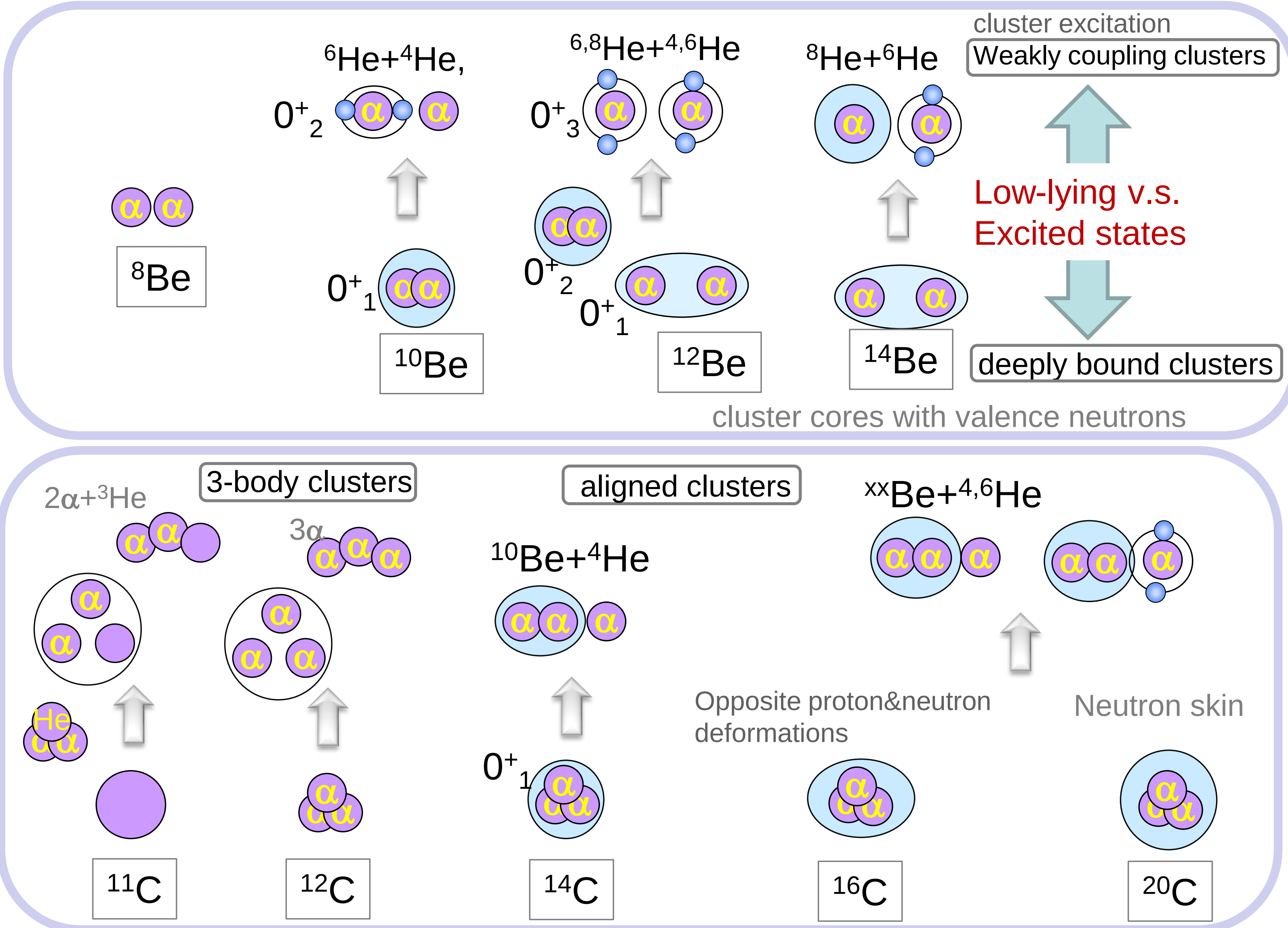
Monopole and dipole transitions in ^{12}C and ^{9,10}Be

Y. Kanada-En'yo (Kyoto)

1. **Introduction**
2. **AMD & shifted basis AMD** Y. K-E. PRC89, 024302 (2014)
3. **ISM & ISD excitations** Y. K-E. PRC93 054307 (2016) Y. K-E. PRC94 024326 (2016)
4. **IVD(E1) & ISD in ^{9,10}Be** Y. K-E. PRC93, 024322 (2016)
5. **Summary**

1. Introduction

Two kinds of clustering: g.s. and excited states

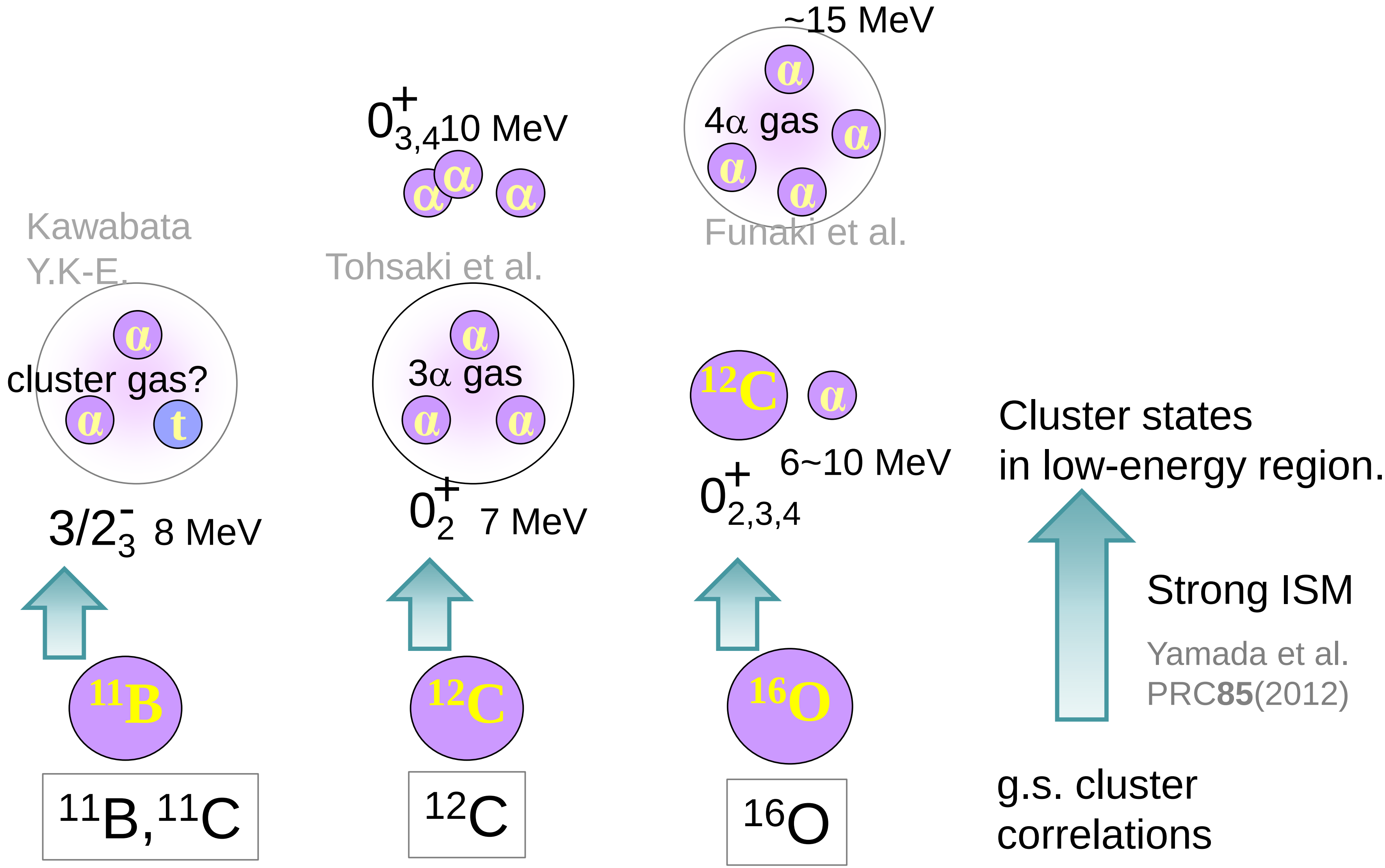


How to experimentally probe clustering

- **Clustering in g.s.**
  - Deformation Q, B(E2)
  - Charge radii isotope shift, charge changing reactions
  - α-transfer, α knock-out ?
- **Clustering in excited states**
  - α-decay width, α-transfer
  - monopole & dipole excitations (inelastic reactions)

Today's talk: ISM and ISD in 12C
E1 and ISD in neutron-rich Be

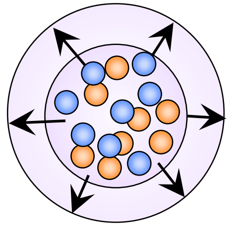
Cluster states in Ex<~15 MeV



Low-energy ISM transition can be a good probe for cluster states!

Isoscalar monopole (IS0) excitations

$$O = \sum_{1}^{A} \left(\mathbf{r}_i - \mathbf{R}_G\right)^2$$



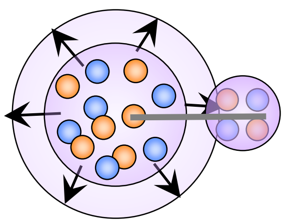
GMR

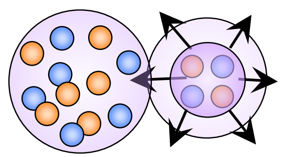
coherent sum of single-particle strengths

Yamada et al. PRC**85**, 034315 (2012)

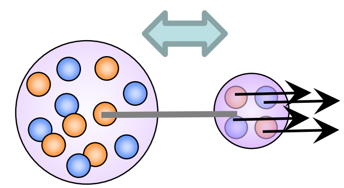
$$= \sum_{i \in C_1} \left(\mathbf{r}_i - \mathbf{R}_{C1}\right)^2 + \sum_{i \in C_1} \left(\mathbf{r}_i - \mathbf{R}_{C2}\right)^2 + \frac{A_1 A_2}{A} \left(\mathbf{R}_{C1} - \mathbf{R}_{C2}\right)^2$$

Internal ISM excitations in clusters





Inter-cluster excitation (relative motion)



coherent sum of 1p strengths from four nucleons

Isoscalar monopole (IS0) strengths in ^{16}O

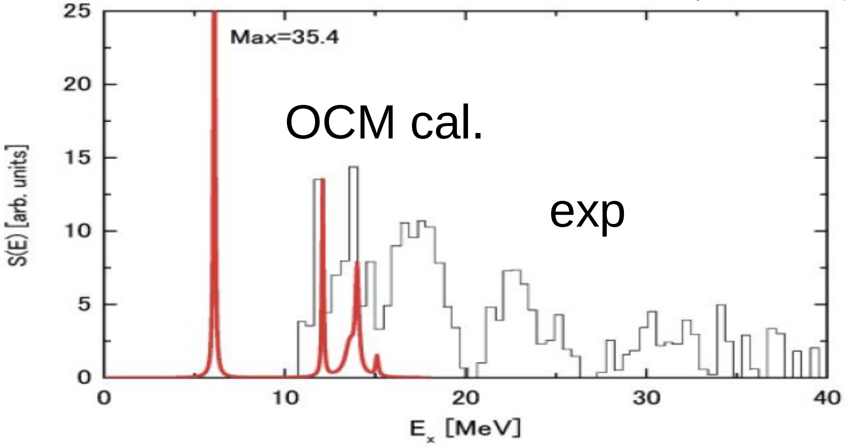
Strong ISM for cluster states

ISM operator excites inter-cluster motion

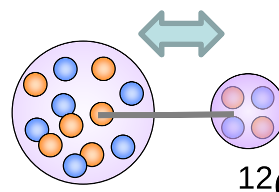
> Cluster mode decouples from collective vibration mode.
> GR feeds low-energy strengths.

4-alpha OCM: Yamada et al. PRC**85**, 034315 (2012)

exp:Y.-W. Lui, et al. PRC**64**,064308 (2001).



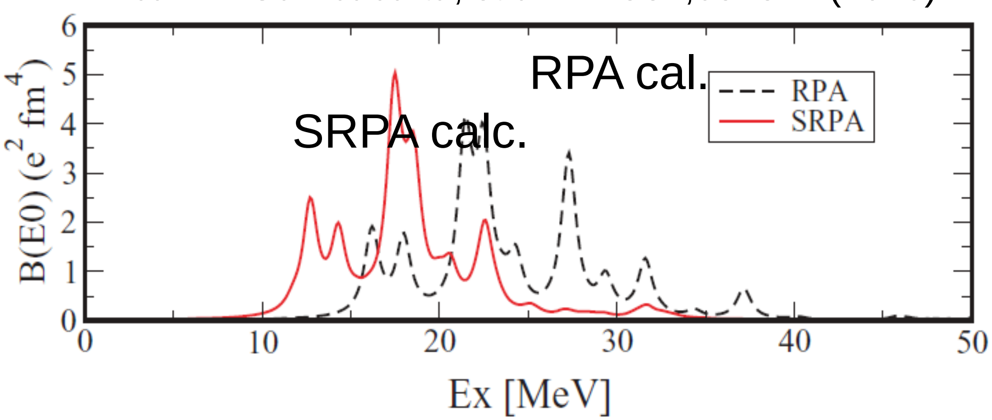
- Low-lying IS0 strengths



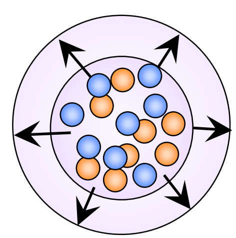
Cluster mode

^{12}C-α radial motion

PRA cal. D. Gambacurta, et al. PRC81,054312 (2010).



- High-lying IS0 (GMR): Collective vibration coherent 1p-1h motion



Breathing mode

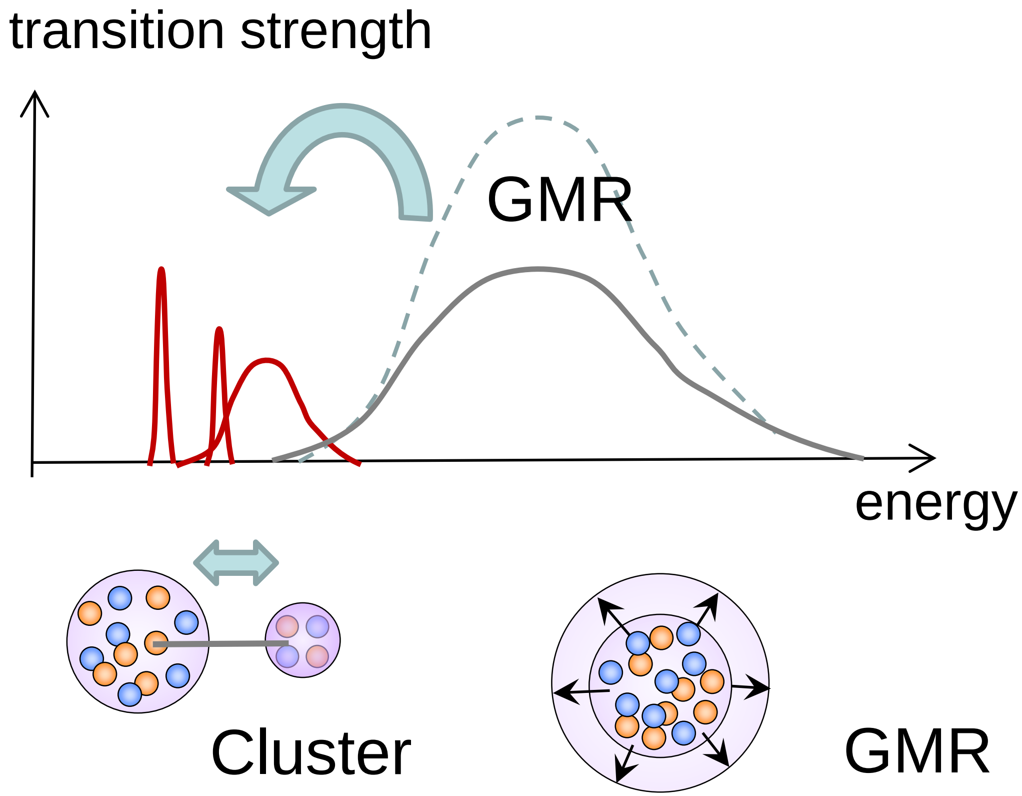
LE strengths decoupling from GR＝Decoupling of Scale

The universal feature

Decoupling of scale（DOF)

⇩

New excitation modes



If cluster modes appear in a low-energy region,
low-energy monopole strengths appear separately from the GMR strengths.

➢ Separation of LE-ISM mode from the GMR mode.

Decoupling of scales(DOFs) between cluster and collective vibration modes.

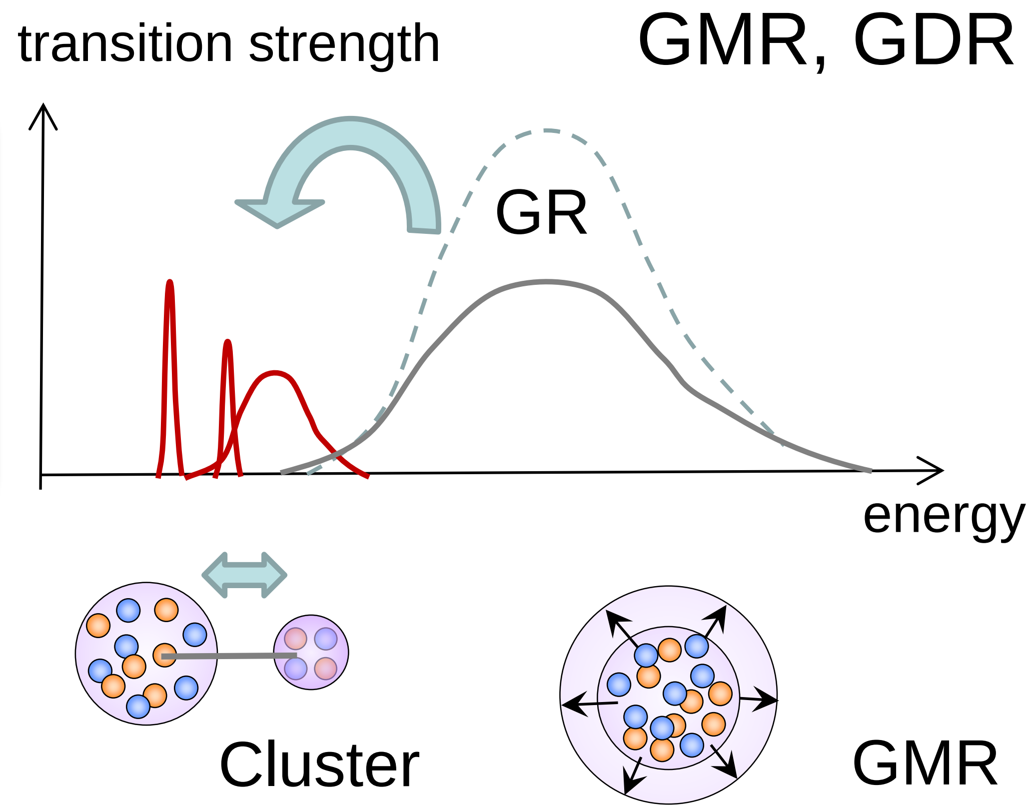
LE strengths decoupling from GR＝Decoupling of Scale

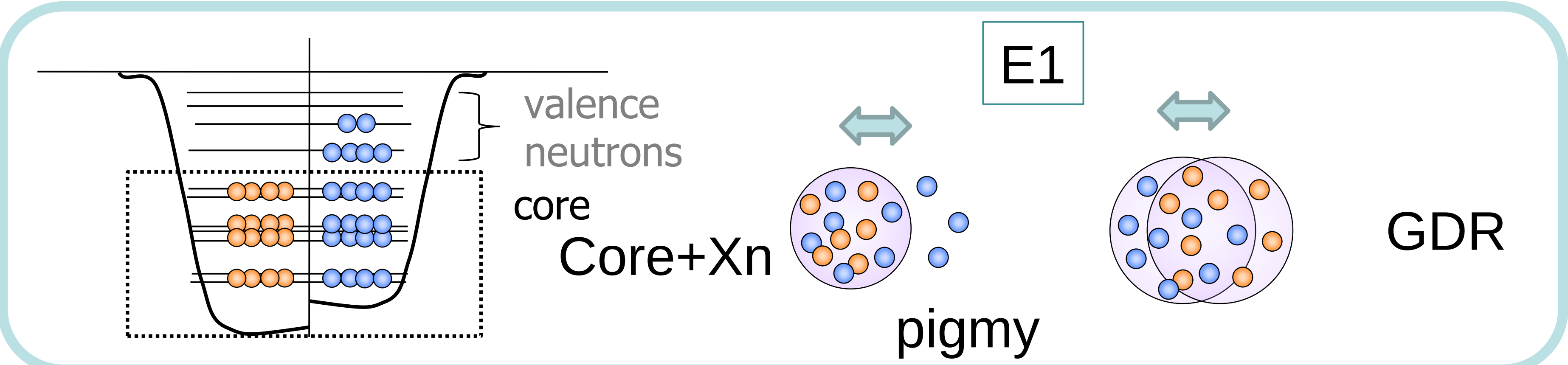
The universal feature

Decoupling of scale（DOF)

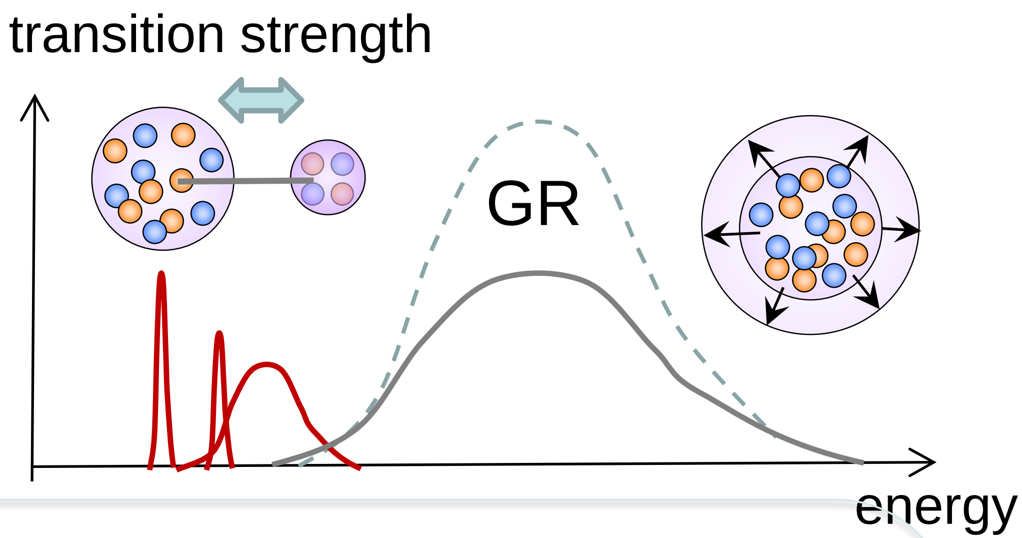
⇩

New excitation modes





Problems to be solved: LE strengths v.s. GR



- Do LE strengths appear separating from the GR strengths.
- If so, what is the origin of the LE modes.
- Can isoscalar monopole and Isoscalar dipole strengths be good probes to search for LE cluster modes?
- What monopole and dipole tras. tell us about cluster structure?

We need a theoretical framework which describes coherent 1p1h excitations in the GRs and the LE (cluster) modes.

Present method: shifted AMD+cluster GCM

small amp. (1p1h) large amp. cluster mode

Y. K-E, Phys.Rev. C89 (2014) , Y. Chiba et al., arXiv:1512.08214(2015)

2.Formulatoion of sAMD

Shifted basis AMD

AMD method for structure study

AMD wave fn.

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

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

Gaussian

spatial

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

isospin

Intrinsic spins

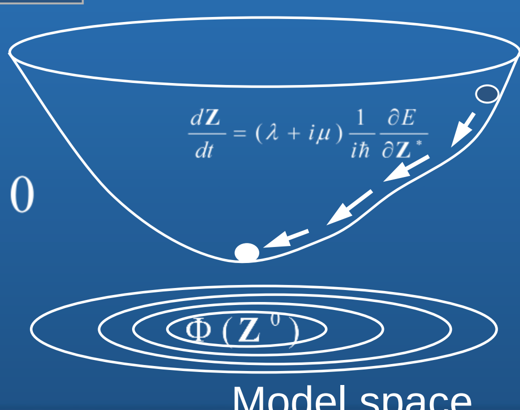
$$\Phi_{\mathrm{AMD}}(\mathbf{Z})$$

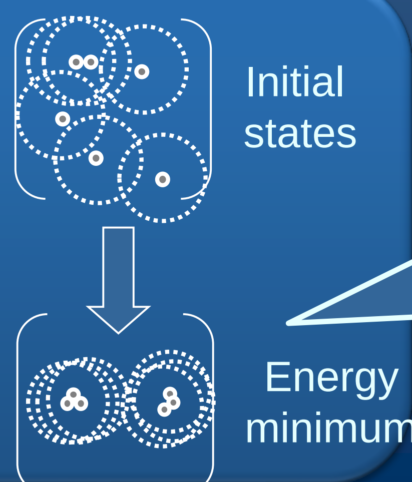
$$\mathbf{Z} = \{\mathbf{Z}_1, \mathbf{Z}_2, \cdots, \mathbf{Z}_A, \xi_1, \cdots, \xi_A\}$$

Variational parameters:
Gauss centers, spin orientations

Energy Variation

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





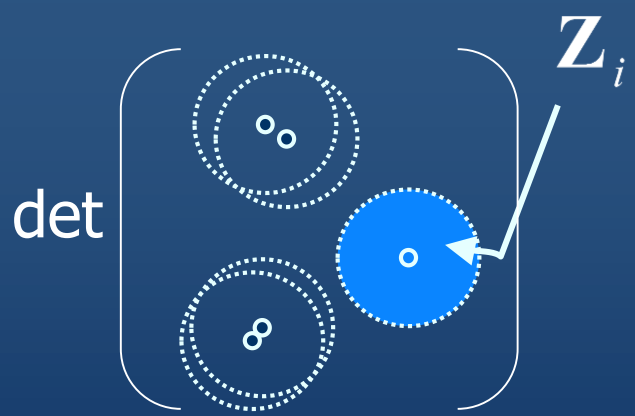
Variation after spin-parity projection(VAP) to get the ground state wave function.

Shifted basis AMD(sAMD)

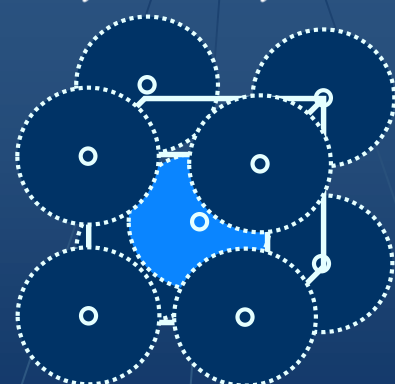
$$\Phi = \det\left\{\varphi_1, \varphi_2, \cdots, \varphi_A\right\}$$ Ground st. wave functions

$$\varphi_i + \delta\varphi_i = \phi_{\mathbf{Z_i}+\delta\mathbf{Z_i}}\chi_\mathbf{i}$$ small shift of spatial part

$$\det\left\{\varphi_1, \cdots, \varphi_i + \delta\varphi_i, \cdots, \varphi_A\right\}$$ A shifted basis



$$\mathbf{Z}_i \rightarrow \mathbf{Z}_i + \delta\mathbf{Z}_i$$

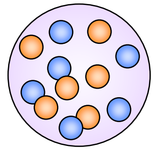
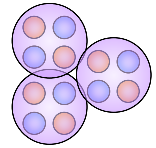


Small shift for 8 orientations

8A basis is enough for IS0,E1,ISD in 12C and Be

sAMD+3αGCM for ^{12}C

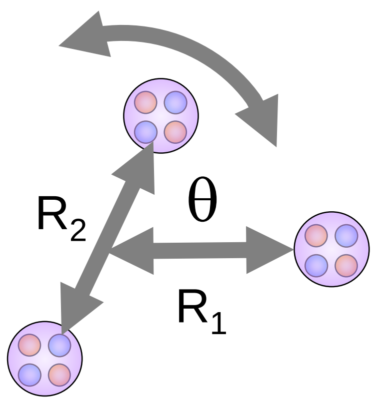
VAP

^{12}C(g.s.)=  +  ⇒ g.s. cluster correlation

sAMD

1p1h excitations on g.s. 8A basis ⇒ GMR

GCM(3α): various 3α configurations



$^{12}C^*(0^+_2, 0^+_3)$ ⇒ Cluster excitation LE modes

All basis wave functions are superposed: ^{12}C(sAMD)+GCM(3α)

Jπ-projection and c.m.m. are taken into account microscopically.

Monopole and dipole excitations

Isoscalar monopole (IS0):

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

Breathing mode
coupling with radial excitation
and cluster mode

0^+ excitations

Isovector dipole (E1):

$$M(E1;\mu) = \sum_{i=proton} r_i Y_{1\mu}(\hat{\mathbf{r}}_i)$$

Translational mode

1^- excitations

Isoscalar dipole (ISD):

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

Compressive dipole mode
coupling with radial excitation
and cluster mode

1^- excitations

3. Results

1. ^{12}C: sAMD+ GCM(3α) for B(ISM) & B(ISD)

2. $^{9,10}Be$:sAMD+GCM($^{5,6}He$+α) for B(E1) & B(ISD)

Phenomenological effective force :

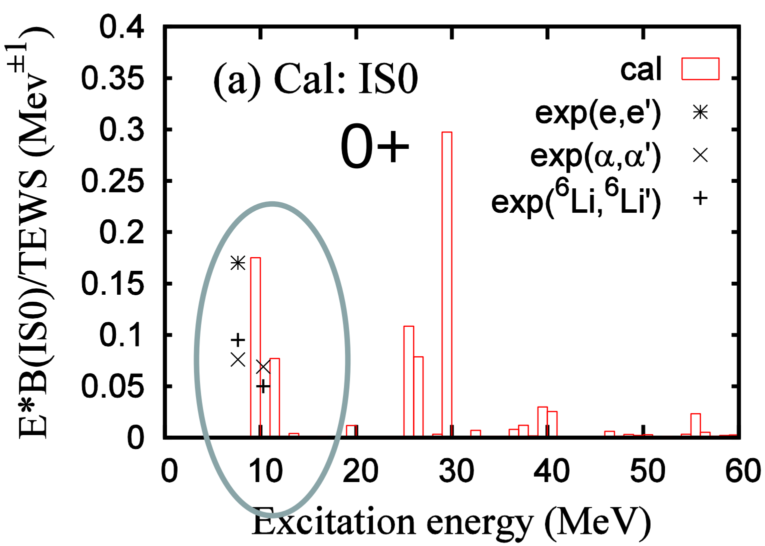
finite-range 2-body & zero-range 3-body

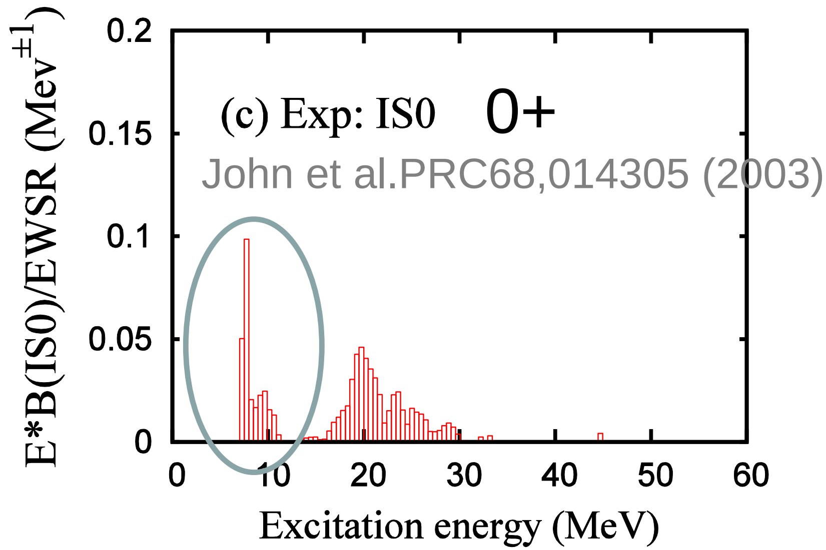
Central (MV1 force)+ Spin-orbit(G3RS force)+Coulomb

3. B(IS0) & B(ISD) in ^{12}C

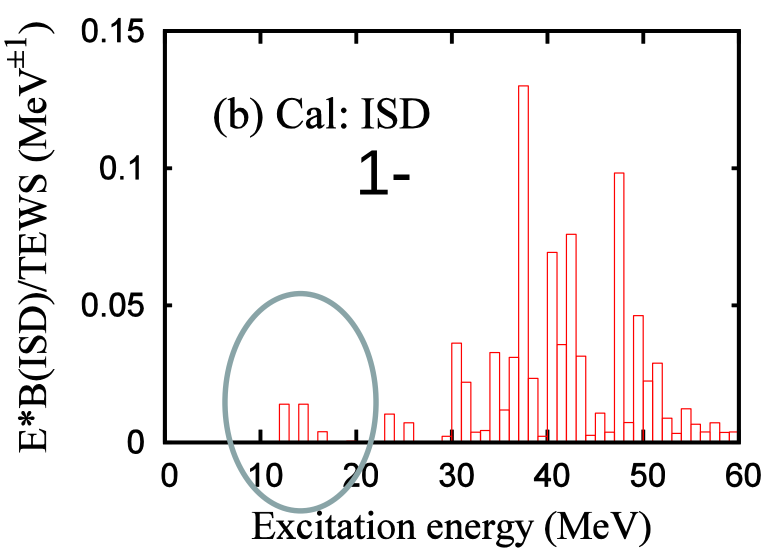
^{12}C(sAMD)+GCM(3α)

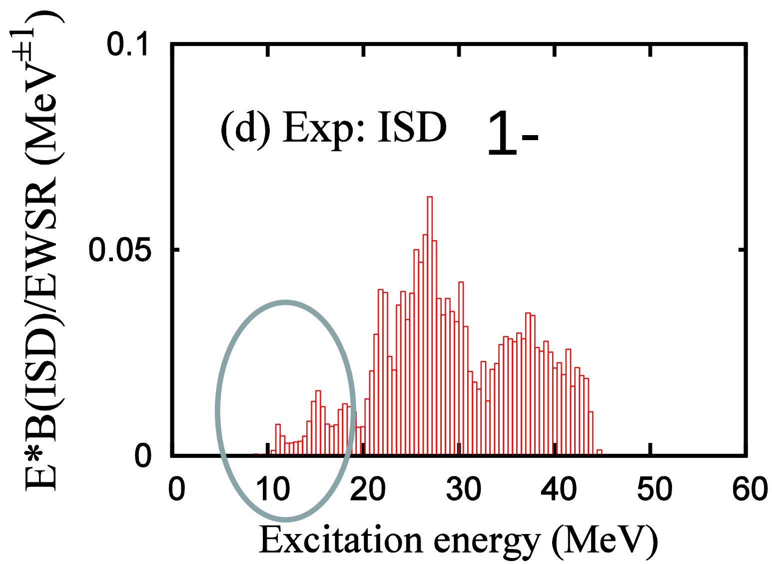
ISM and ISD strengths in 12C: sAMD+GCM(3α)





Low-energy strengths for cluster states separately from GRs.
Why the LE strengths are fragmented into a few cluster states?

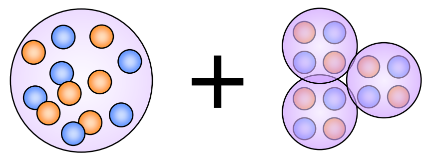




Mode analysis: sAMD+αGCM for ^{12}C

^{12}C(sAMD)+GCM(3α)

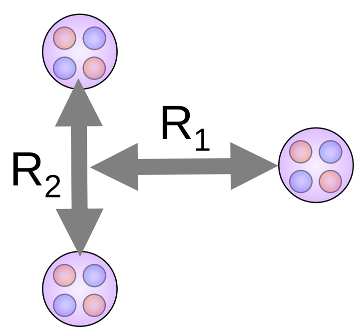
^{12}C(g.s.)=

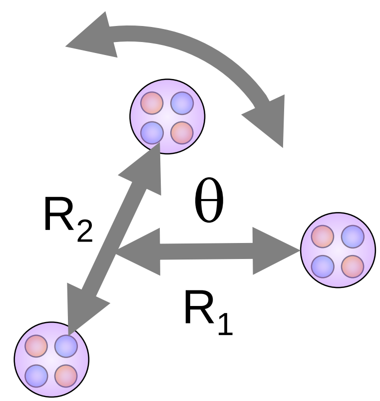


VAP result contains
the g.s. cluster correlation

^{12}C(sAMD): 1p1h excitations on g.s.

GCM(3α)





(A) Distance mode

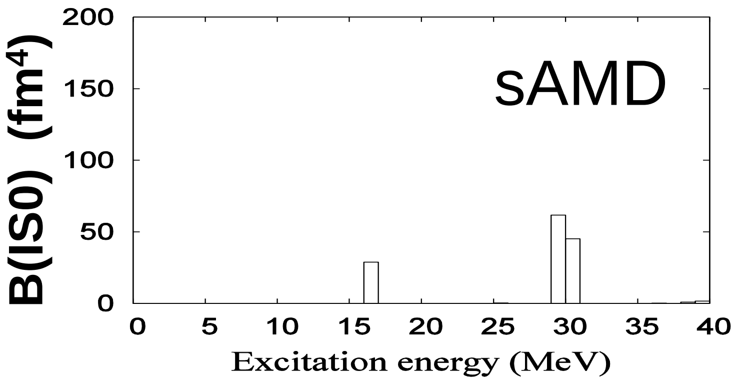
(B) Distance & rotation mode

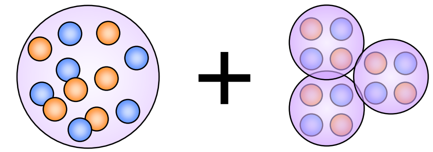
Significant to $^{12}C(0^+_2)$

Significant to $^{12}C(0^+_3)$

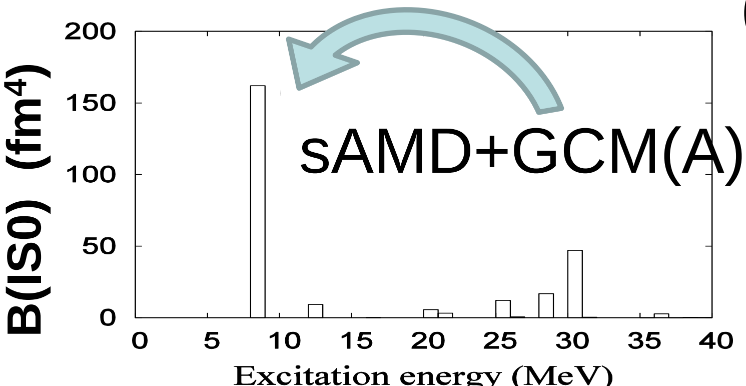
Details of 3α mode are investigated by Y. Yoshida.

B(ISM) of ^{12}C

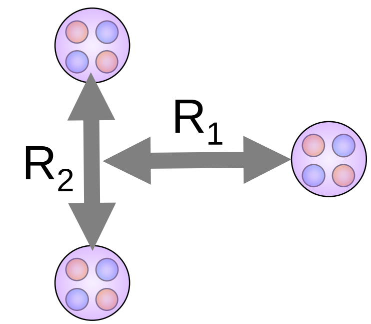




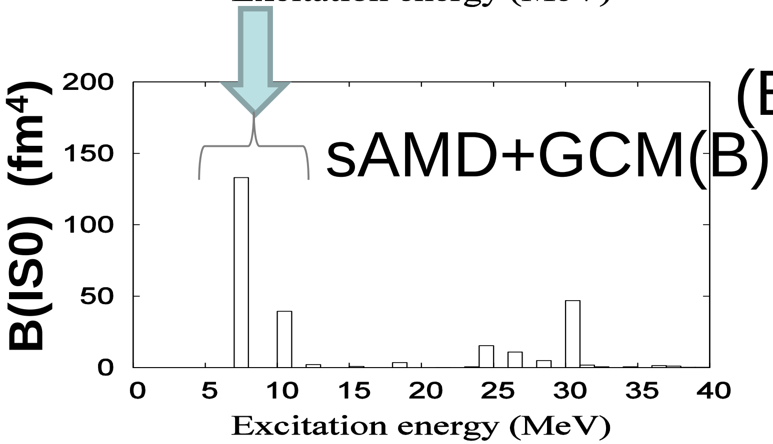
sAMD: small amplitudes single-particle motion -> GMR



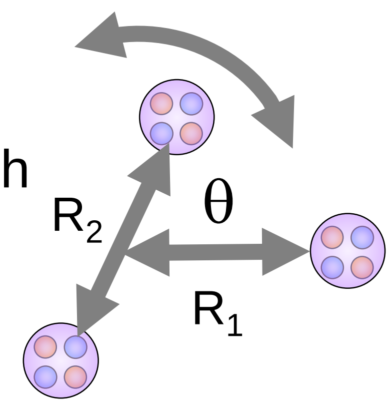
(A) 3α: distance mode



Large amplitude cluster mode -> LE-IMS strength



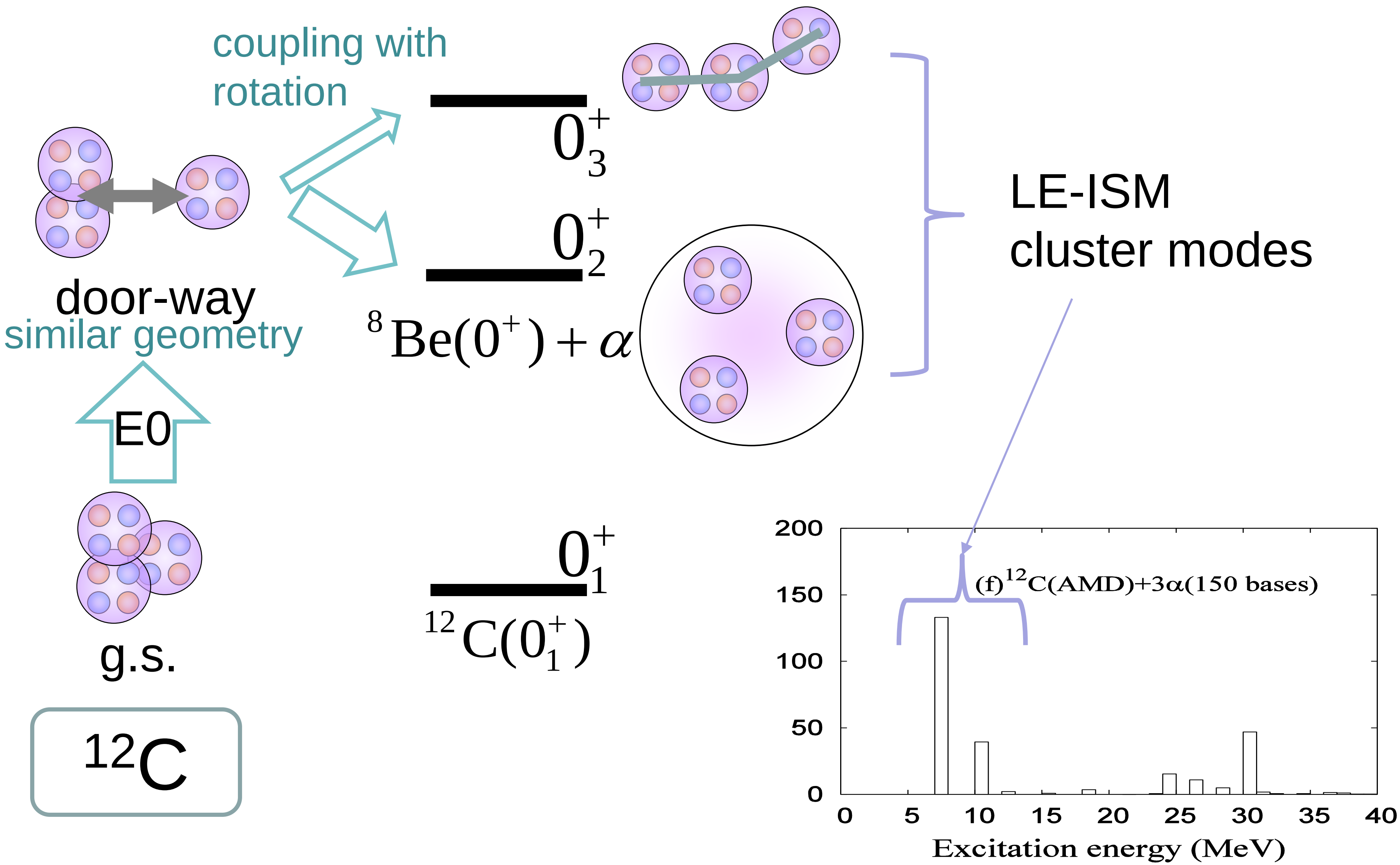
(B) 3α: rotation mode



Coupling of 8Be rotation with distance mode

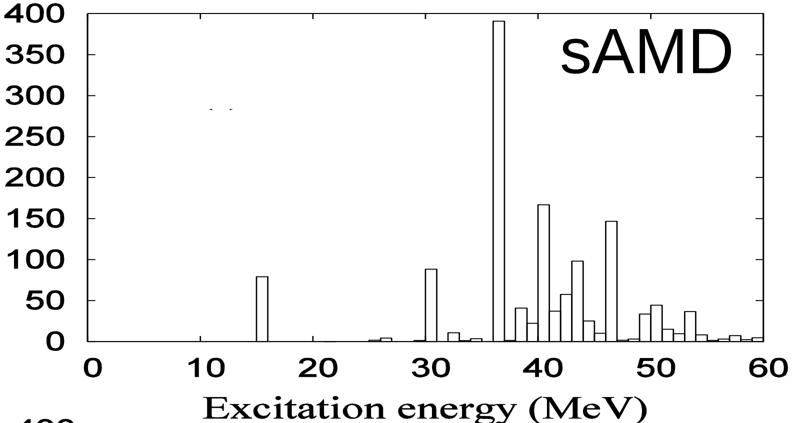
plit LE-ISM

B(ISM) of 12C

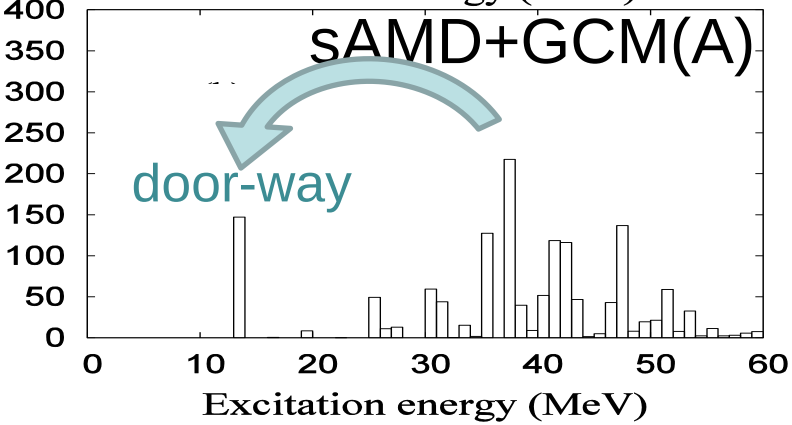


coupling with
rotation
0_3^+
0_2^+
door-way
similar geometry
$^8Be(0^+) + \alpha$
LE-ISM
cluster modes
E0
0_1^+
$^{12}C(0_1^+)$
g.s.
^{12}C
(f)^{12}C(AMD)+3α(150 bases)
200
150
100
50
0
0
5
10
15
20
25
30
35
40
Excitation energy (MeV)

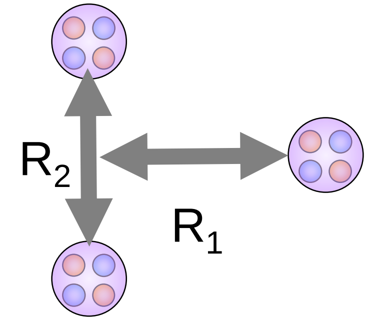
IS-Dipole: B(ISD) of ^{12}C



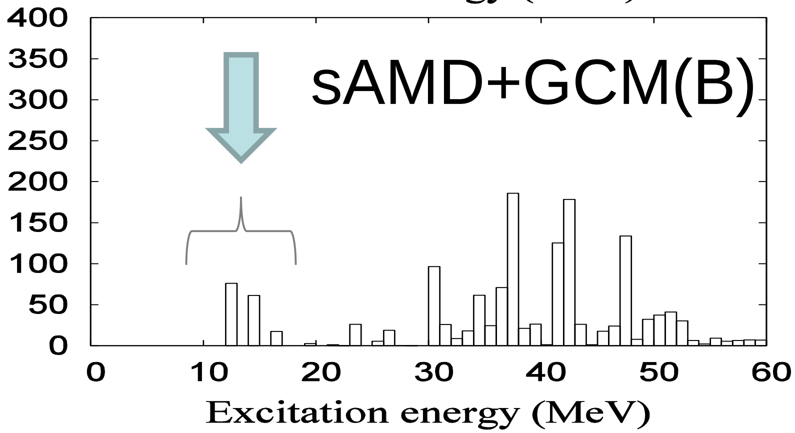
sAMD contains g.s. cluster corr.
LE cluster mode & GR



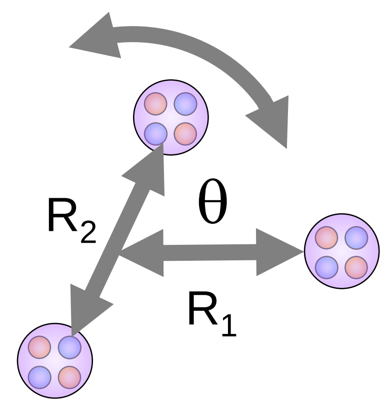
(A) 3α: distance mode



GR feeds
strength of LE cluster mode

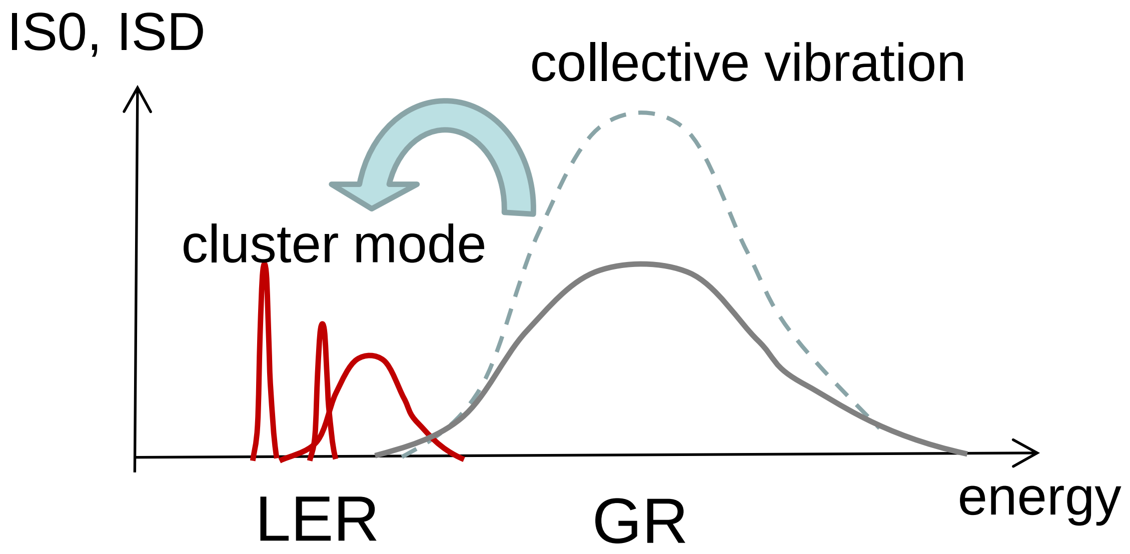


(B) 3α: rotation mode



Split ISD of
LE cluster mode

general trend of ISM and ISD



- ✓ LE strengths of cluster modes separated from the GR.
- ✓ GR feeds LE strengths
- ✓ LE strengths are fragmented into cluster states:
  coupling of inter-cluster motion and cluster rotation

3-2. B(ISM) in ^{10}Be

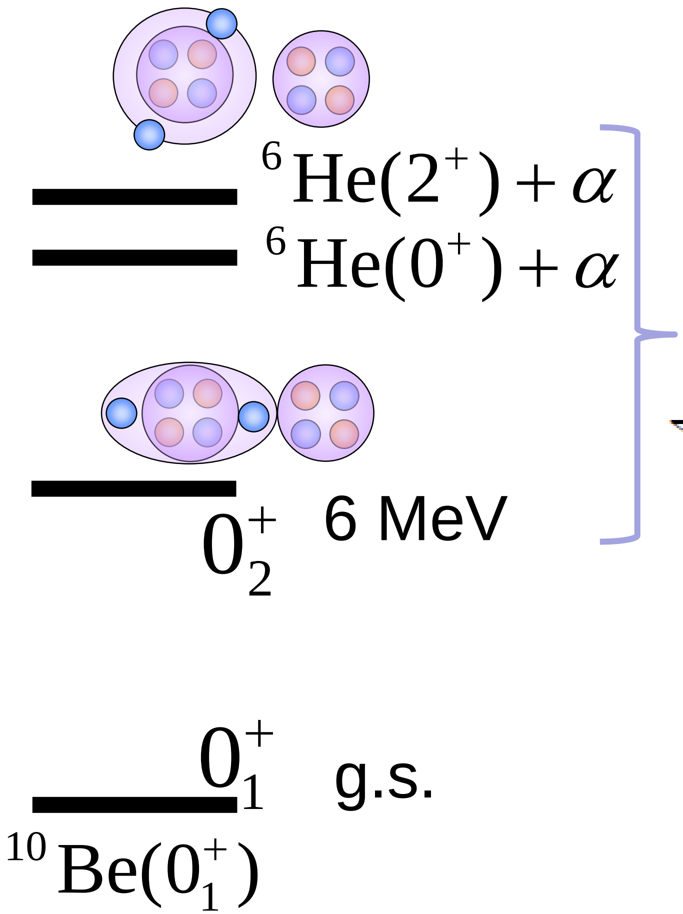
GCM($^{6}He+\alpha$) for B(ISM)

B(ISM) of 10Be

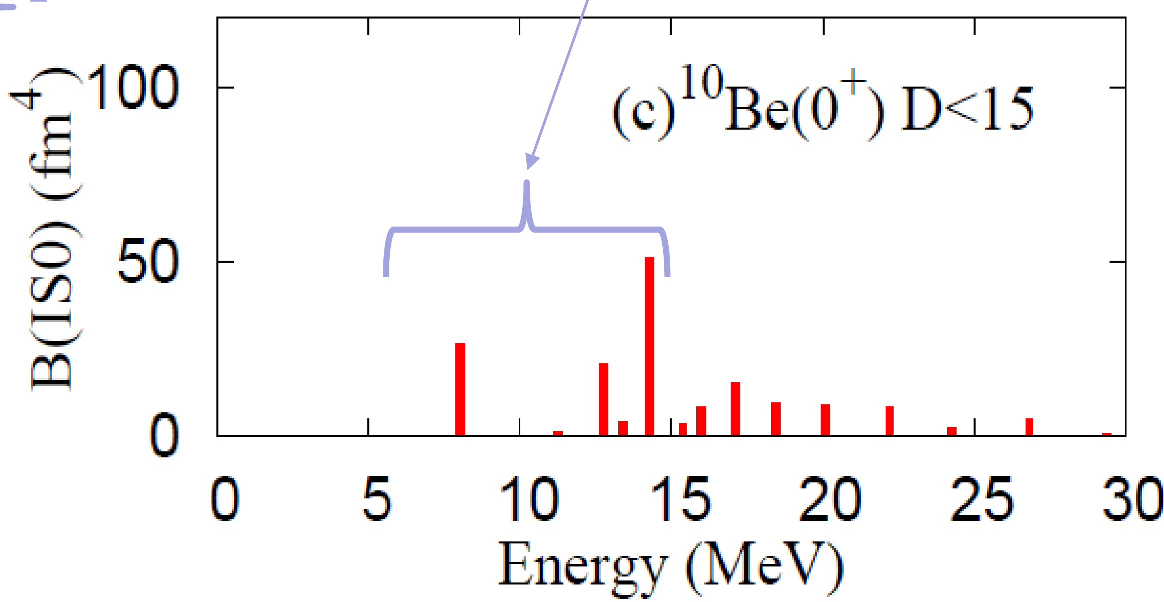
Y. K-E.,Phys.Rev. C94 (2016)

Also discussed by M.Ito, Rep. Prog. Phys. 77 (2014) 096301

^{10}Be



LE-ISM
cluster modes



4. B(E1)&B(ISD) in ^{9,10}Be

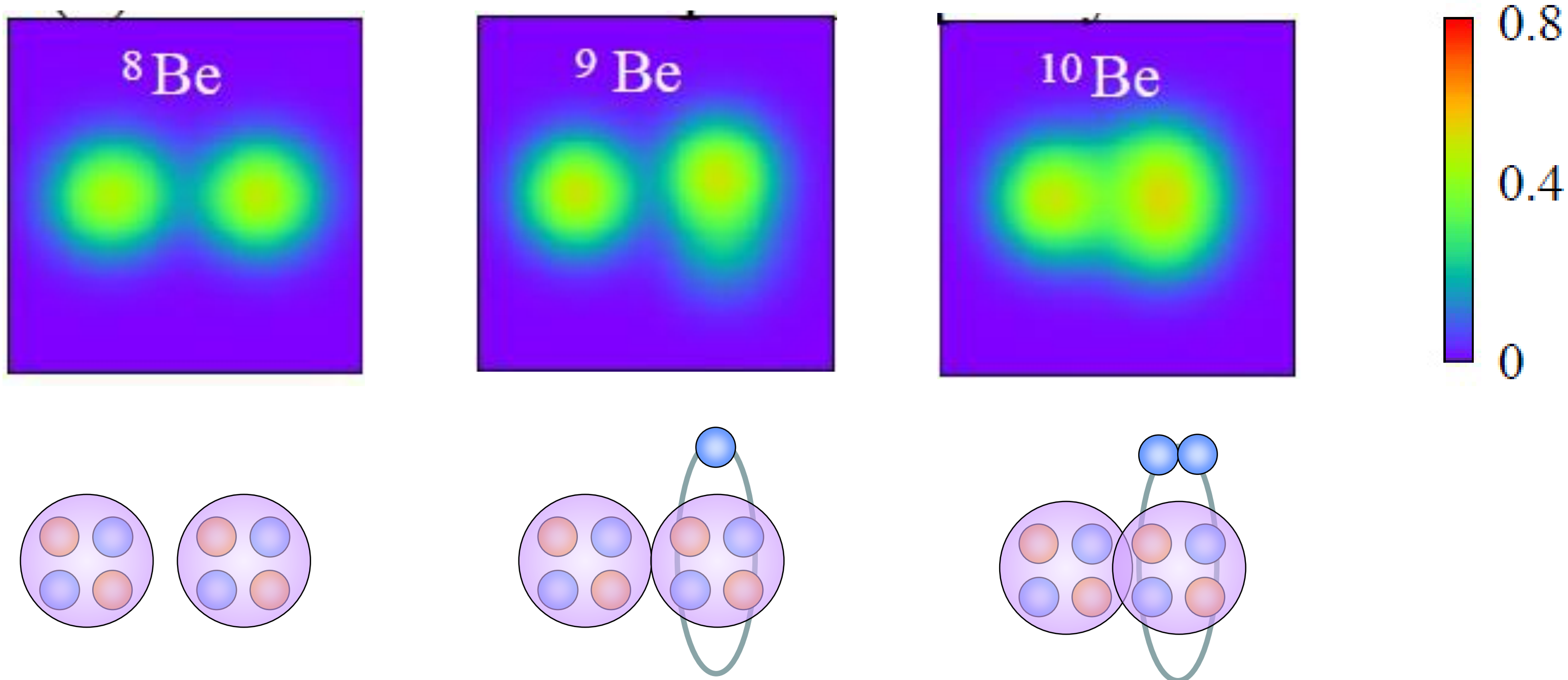
sAMD+αGCM

$rY_{1\mu}$ E1: translational mode

$r^3Y_{1\mu}$ ISD: compressive mode, radial excitation
sensitive to coupling with cluster mode

Cluster structures in ground states of Be isotopes

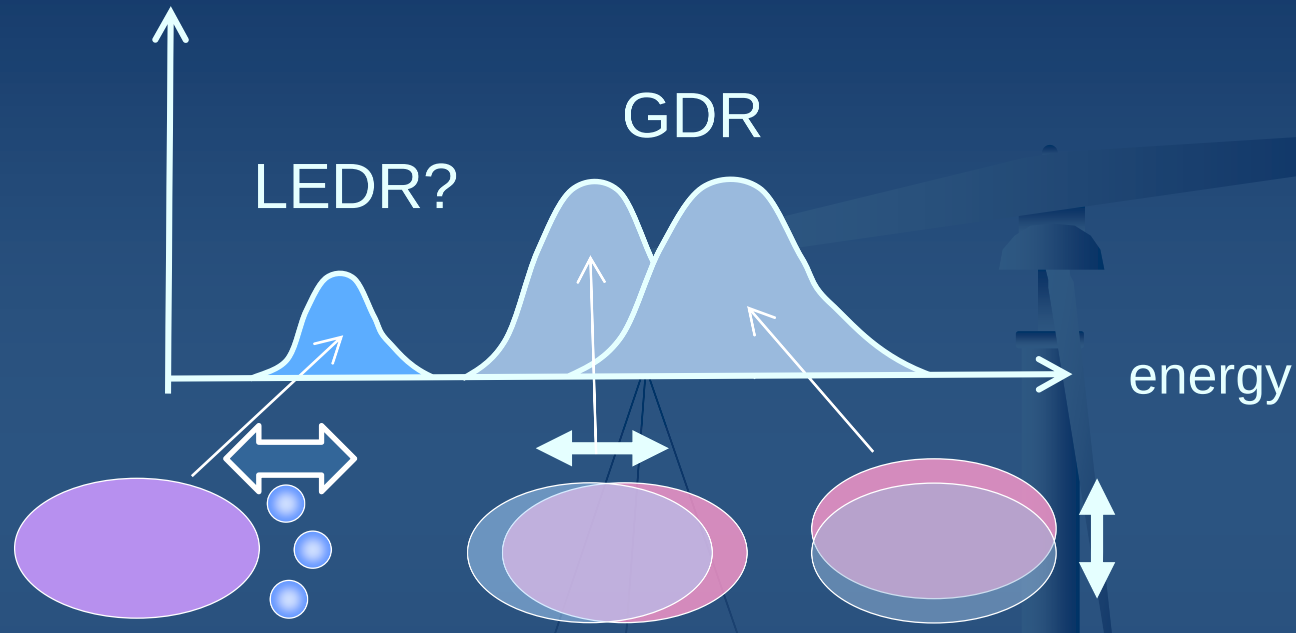
^{8}Be | ^{9}Be | ^{10}Be



2α | $2\alpha+n$ | $2\alpha+2n$

cluster core with
valence neutrons

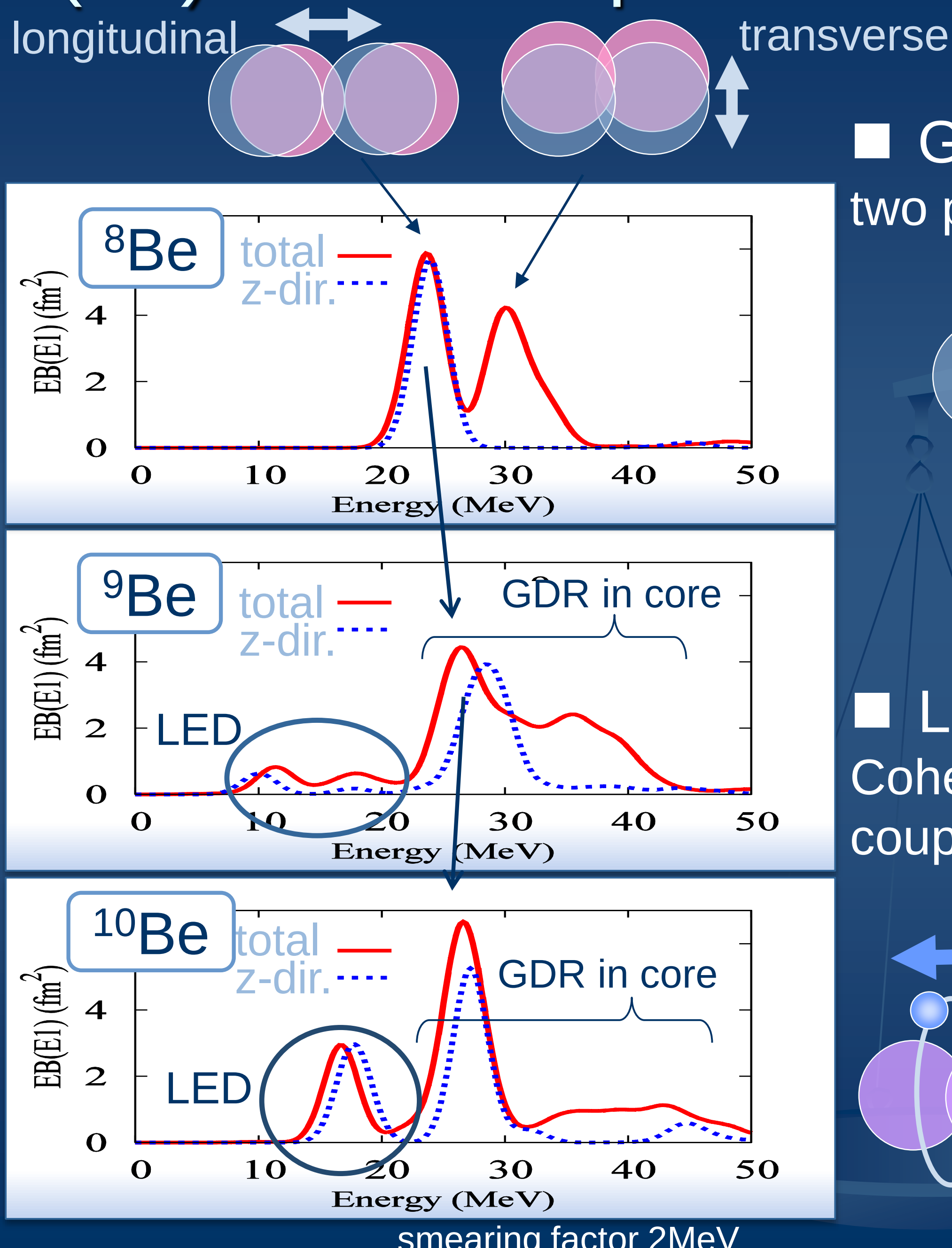
deformed neutron-rich nuclei



Valence neutron modes against core

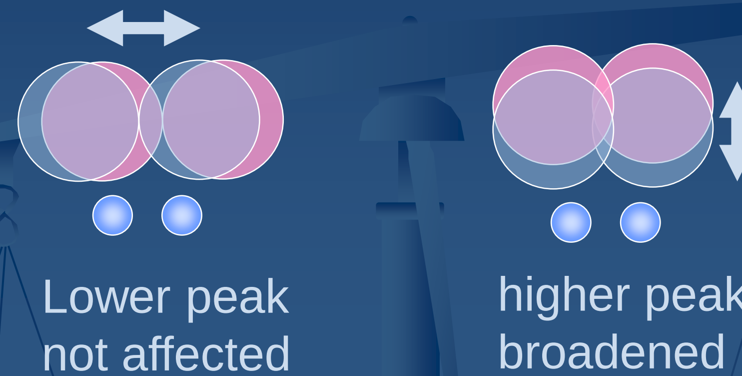
Two peak structure in prolate deformation

B(E1) of Be isotopes calculated by shifted AMD



- **GDR in ^{8}Be core**

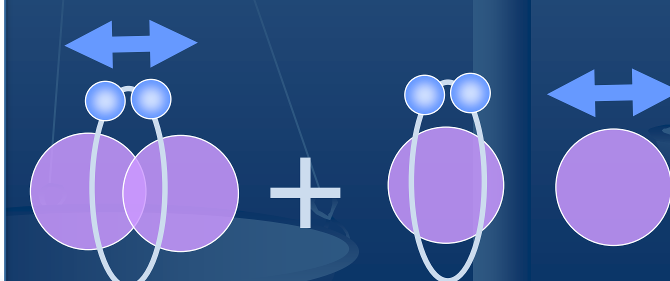
two peaks in prolate state



- **LEDR:**

Coherent two-neutron motion coupling with 6He+α

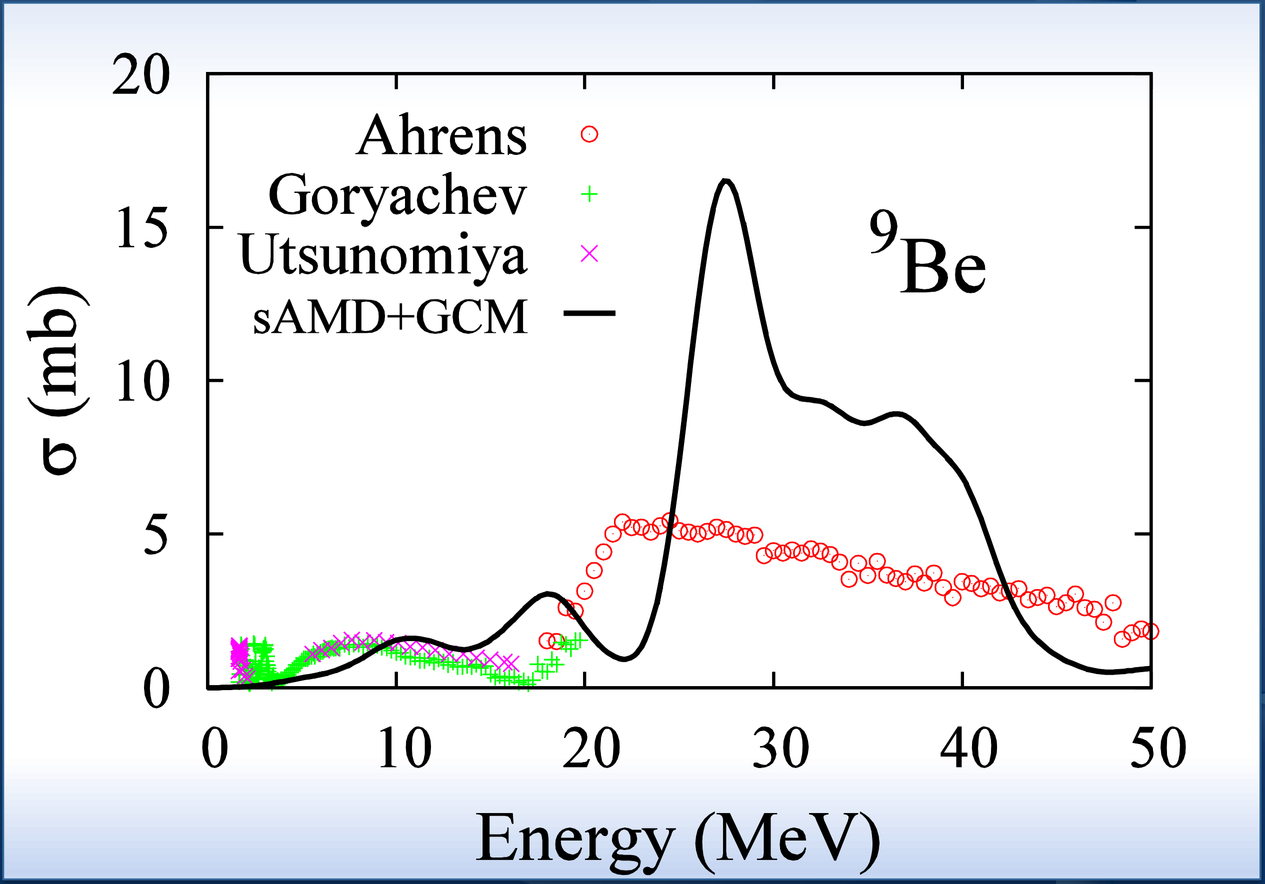
B(ISD) ↗



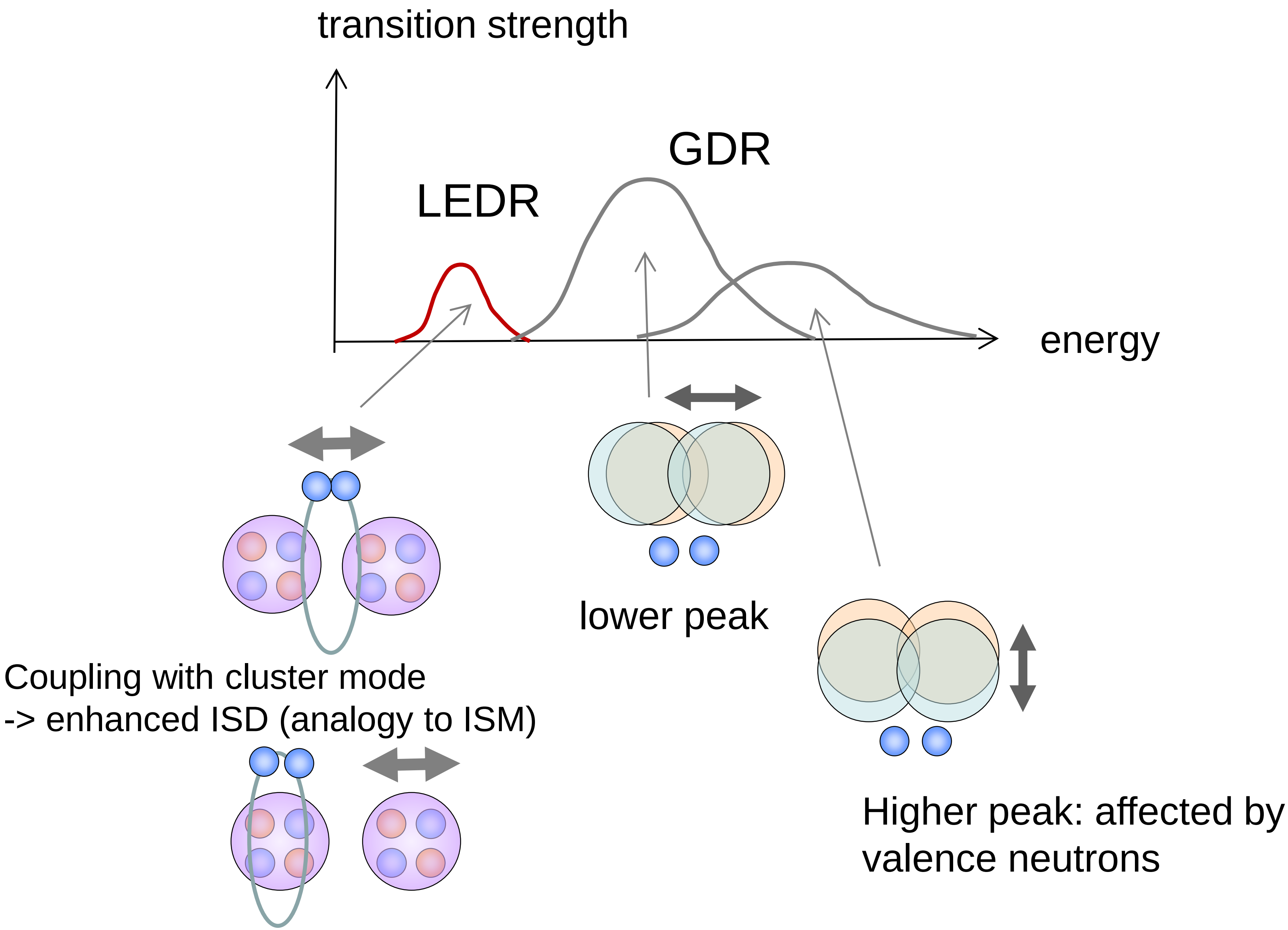
B(E1) in ^{9}Be compared with experimental data

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

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



Particular interest in neutron-rich Be



5. Summary

Summary

- sAMD+GCM

  1p1h+cluster excitations, Jπ-projections

- Monopole & Dipole excitations
- Low-energy excitations decoupling from GR

  LE ISM & ISD in 12C: cluster mode

  LE ISM & ISD in 10Be: cluster mode

  LE E1 in 9,10Be: valence neutron mode