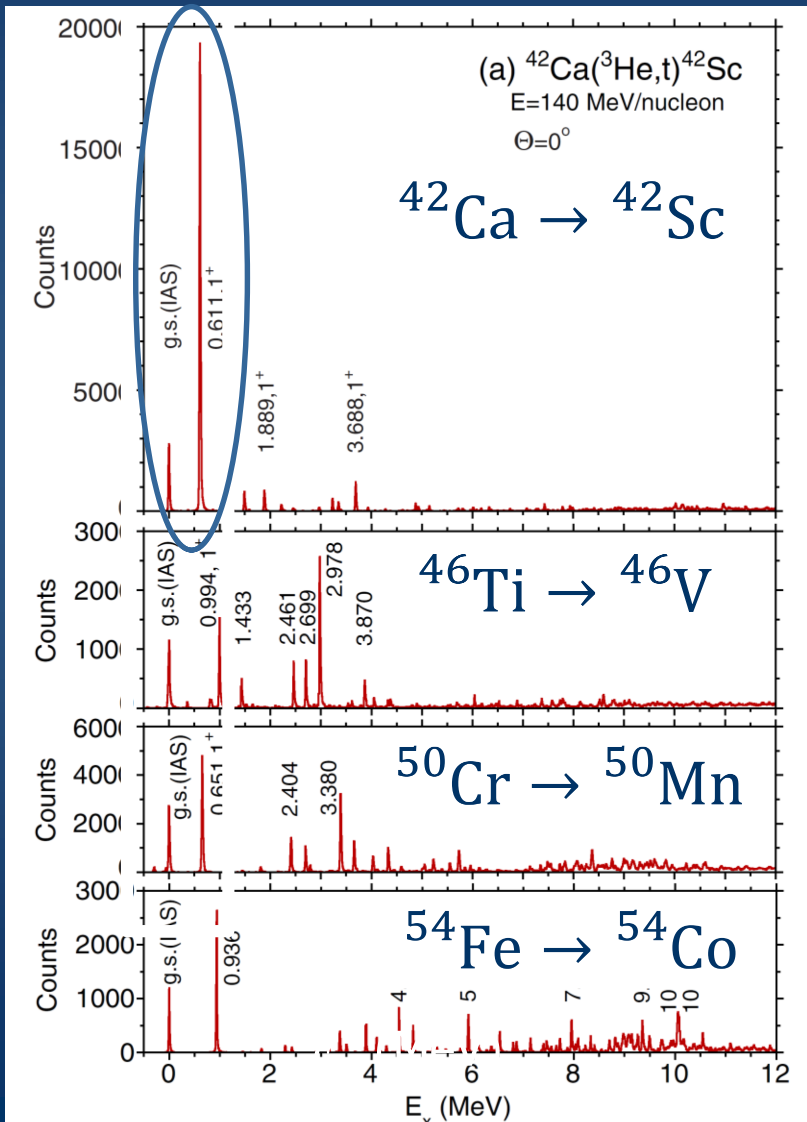
Gamov-Teller = spin-isospin flip transition
Rotation in SU(2)xSU(2) space
Strong GT in SU(4) symmetry





Super-allowed GT
by SU(4) symmetry

GT strength: N=Z+2 to N=Z=odd



$\left({}^{40}\mathrm{Ca} + \mathrm{NN}\right)$

Super-allowed GT by SU(4) symmetry

$\left({}^{40}\mathrm{Ca} + 6\mathrm{N}\right)$

GT splitting (partially broken SU(4) symmetry)

$\left({}^{40}\mathrm{Ca} + 10\mathrm{N}\right)$

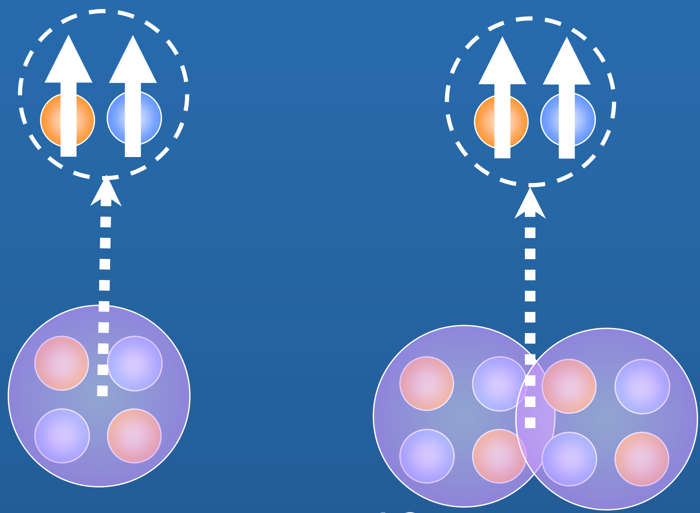
GT fragmented symmetry broken by spin-orbit int.

$\left({}^{40}\mathrm{Ca} + 14\mathrm{N}\right)$

Y. Fujita et al., Phys. Rev. Lett. 112, 112502 (2014) at RCNP

GT transition: pn pairs in p-, sd-shell

S=1,T=0 pn pair
with spatial development



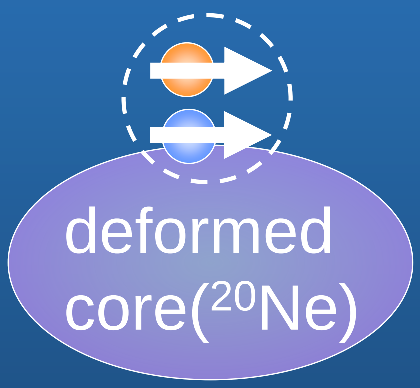
^{6}Li(1^{+}_{gs}) ^{10}B(1^{+})

Super-allowed GT

^{18}F(1^{+}_{gs})

Super-allowed GT
by SU(4) symmetry

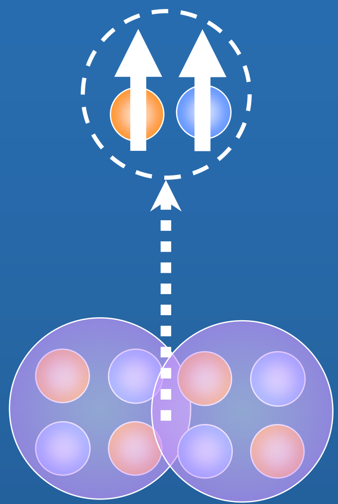
^{22}Na(1^{+})← ^{22}Ne(0^{+})



GT splitting by
partial breaking of
SU(4) symmetry
(ls force in deformed
system)

GT transition: pn pair in deformed nuclei

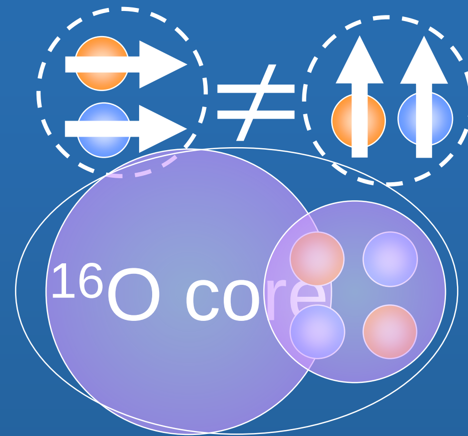
$^{10}B(1^+) \leftarrow {}^{10}Be(0^+)$



S=1,T=0 pn pair
with spatial development
free from
spin-orbit potentials

Super-allowed GT

$^{22}Na(1^+) \leftarrow {}^{22}Ne(0^+)$



ST=10 pair
⊗
ST=0 core

deformed core(^{20}Ne)

partial breaking
of SU(4) symmetry
by spin-orbit potential
in deformation

decoupling of
core+(NNNN)+NN
in SU(2)xSU(2)

coupling of
spin-SU(2)
x coordinate

GT splitting into two 1+ states

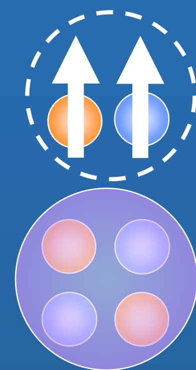
Spin S≠0 world pn pair in Z=N=odd nuclei

nn→pn GT(στ)

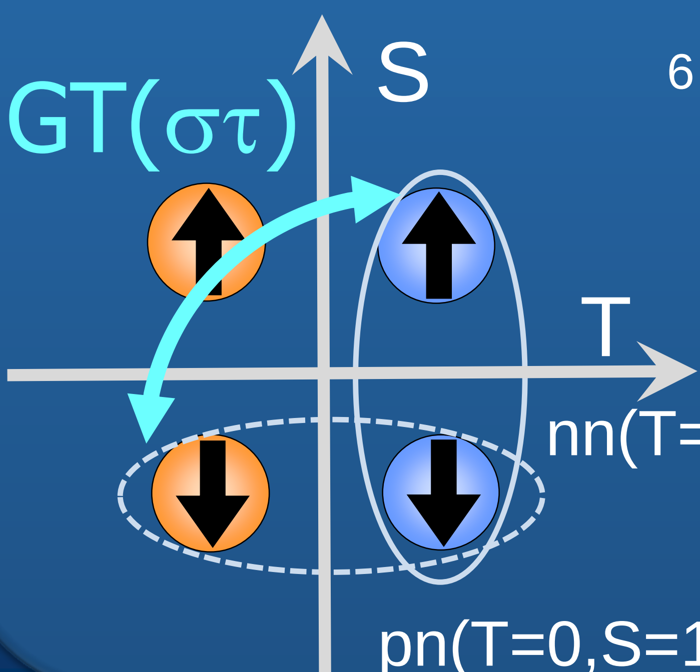
Gamov-Teller transition
Rotation in SU(2)xSU(2) space
Strong GT in SU(4) symmetry

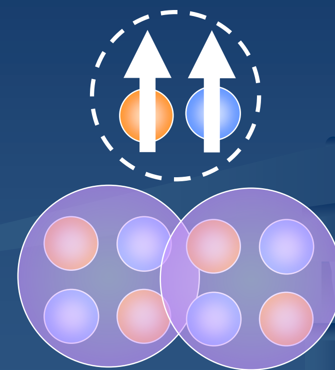
Super-allowed GT
by SU(4) symmetry

S=1,T=0
pn pair

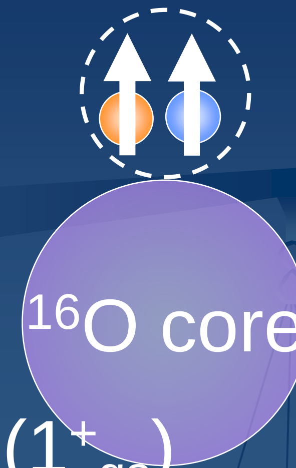


^{6}Li(1^+_{gs})



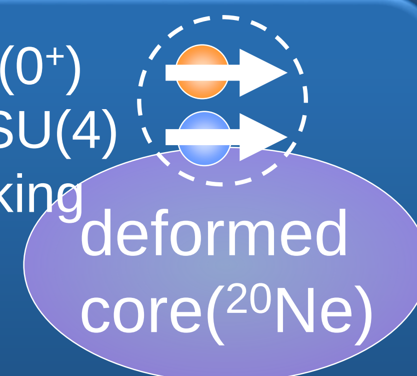


^{10}B(1^+)



^{18}F(1^+_{gs})

^{22}Na(1^+)← ^{22}Ne(0^+)
GT splitting by SU(4)
Symmetry breaking
in spin space
(defo. ls force)



Lesson 4.
cluster phenomena in neutron-rich Be isotopes

Model setting: AMD wave function

AMD wave fn. Similar to FMD wave fn.

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

$$\Phi_{\rm AMD} = \det\left\{\varphi_1, \varphi_2, \cdots, \varphi_A\right\}$$

$$\varphi_{\rm i} = \phi_{\mathbf{Z}_{\rm i}} \chi_{\rm i} \begin{cases} \phi_{\mathbf{Z}_{\rm i}}(\mathbf{r}_{\rm j}) \propto \exp\left[-\nu\left(\mathbf{r} - \frac{\mathbf{Z}_{\rm i}}{\sqrt{\nu}}\right)^2\right] \\ \chi_{\rm i} = \begin{pmatrix} \frac{1}{2} + \xi_{\rm i} \\ \frac{1}{2} - \xi_{\rm i} \end{pmatrix} \times \quad p \text{ or } n \end{cases}$$

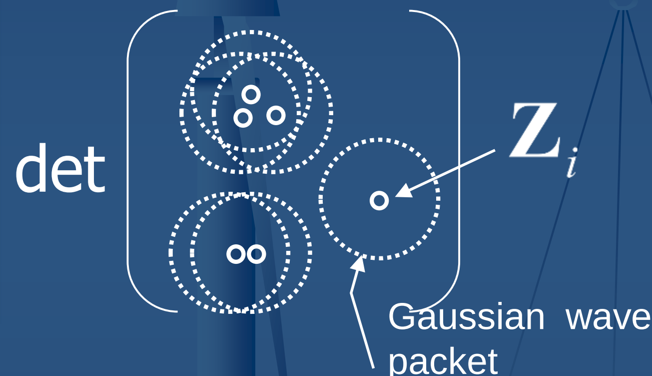
Intrinsic spins, isospin

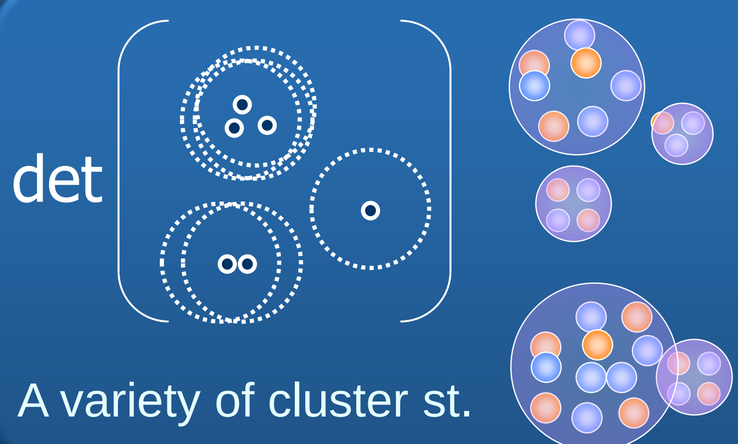
$$\Phi_{\rm AMD}(\mathbf{Z})$$

Variational parameters:

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

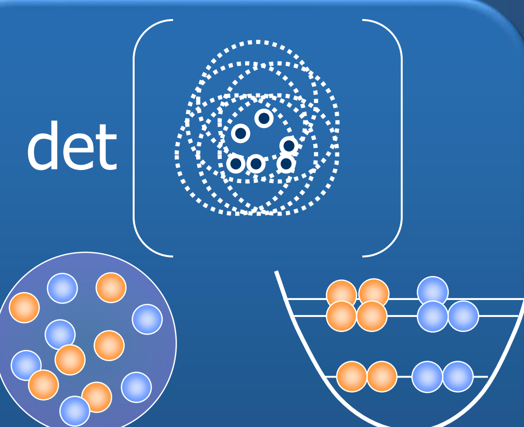
Gauss centers, spin orientations





A variety of cluster st.

Cluster and MF formation/breaking



Shell-model states

Energy variation

Model wave fn. $\Phi(\mathbf{Z})$

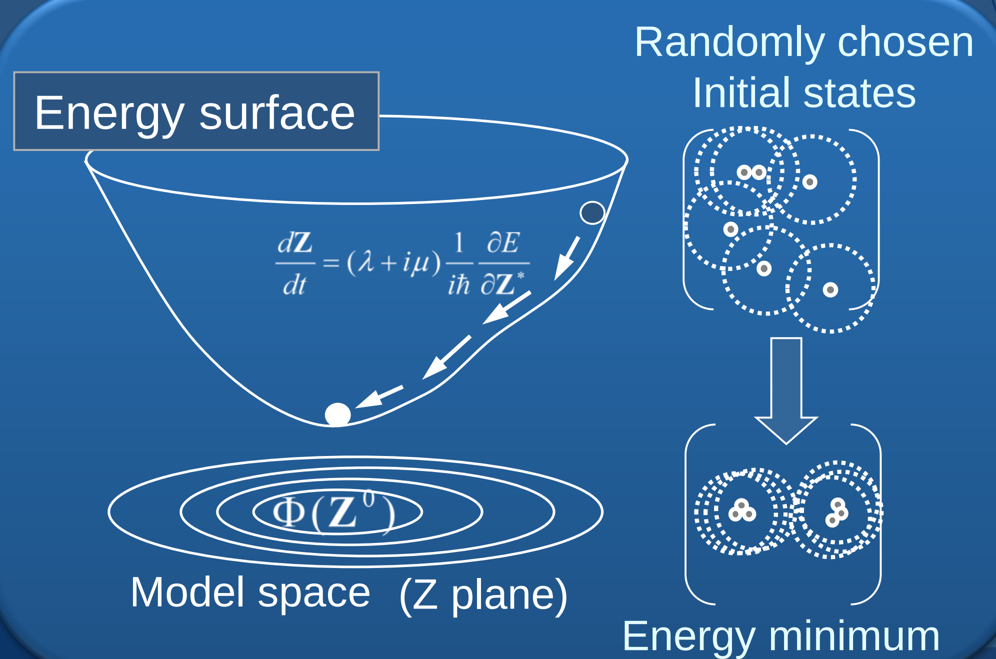
$$\delta \frac{\langle \Phi(\mathbf{Z}) | H | (\mathbf{Z}) \rangle}{\langle \Phi(\mathbf{Z}) | \Phi(\mathbf{Z}) \rangle} = 0$$

For $\delta\mathbf{Z}$

Phenomenological effective nuclear force

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

Volkov, MV1, Gogny etc.



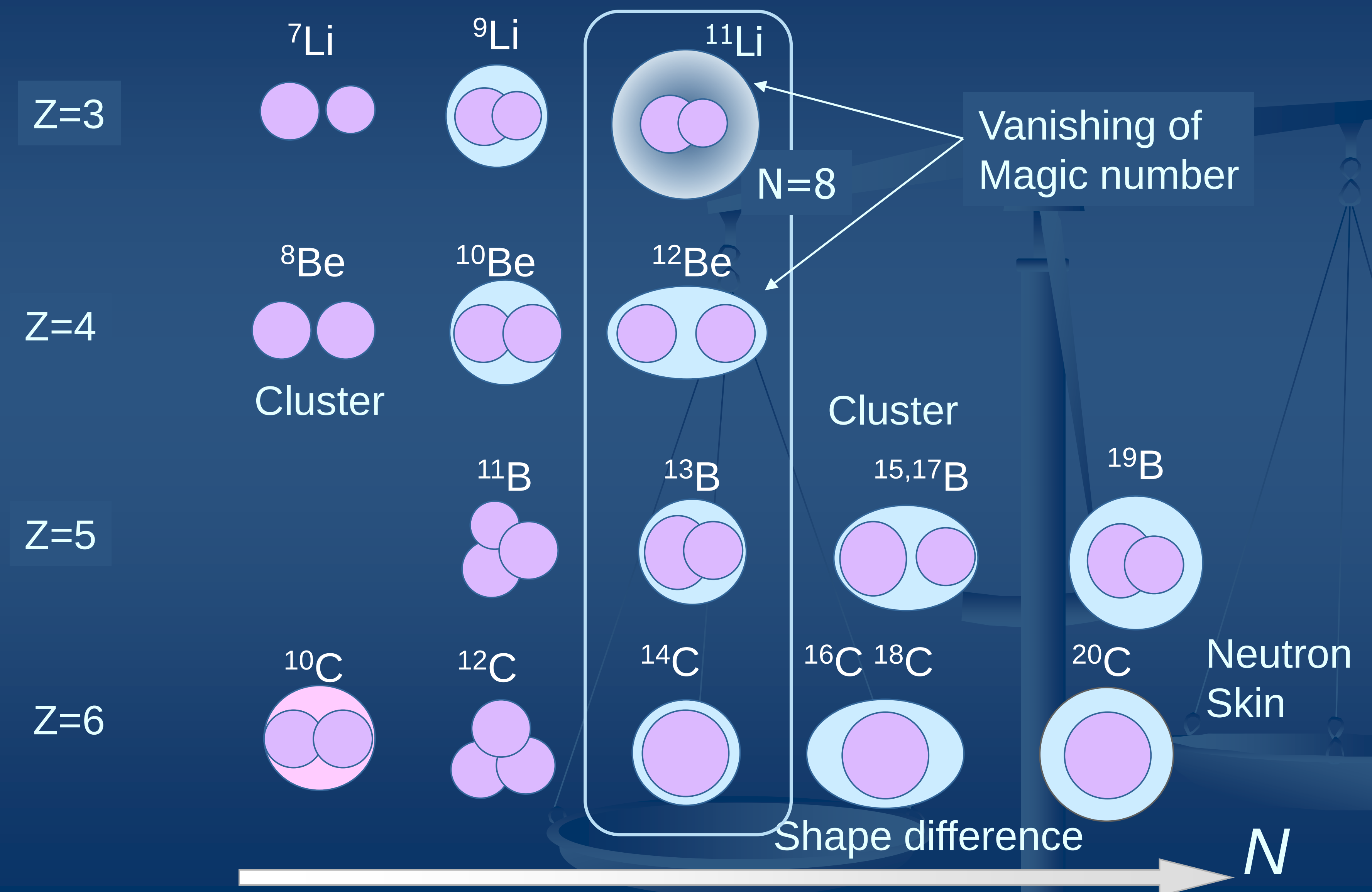
Variation, J^π -projection

- Variation after/before J^π–projection (VAP/VBP)
- Constraint AMD+GCM

- Z-,N-dependence of g.s. structure
- MO & magic number breaking
- Cluster resonances

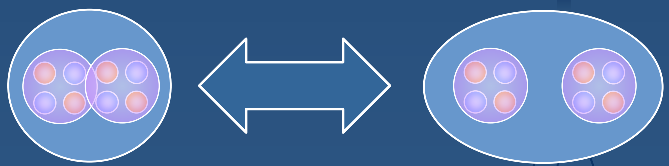
- Z-,N-dependence of g.s. structure
- MO & magic number breaking
- Cluster resonances

Z-, N-dependence of ground states



How to experimentally probe N-dependence of clustering

- Clustering in g.s.

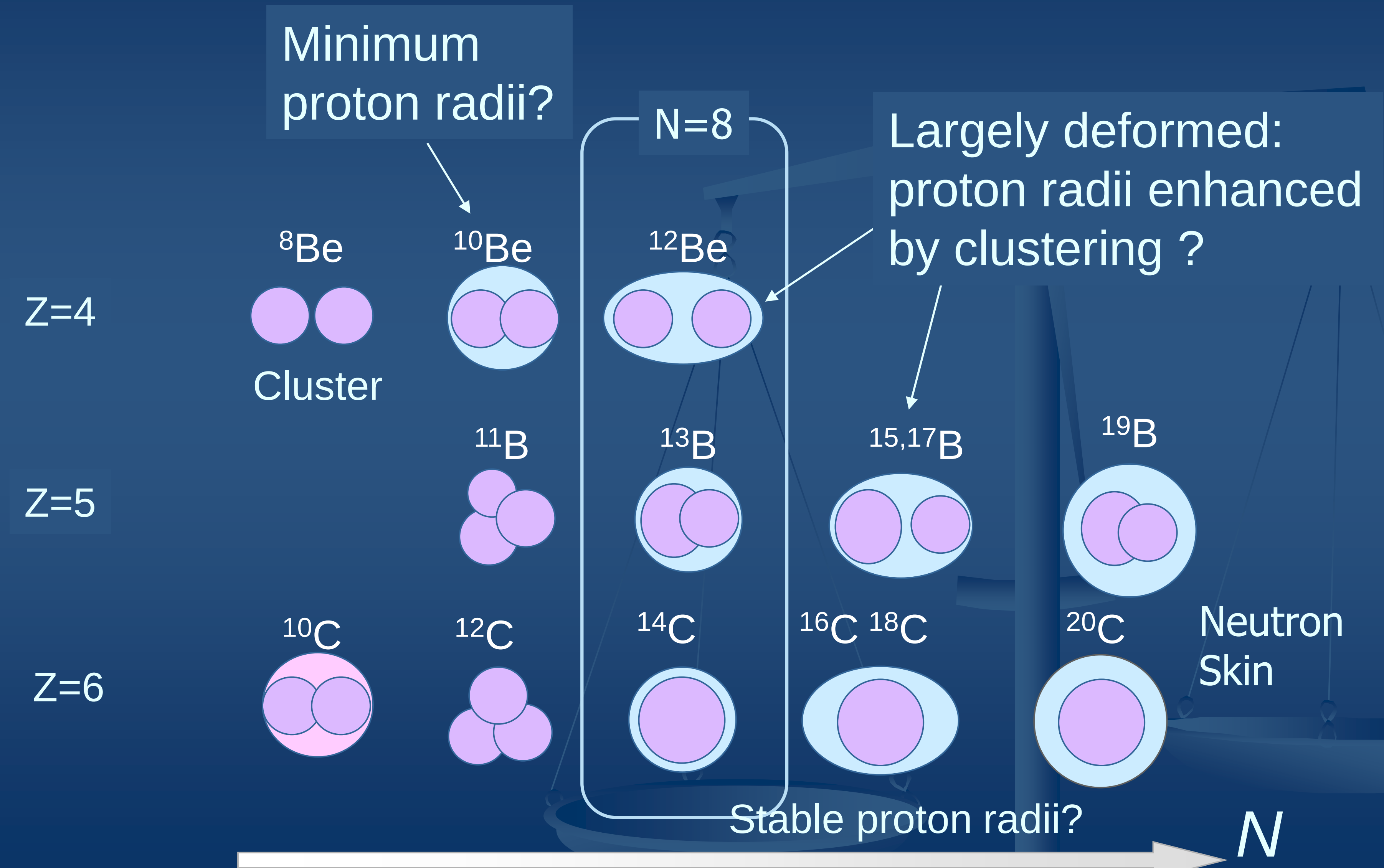


β_p, r_p enhanced

- Deformation Q, B(E2)
- Charge radii
  - isotope shift: Be
  - charge changing σ : B, C
- α-transfer, α knock-out ?

- Clustering in excited states
  - α-decay width, α-transfer

Z-, N-dependence of g.s. structure

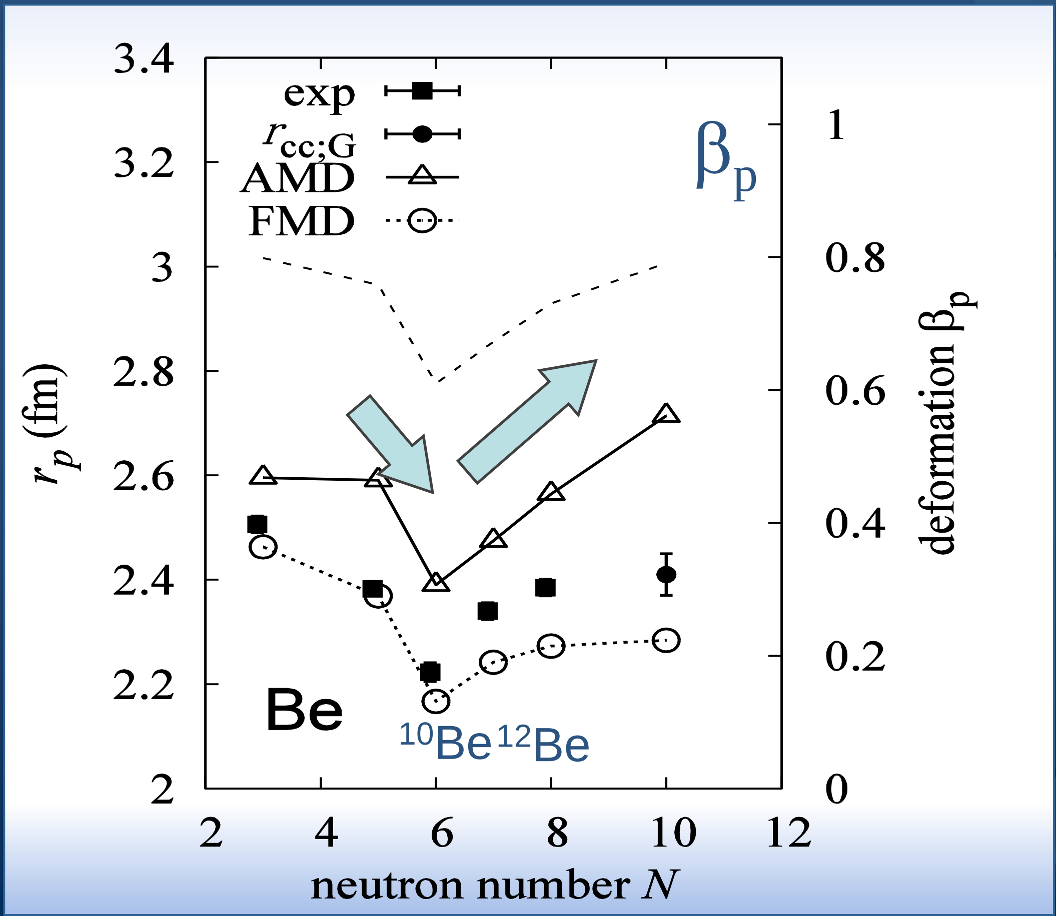


proton radii along isotope chain

Exp data:

Isotope shift W. Nortershauser et al. PRL102, 062503 (2009); A. Krieger, PRL108, 142501 (2012).

CC :Terashima et al.



- minimum at N=6 (^{10}Be)

  new magic?

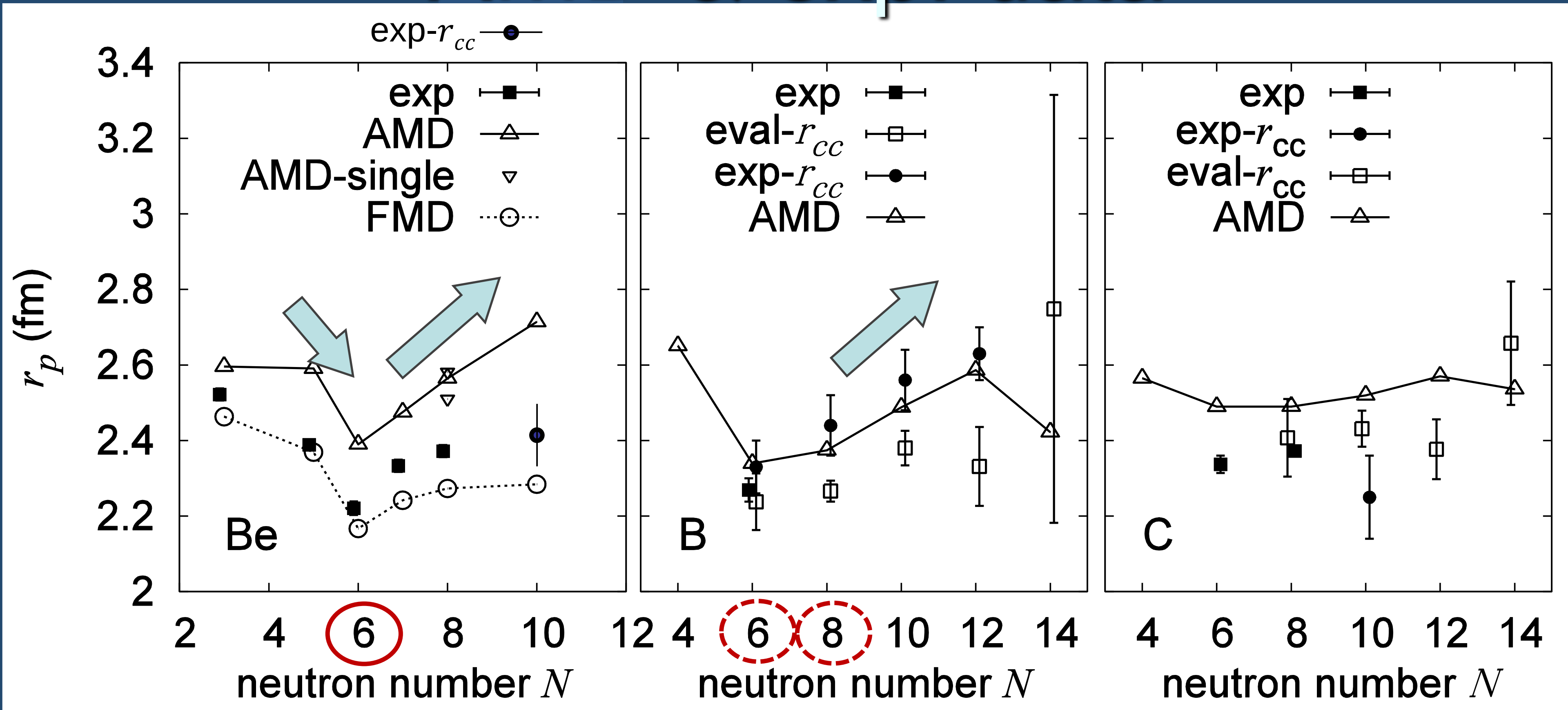
- Increasing in N>6.

proton radii(charge radii) ref

N dependence of clustering.

Good probe for cluster structure

N dependence of r_p in Be,B,C AMD & exp. data



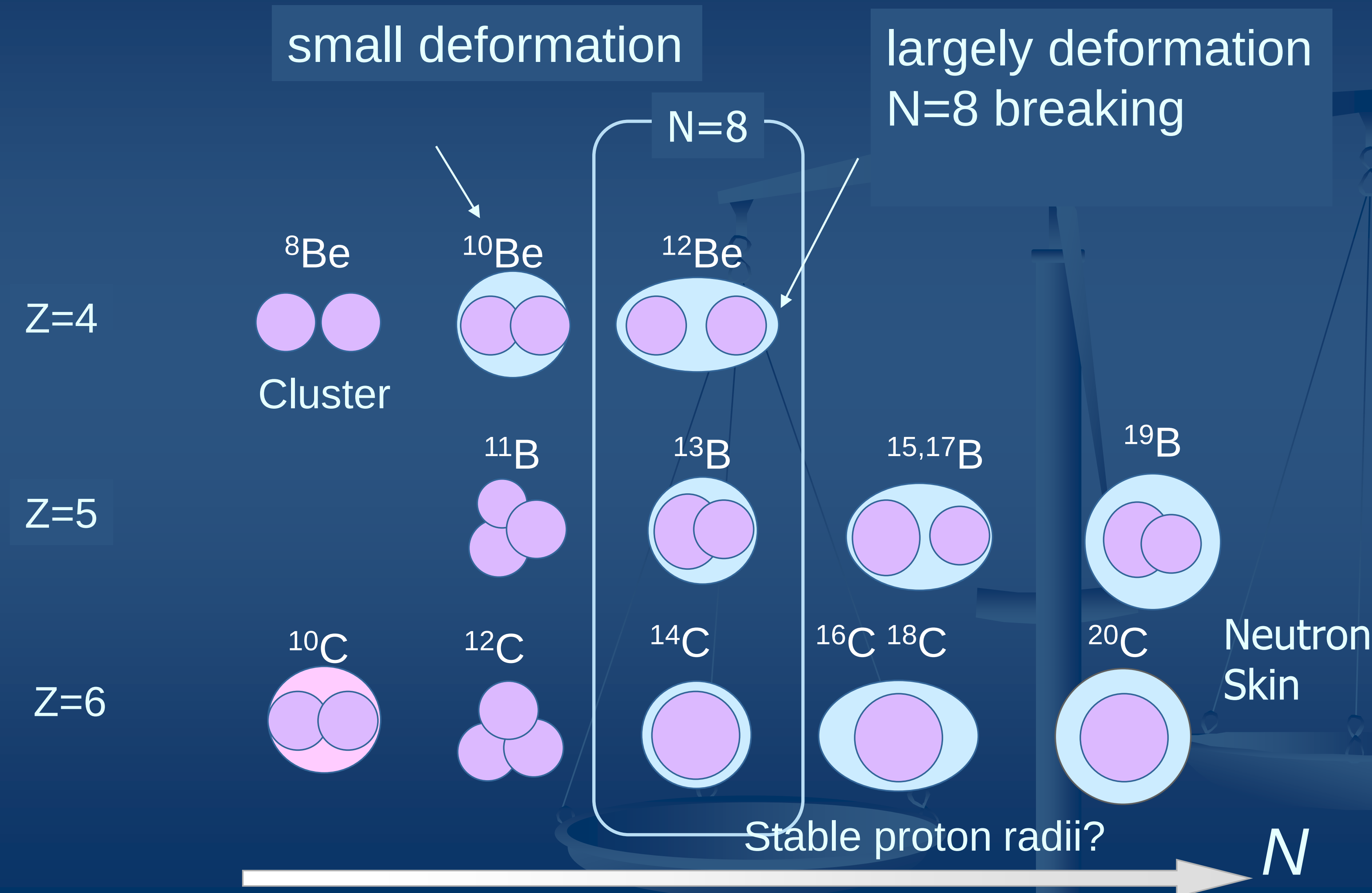
exp :determined by isotope shift

exp-r_{cc} :determined by charge changing(cc) cross section

eval-r_{cc} : evaluated by relation $\sigma_{cc} \propto \pi(R_p(P) + R_m(T))^2$ using cc cross section

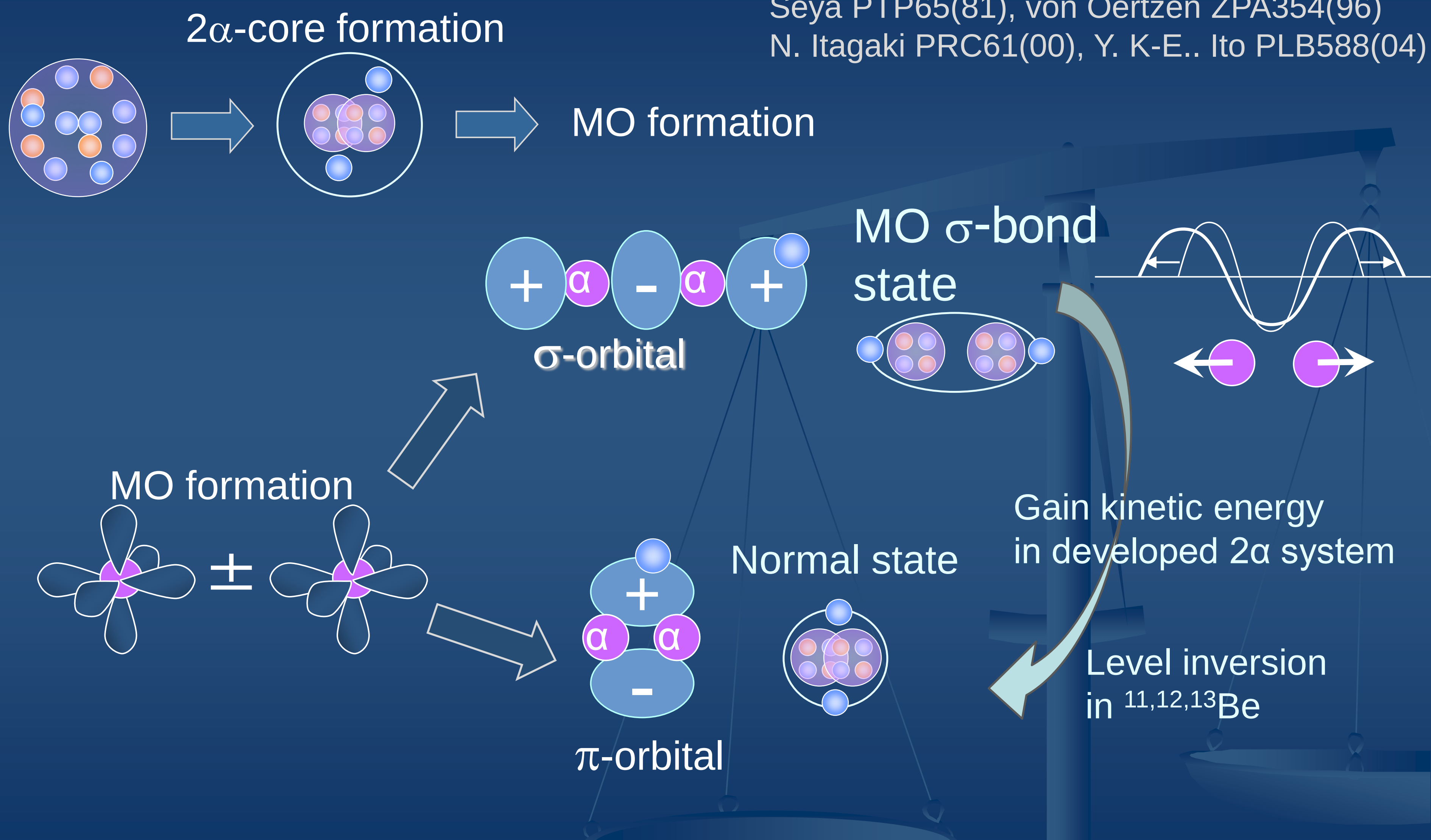
- Z-,N-dependence of g.s. structure
- MO & magic number breaking
- Cluster resonances

Z-, N-dependence of g.s. structure



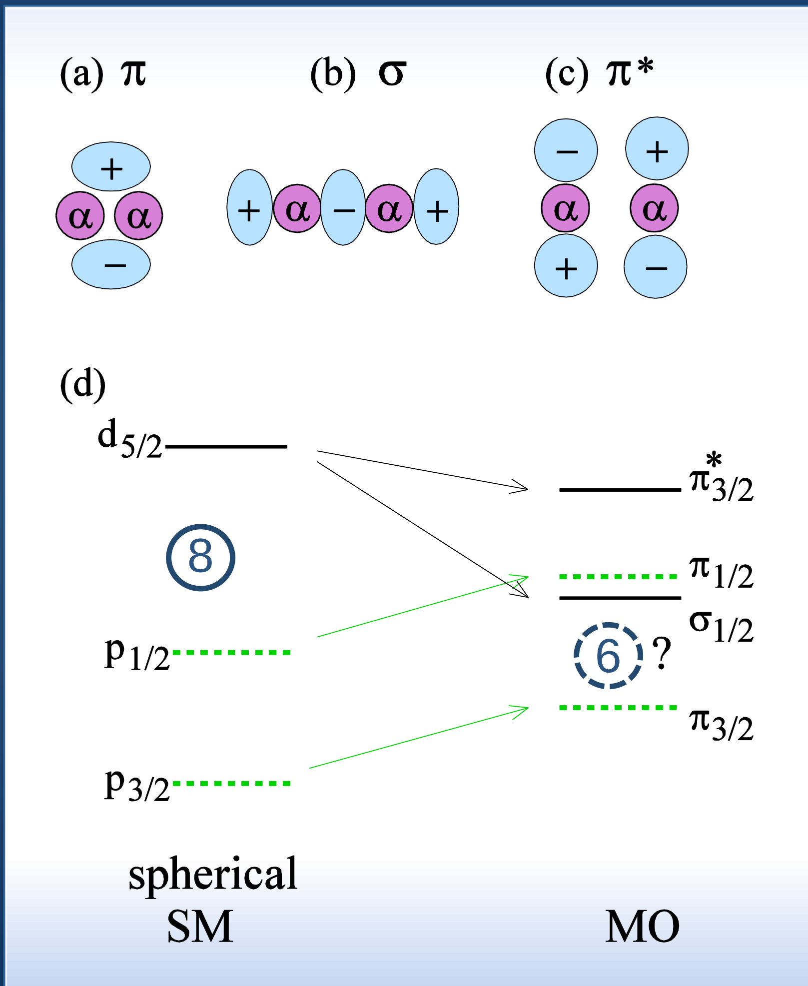
Molecular orbital(MO) structure in 2α

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

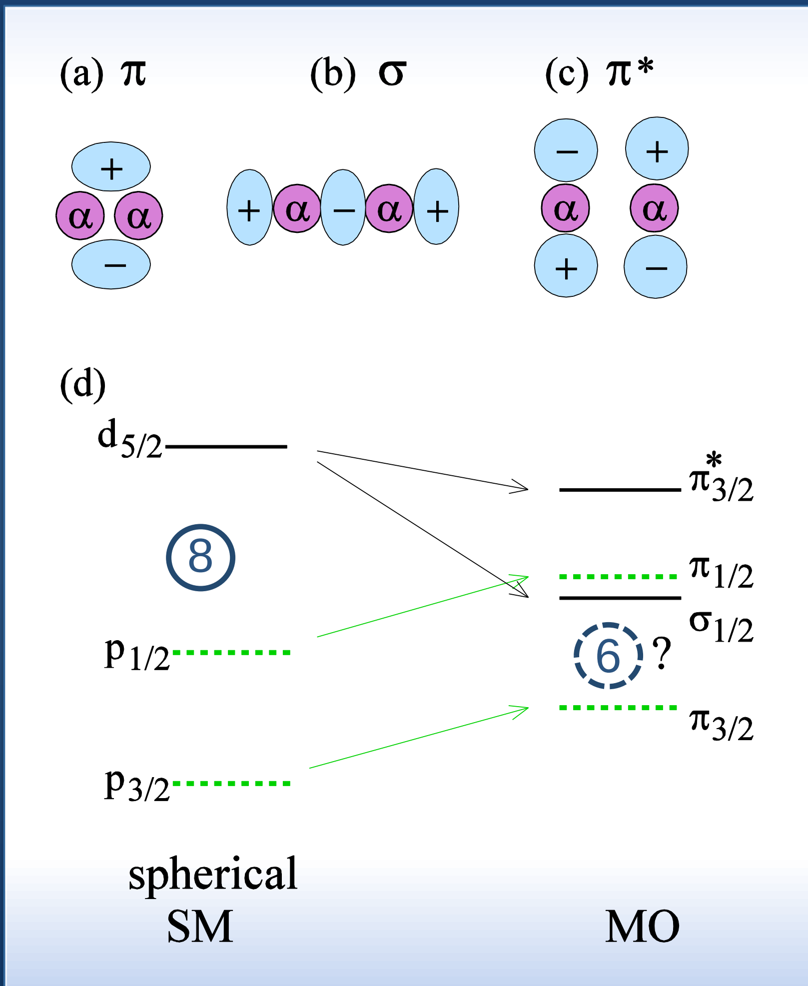


spherical

enhanced cluster core

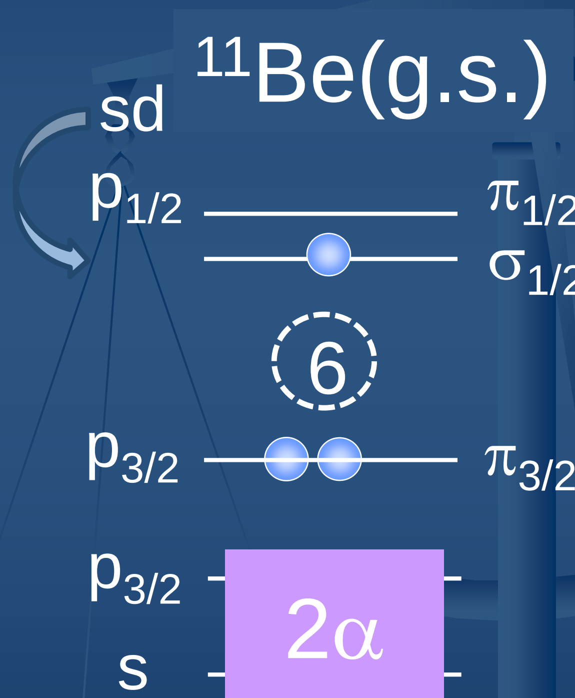
- Level inversion in developed cluster system
- N=8 shell vanishes at N=7,8 (11Be, 12Be)
- Positive- and negative-parity states degenerate
- New magic N=6 appears?
- σ-orbital neutron enhances clustering

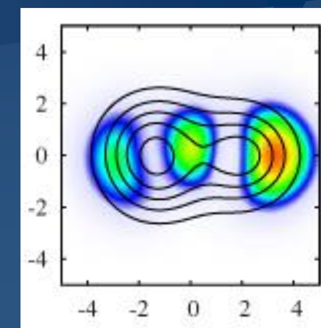
N=8 magic number breaking

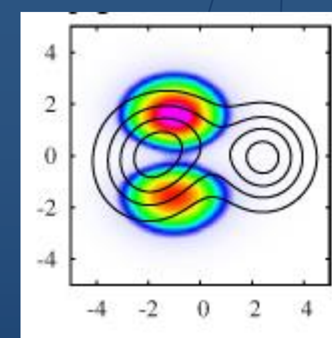


spherical

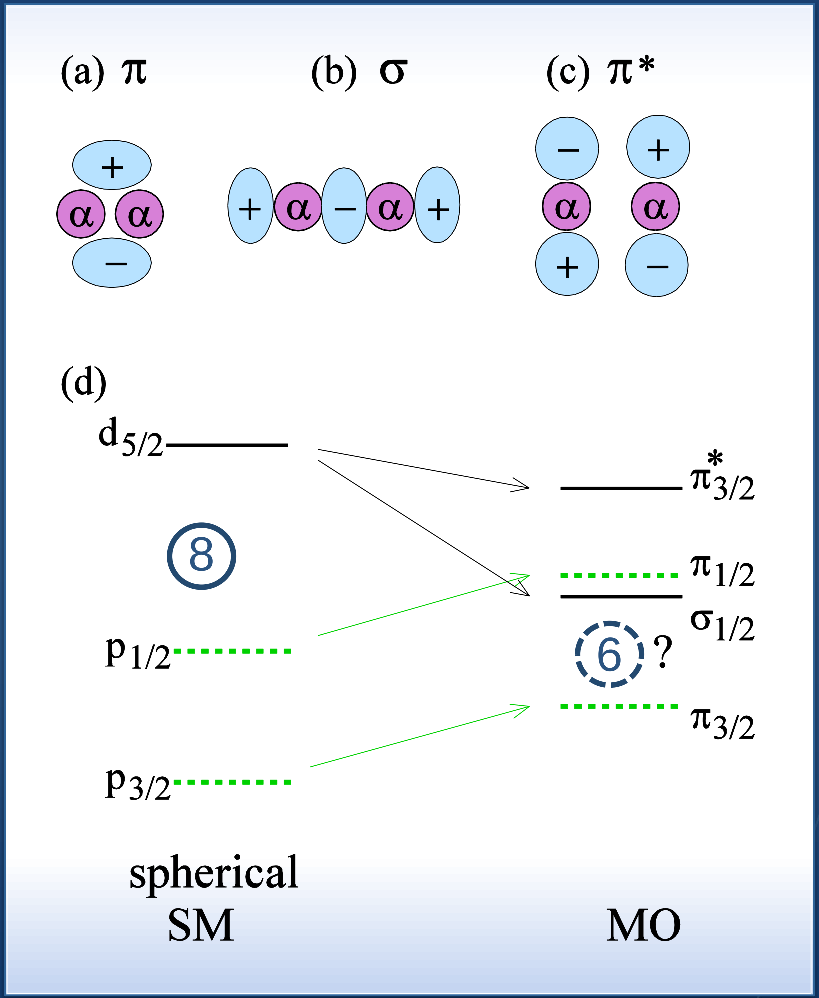
enhanced cluster core





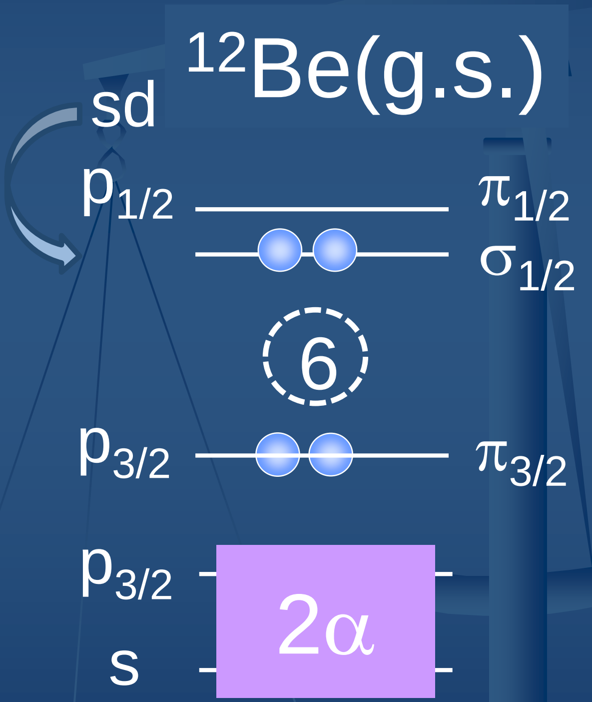


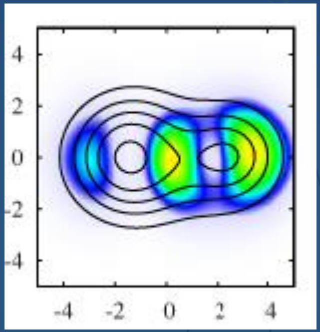
N=8 magic number breaking

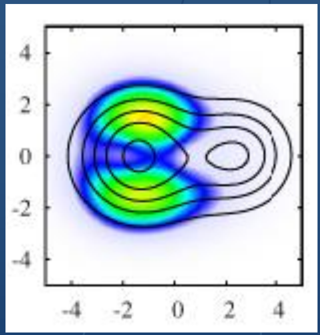


spherical

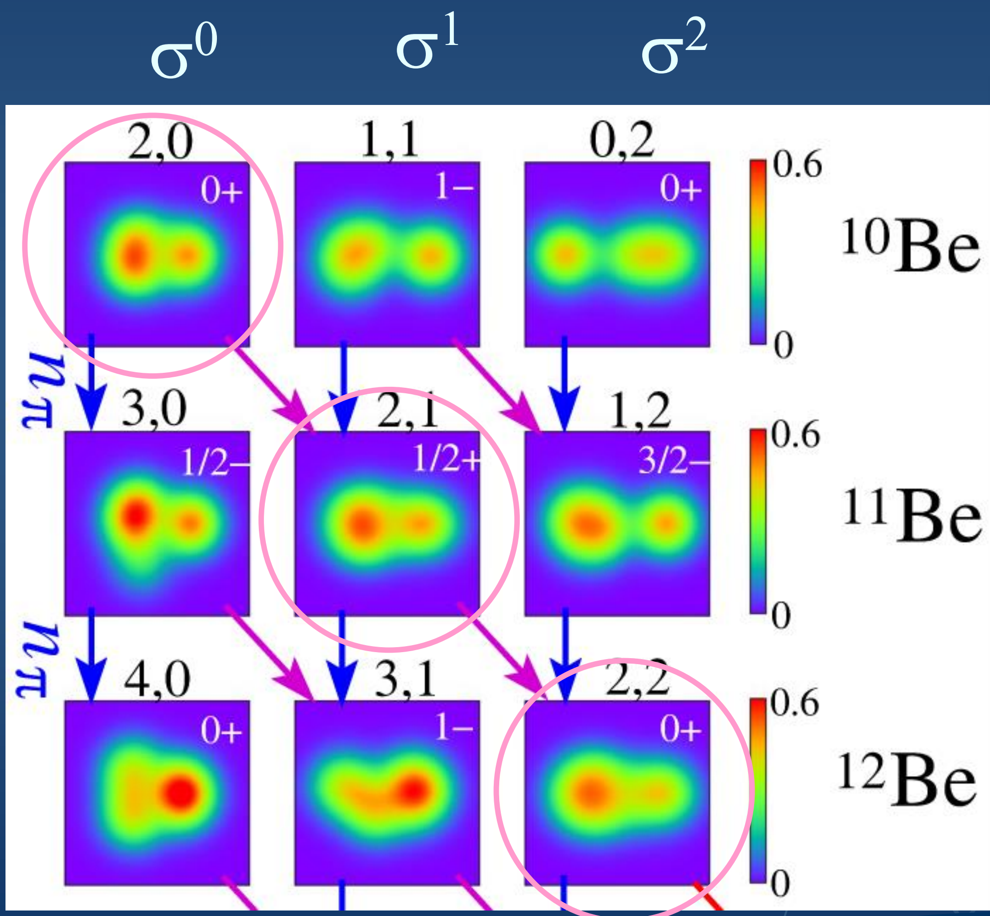
enhanced cluster core

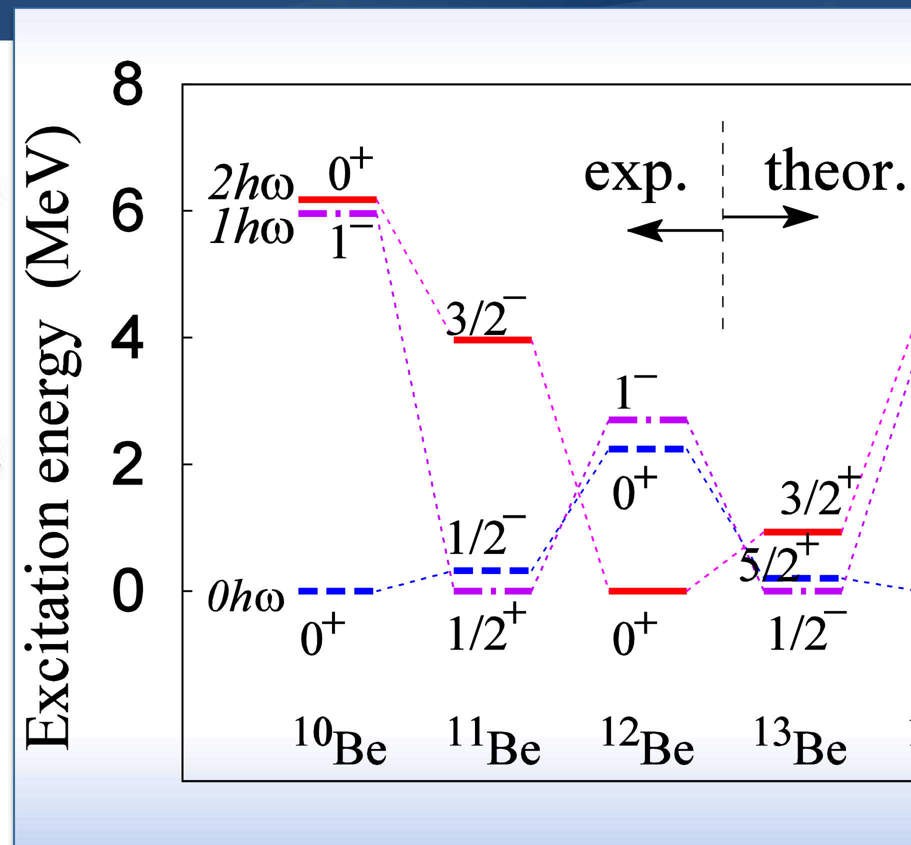






Cluster enhanced by σ-orbital neutrons

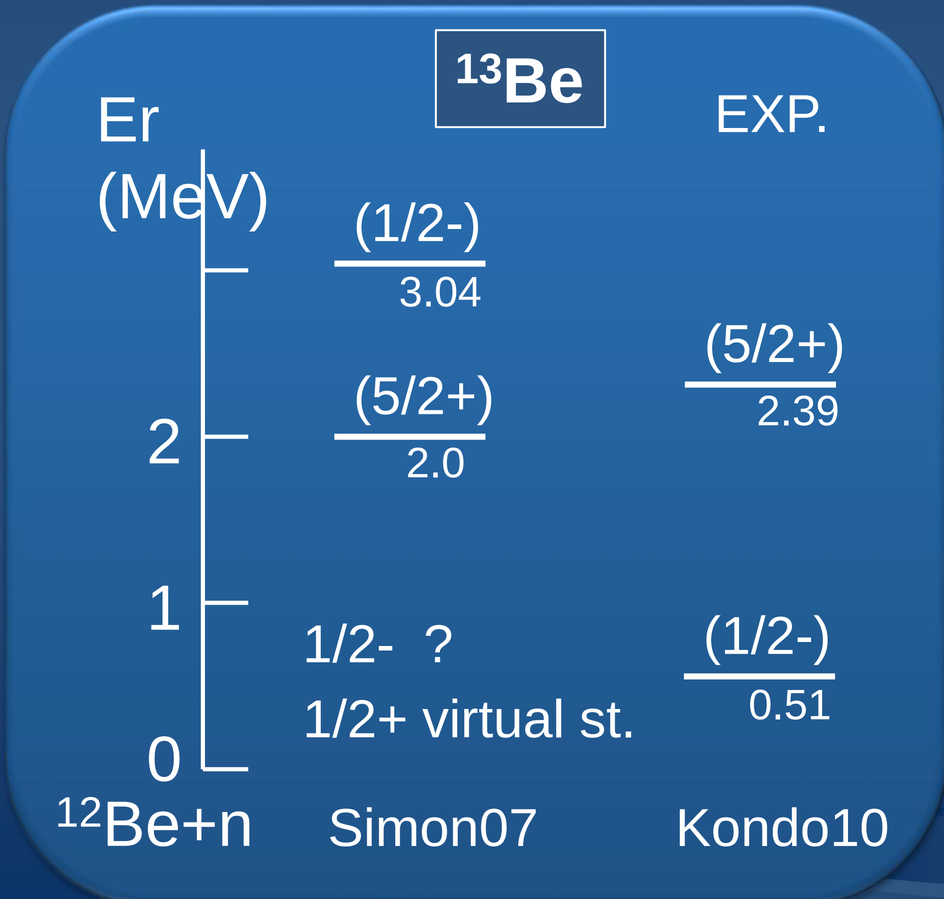




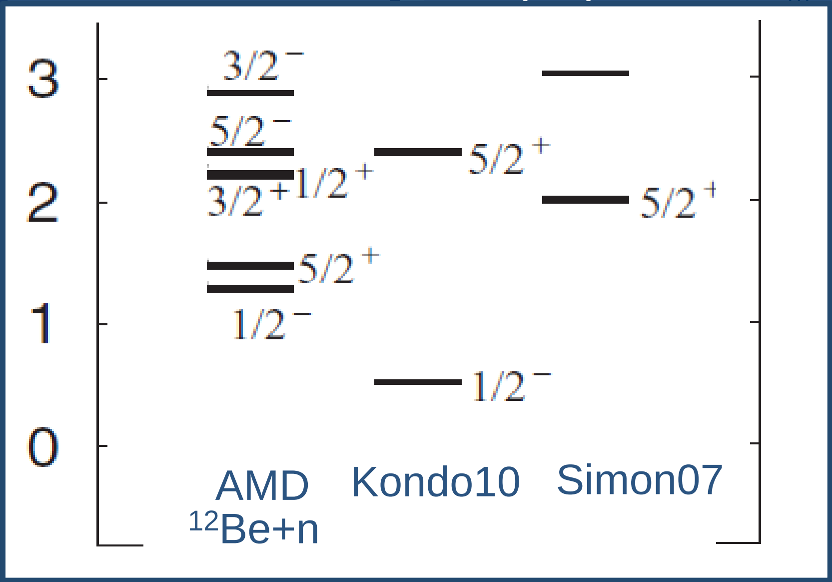
Breaking of magic number in ^{13}Be

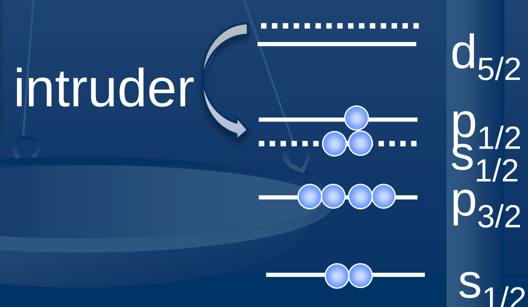
^{13}Be: unbound

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



AMD calc. Y. K-E. PRC(12)

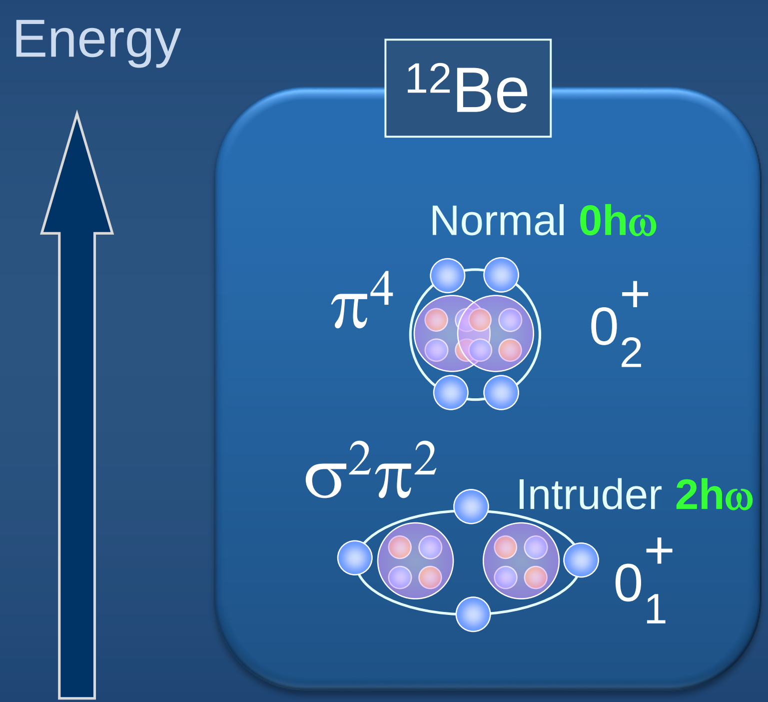




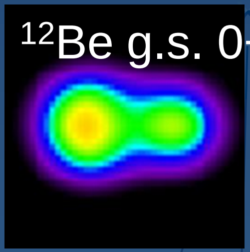
1/2- is lowest in ^{13}Be

Experimental evidence of N=8 shell vanishing in ^{12}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)

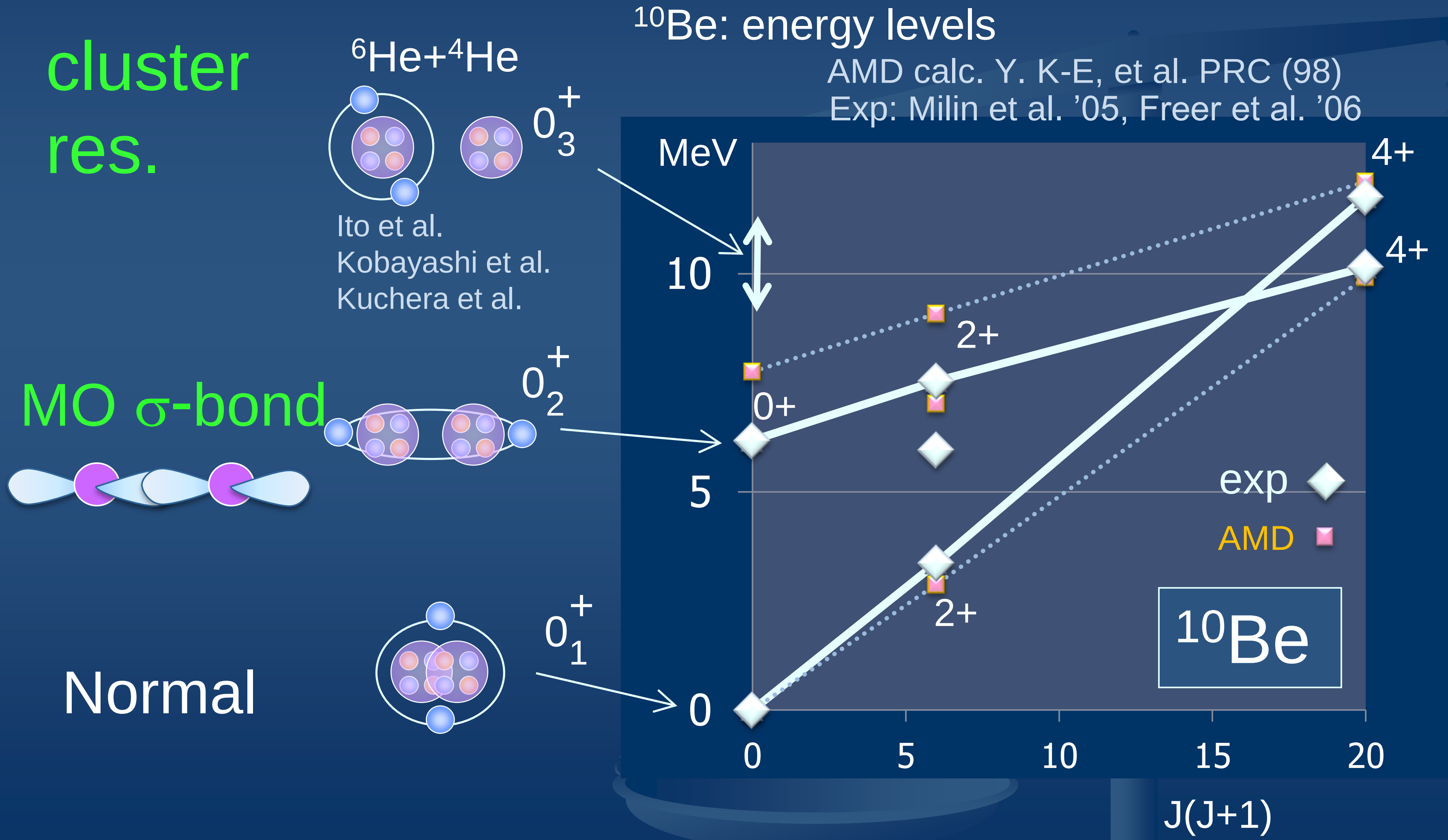


- intruder config. in ^{12}Be(gs)
  - 1n-knockout reac.:
    Navin PRL85(00),
    Pain PRL96(06)

- ^{12}Be(0_2^+) with p-shell config.
  - Shimoura PLB654 (07)
  - B(GT) with charge ex.:
    Meharchand PRL108 (12)

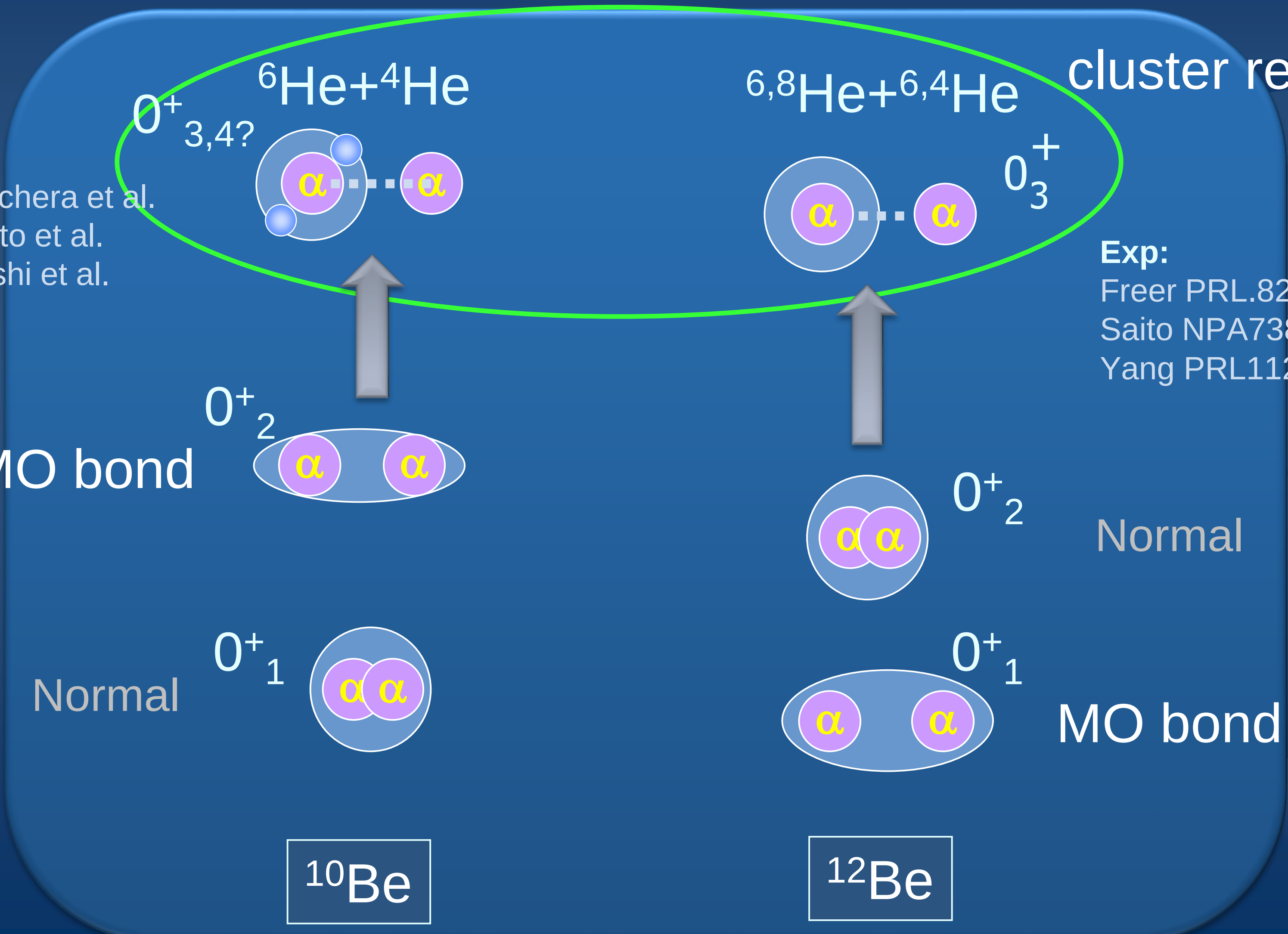
- Z-,N-dependence of g.s. structure
- MO & magic number breaking
- Cluster resonances

Spectra of 10Be



Cluster resonances

Exp: Kuchera et al.
Theor: Ito et al.
Kobayashi et al.

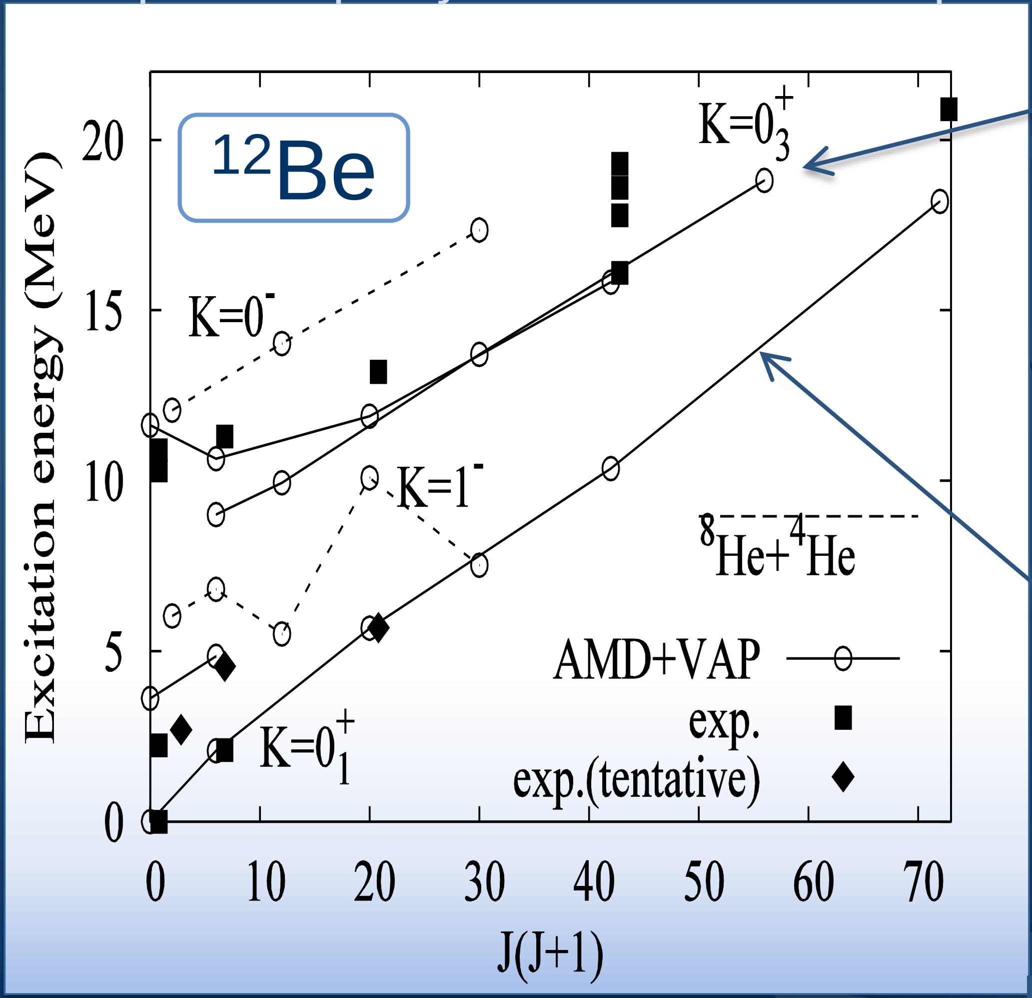


Exp:
Freer PRL.82(99)(06)
Saito NPA738 (04)
Yang PRL112 (14)

Energy spectra of ^{12}Be

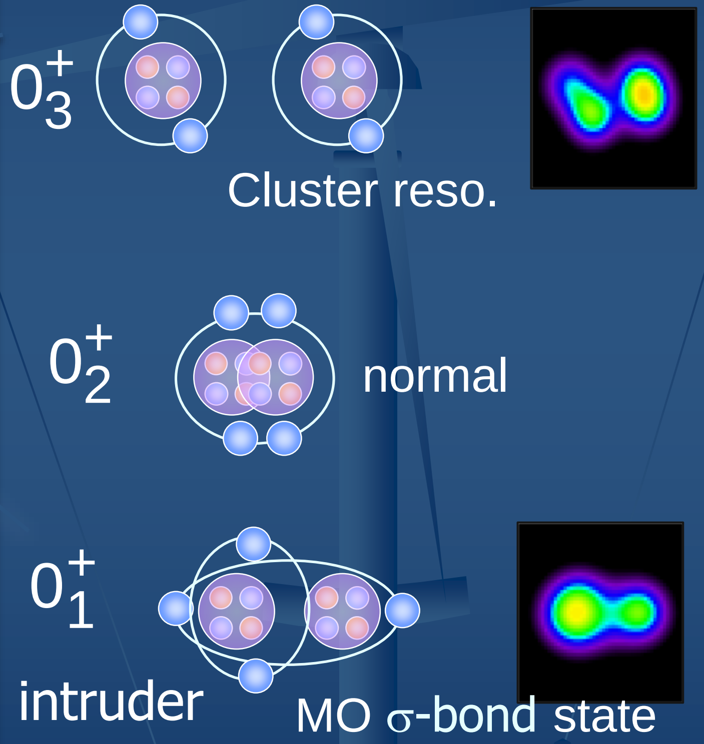
VAP calculation with AMD method

positive parity states withnormal spins



^{12}Be

$^6He+^6He$, $^8He+^4He$?



Breaking of N=8 magicity

Formation of 2a+molecular orbitals

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

MO v.s. Cluster resonance in other n-rich systems

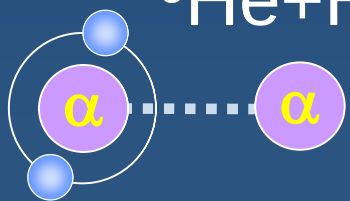
^{10}Be

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.

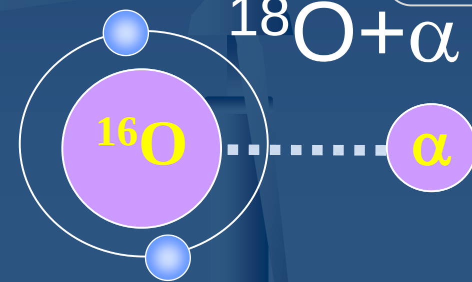
^{22}Ne

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

^{6}He+He

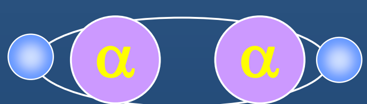


$^{18}O+\alpha$

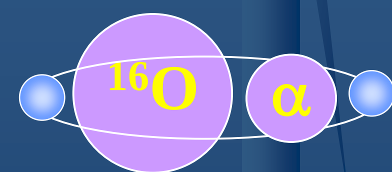


Atomic:
Cluster resonance

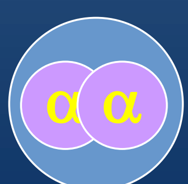
Weak coupling



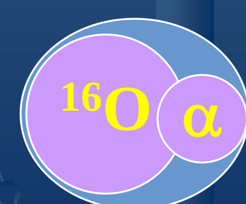
Molecular Orbital:
σ-bond structure



Strong coupling



Normal states



shell model-like

Be isotopes

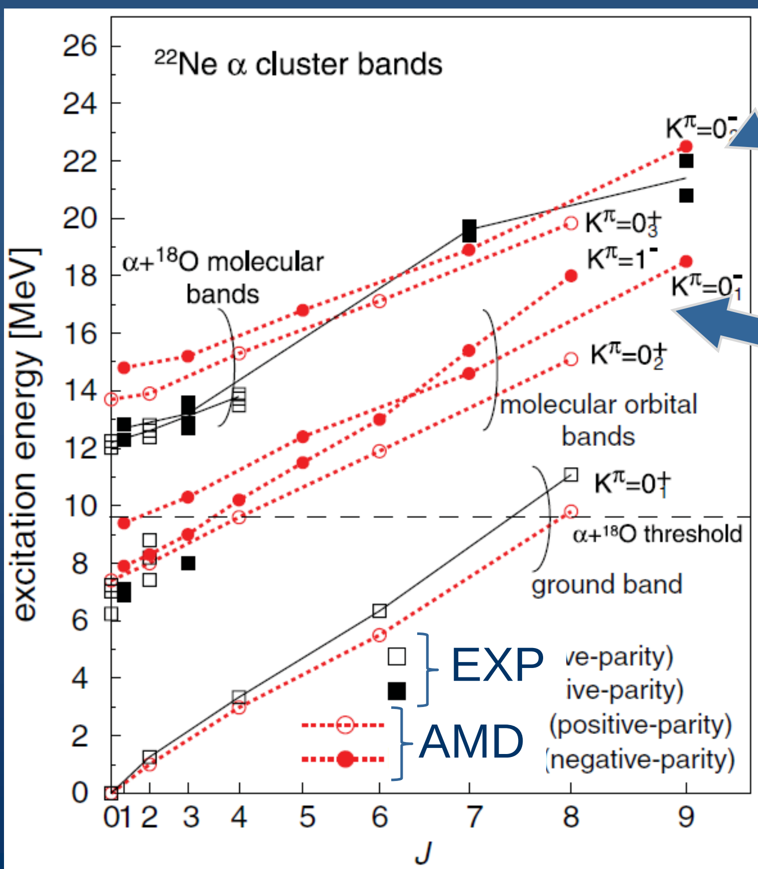
Ne, F, O isotopes

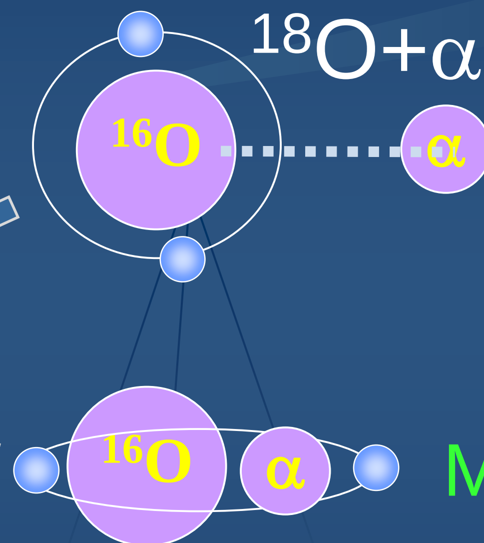
MO bond and Cluster res. in ^{22}Ne

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

^{22}Ne

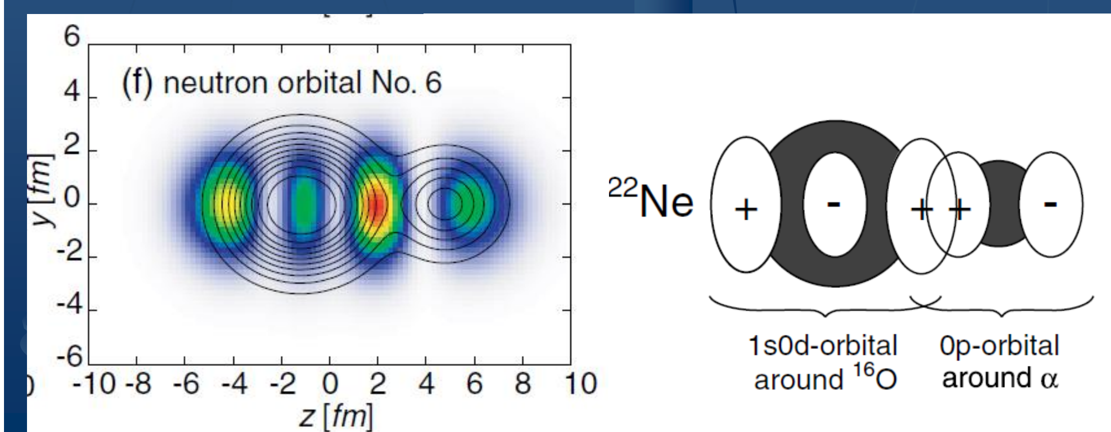
AMD study by Kimura, PRC75 (2007)



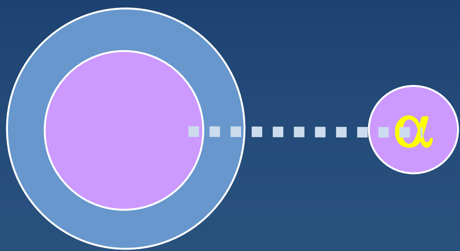


Cluster res.

MO σ-bond



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.

Lesson 5. Nuclear excitations Isoscaler monopole and dipole excitations

how to probe clustering in nuclei with reactions

- charge ex (3He,t) reactions: GT transitions
- α-transfer, α-knockout reactions
- (α,α') scattering:

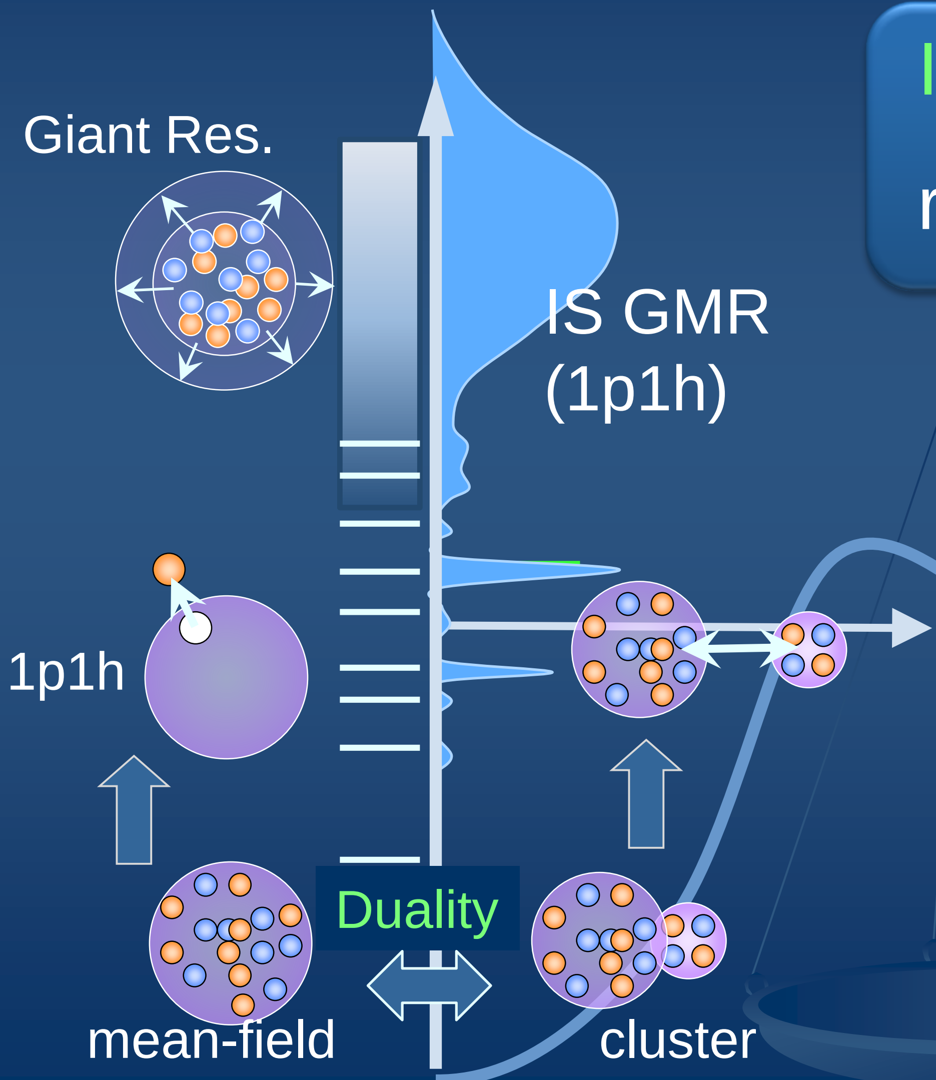
  isoscalar monopole & dipole excitations
- (p,p') ....

Isoscalar monopole excitations

T=0,S=0 excitations in coordinates(r,L) space

Isoscalar Monopole (ISM)

r^2-excitation (L=0)



single-particle vs cluster

Low-energy ISM
for cluster states

Kawabata et al.
Yamada et al.

Y. K-E. PRC89 (2014)
Y. K-E. PRC94 (2016)
Y. Yoshida and Y. K-E. PTEP2016 (2016)
Y. K-E. PRC93 (2016)
H. Matsuno,.. Y. K-E. et al. PTEP2014 (2014)

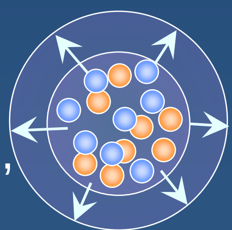
Giant monopole and dipole resonances

IS monopole (IS0):

$$\sum_i r_i^2 Y_{00}(\hat{\mathbf{r}}_i)\sqrt{4\pi}$$

GMR

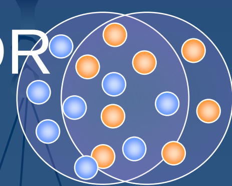
Compressive, breathing



IV dipole (E1):

$$\sum_{i=proton} r_i Y_{1\mu}(\hat{\mathbf{r}}_i)$$

IVGDR

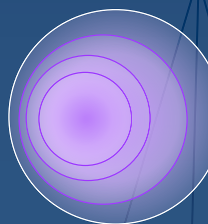


translational ⇔

IS dipole (IS1):

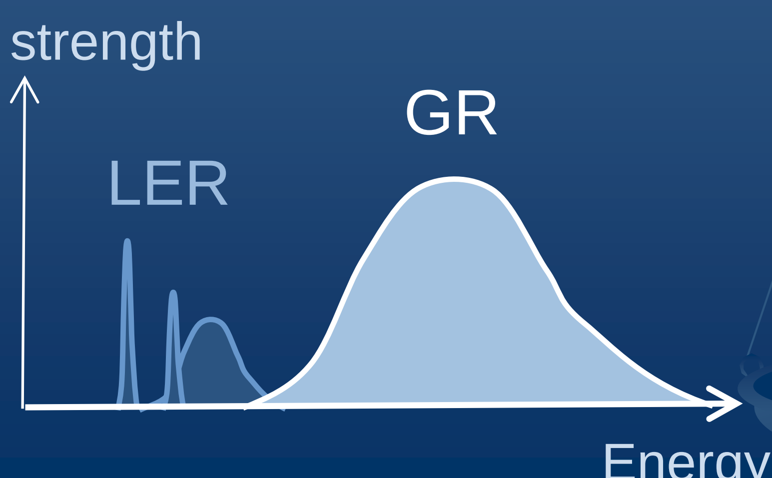
$$\sum_i r_i^3 Y_{1\mu}(\hat{\mathbf{r}}_i)$$

ISGDR



compressive ⇔

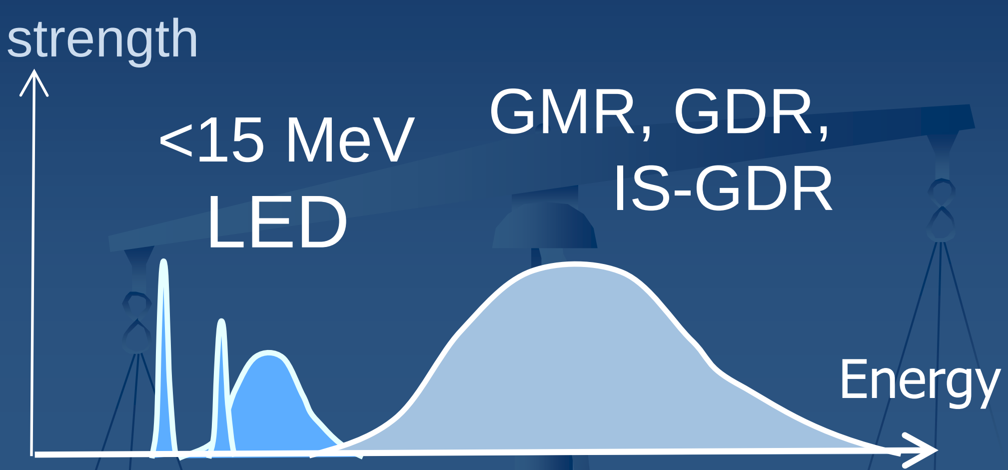
Response to external perturbation



- GR: broad bump in HE region
  ISM:10-20 MeV, IVGDR:10-30MeV
- Collective oscillation of system
  coherent 1p-1h excitation
- Physical aspects:matter properties
  ISGMR: Incomressibility,
  IVGDR:Symmetry energy

LED v.s. GDR

Low-energy (<15 MeV) strengths below GRs observed



80's: ISM, ISD, IVD(E1) in stable nuclei

90's: IVD(E1) in neutron-rich nuclei

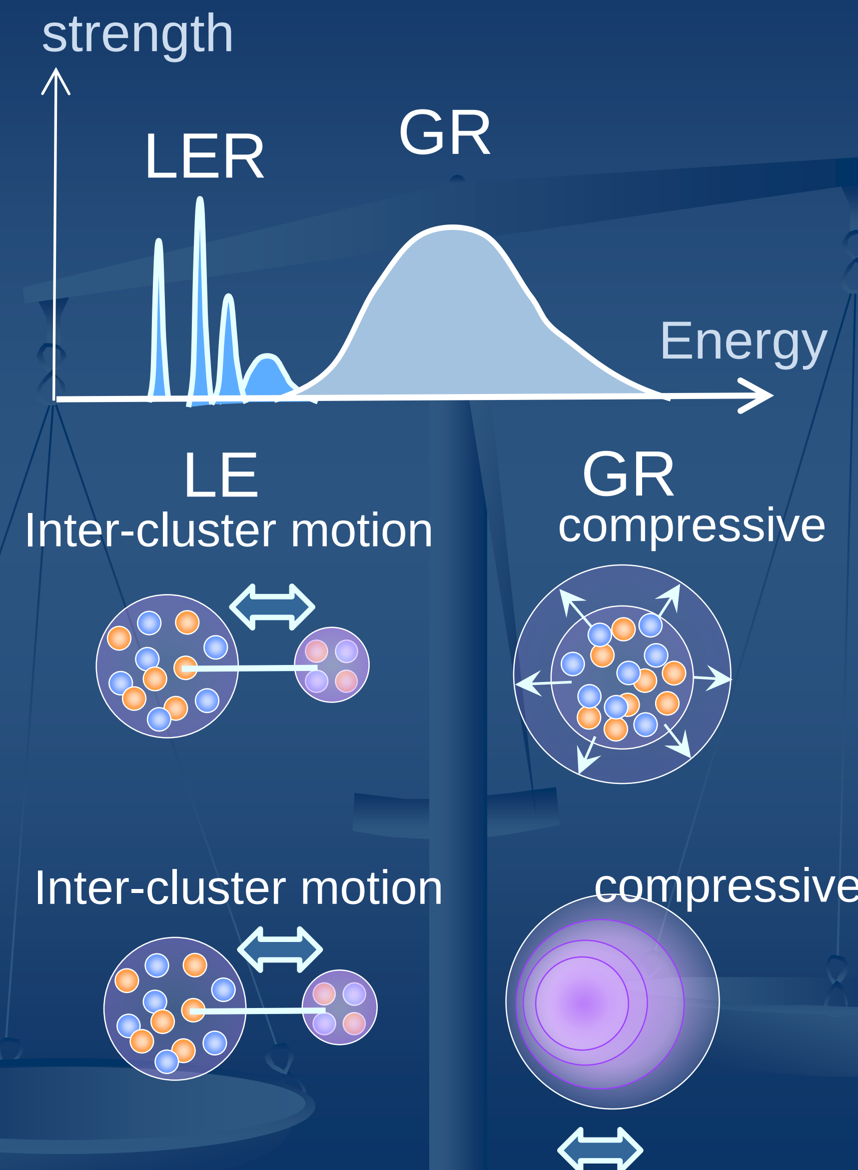
Separation of LE strengths from GRs

⇨ New excitation modes decoupled from GRs.

Origins of LE strengths have not clarified yet.
Various origins?

LE-ISM, LE-ISD for cluster states

Yamada et al. PRC**85**, 034315 (2012)
Chiba et al. PRC93 (2016) no.3, 034319



Isoscalar monopole (IS0):

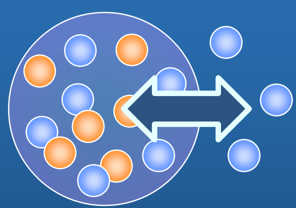
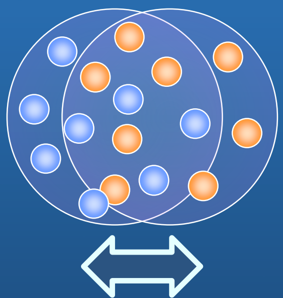
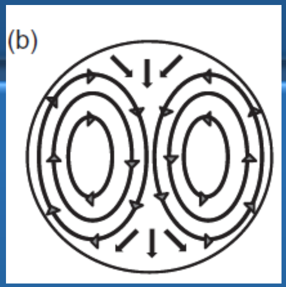
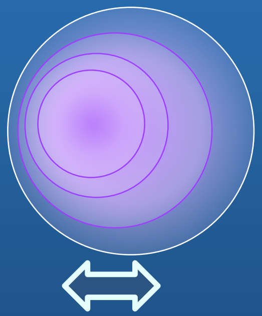
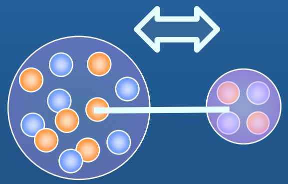
$$M(IS0) = \sum_i \boxed{r_i^2} Y_{00}(\hat{\mathbf{r}}_i)\sqrt{4\pi}$$

sensitive to radial motion

Isoscalar dipole (ISD=CD):

$$M(ISD;\mu) = \sum_i \boxed{r_i^3} Y_{1\mu}(\hat{\mathbf{r}}_i)$$

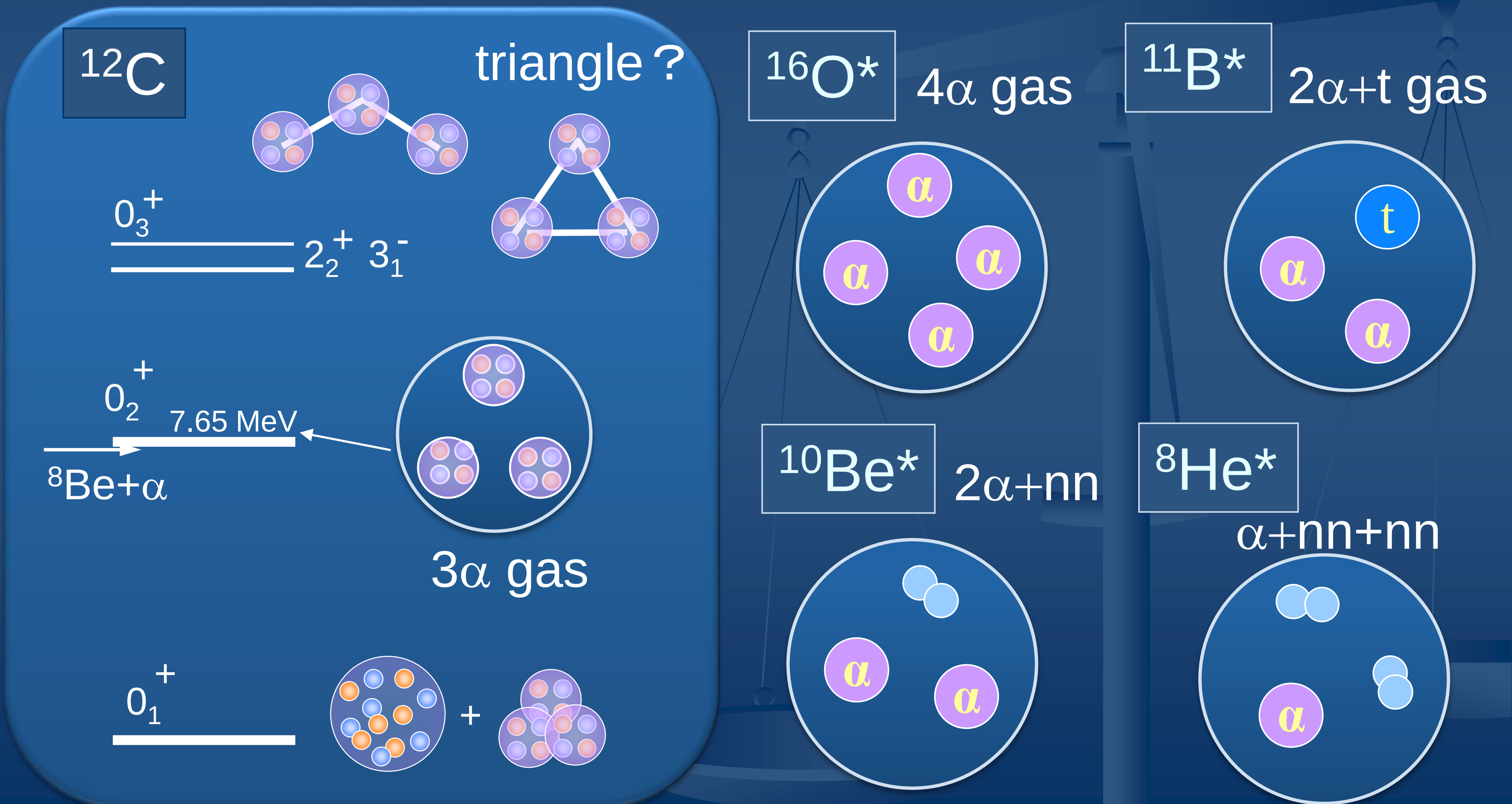
What are natures of LED?

	LED		HED	
IVD (E1)		Neutron skin only in N>Z nuclei not in N=Z nuclei	IVGDR	
ISD		Toroidal	ISGDR	
		Cluster		

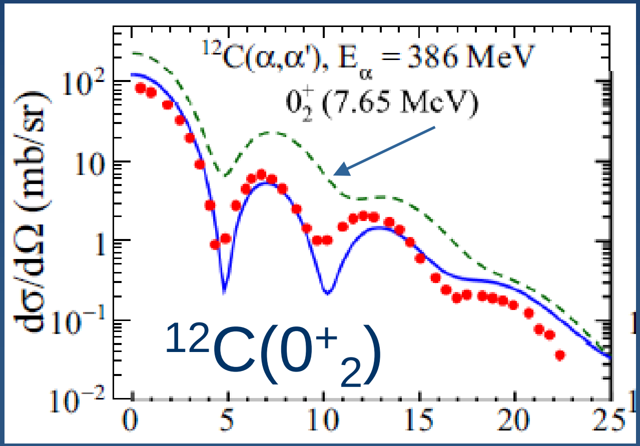
Maybe, not a single but various modes contribute to the LE strengths.

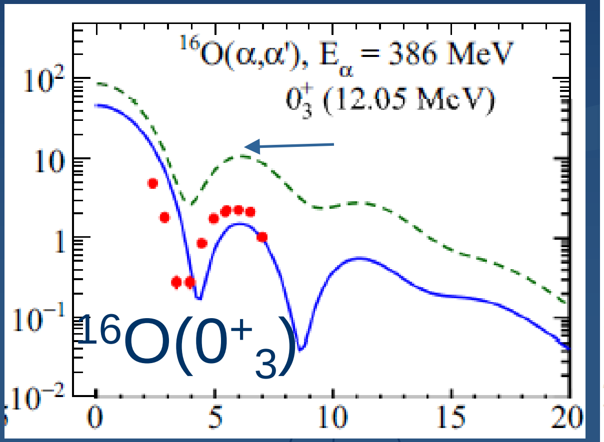
multi-cluster gas: 3-,4-body efimov states ?

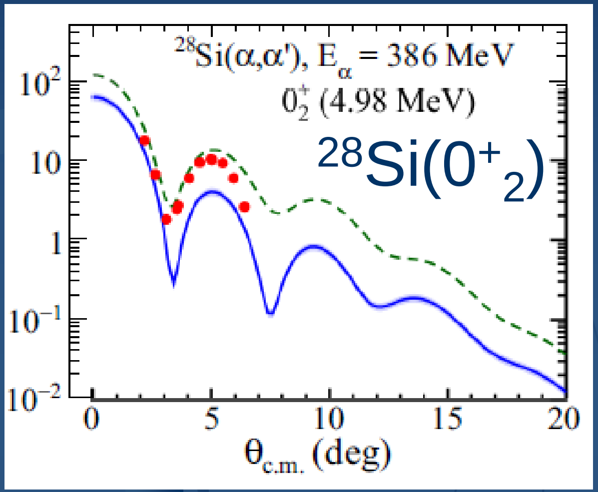
strong ISM(E0) transitions
probed by (α,α') scattering



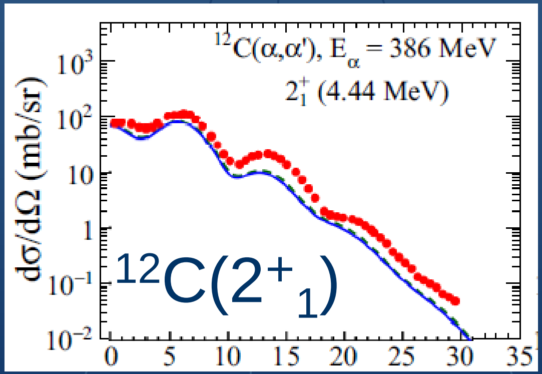
A puzzle: missing monopole strengths

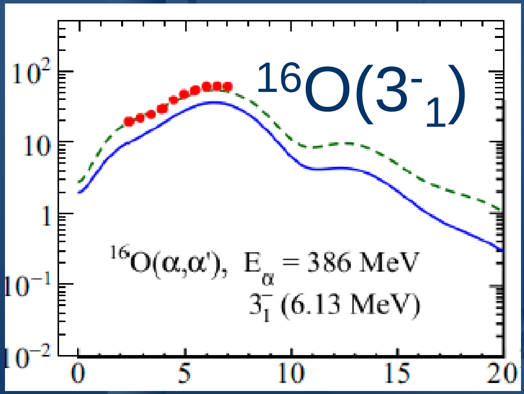






traditional reaction model
no problem in 2+, 3-,
but overshoot
0+ cross section
by a factor of 3-5

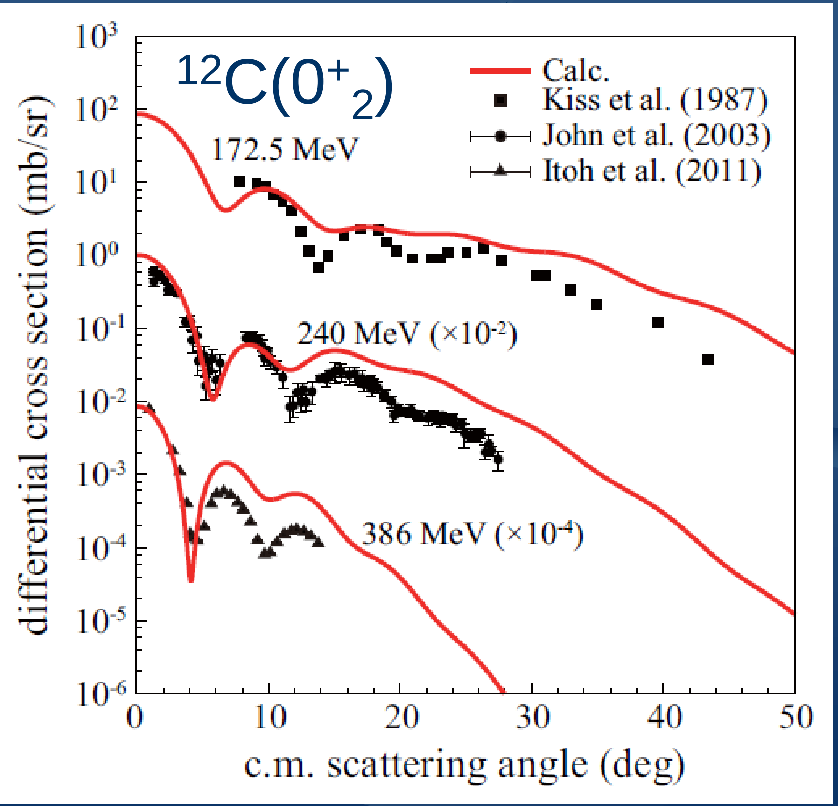




Adachi et al. PRC97,014601(2018)

microscopic reaction calculations with g-matrix folding model

- The puzzle is solved: no problem in 0+ cross sections *Minomo et al. C 93, 051601(R) (2016)*



Lesson 6. Advanced course analogy to other systems

What we learn and where we are going in this project?

discretized symmetry decoupling in SU(N)

without spatial correlation

- nucleon systems:

  BCS nn pairing, GT in pn pair
- quark hadron system:

  quarkyonic, heavy quark symmetry
- cold atom

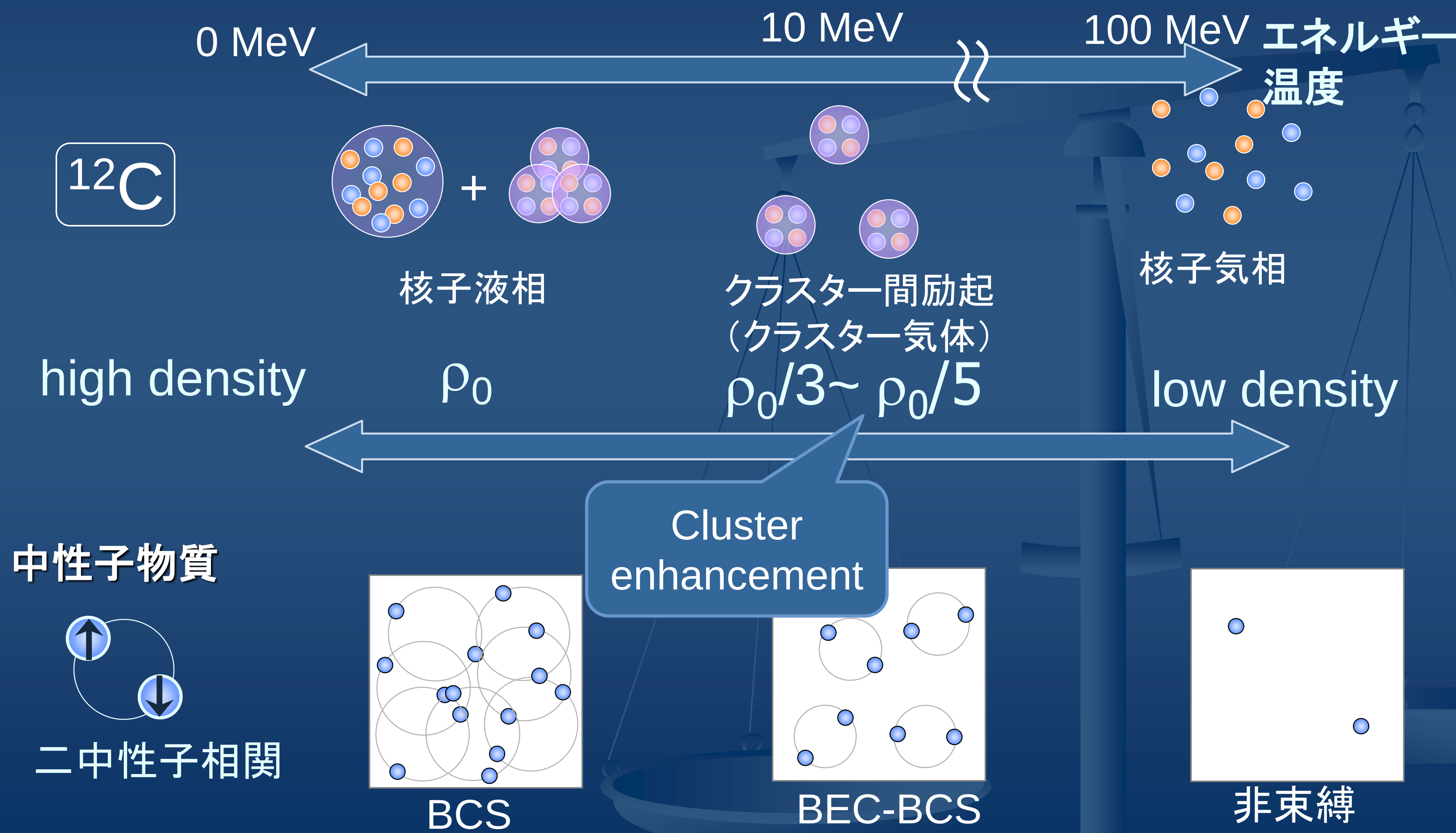
  BEC-BCS

symmetry breaking and restoration inhomogeneous matter

- discrete symmetry: multi-alpha systems
  triangle, tetrahedral, linear, planer
- symmetry in uniform matter: BEC-BCS
- symmetry in inhomogeneous matter
  - density wave in nuclei (cluster states)
  - pion condensation in nuclear matter
  - chiral DW(spiral) in quark matter
  - LOFF states ...

環境依存性：cluster enhancement

エネルギー、密度の関数



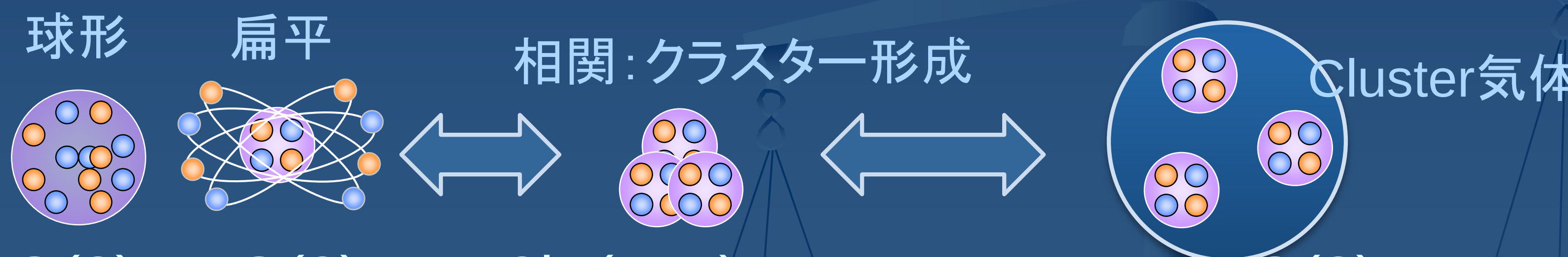
Matsuo et al. PRC73 044309 ('06)

階層化・対称性:breaking & restoration

Y. K-E., Hidaka
PRC84 (2011); PRC96 (2017)
with 日高

階層化=自由度(スケール)の分離:
クラスター相関(形成)と発達→対称性の破れと回復を誘発

二面性:微視的ダイナミクス(核子レベルからのクラスター形成)が本質!



相関なし O(3) → O(2) → D3h (DW) → 回転対称性回復 → O(3) 強相関

回転対称 破れ 回転対称性回復

並進対称 破れ 並進対称性回復

非一様密度
Density wave(DW)
or BCS?

対称
核物質

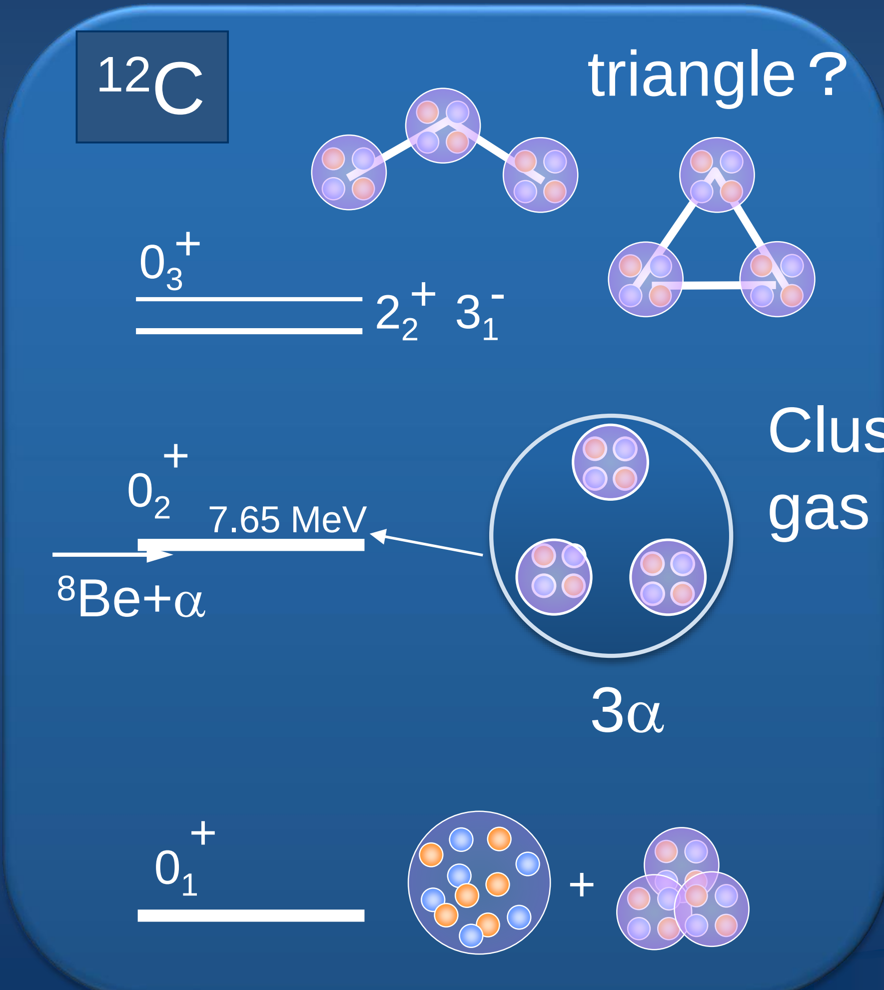
Fermi gas

BEC: strong corr.

k=0

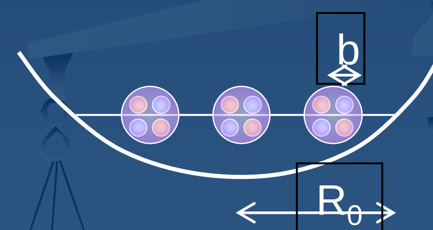
Infinite matter

α condensation v.s. microscopic superfluidity

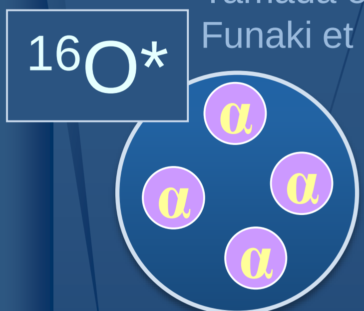


Cluster (boson) gas

Y. K-E PRC96 (2017)
Y. K-E. PRC89 (2014)



Yamada et al., Funaki et al



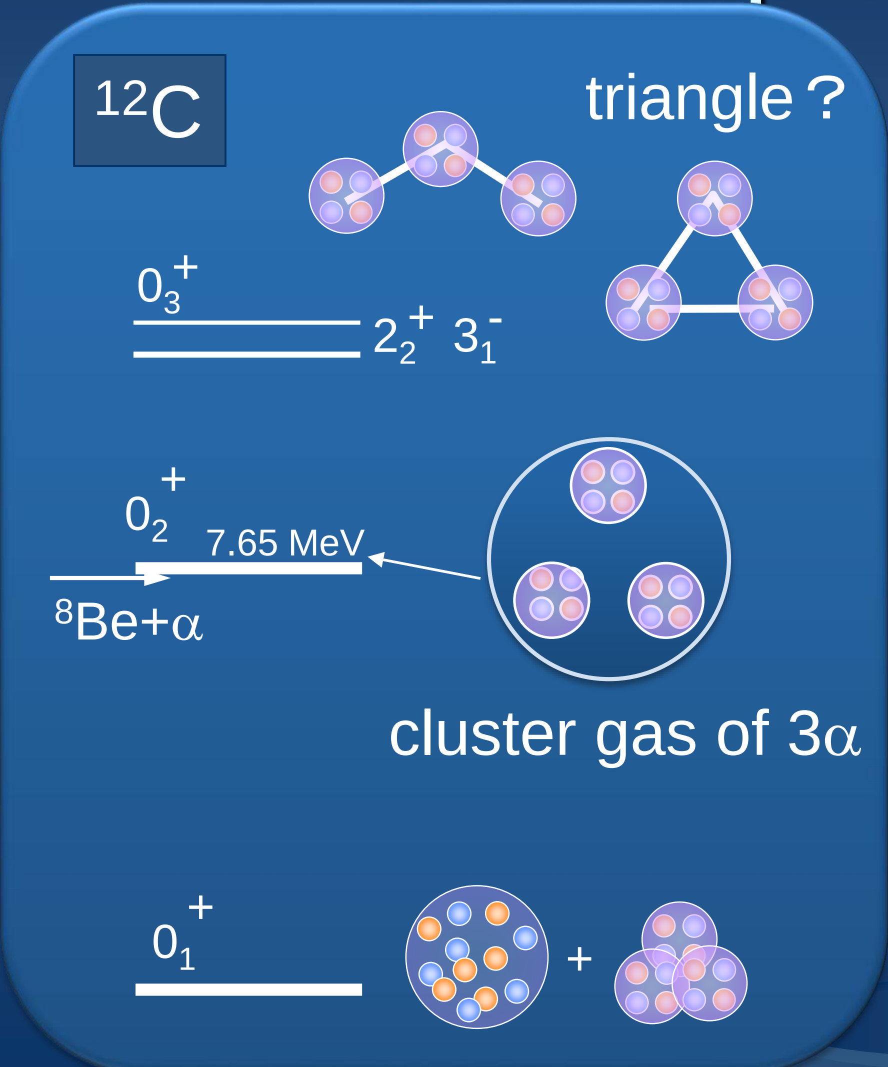
4α gas

te

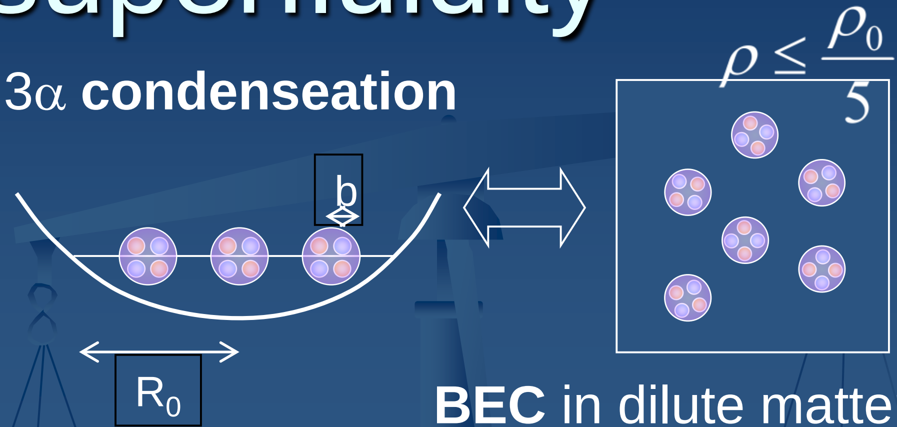
microscopic superfluidity?

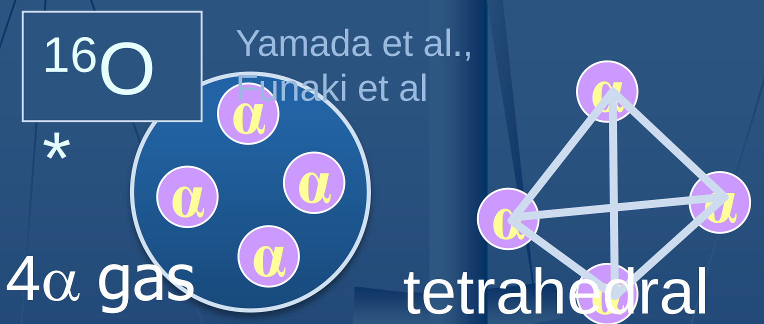
cf. Momose’s lecture

α condensation v.s. microscopic superfluidity



3α **condenseation**





microscopic superfluidity?

cf. Momose's lecture

H_2 in He liquid

cluster gas, halo v.s. Efimov states

To be Efimov or not?

- 2n-halo: Borromean
- Hoyle states (3a gas) in 12C*

What is efimov?

- universality of weakly-bound 3-body systems
- independent from interactions

Naidon&Endo's : Not Efimov

Wiki, Suno et al. : Yes an efimov analogue