effects of clustering in dipole and monopole transitions

Y. Kanada-En'yo (Kyoto)

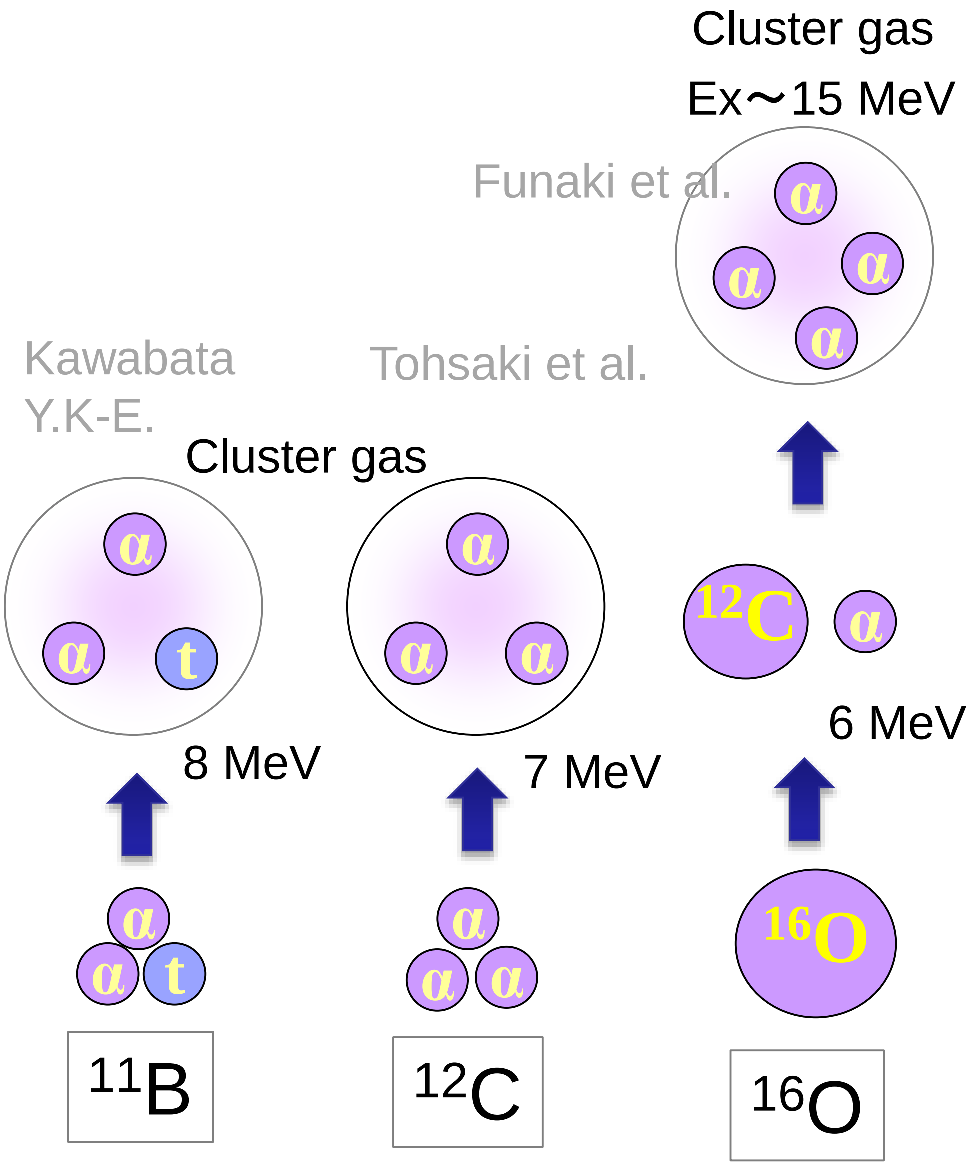
1. **Introduction**
2. **Monopole excitations in ^{16}O and ^{12}C**

   Y. K-E. PRC89, 024302 (2014)
3. **Dipole excitations in ^{9,10}Be**
4. **Summary**

1. Introduction

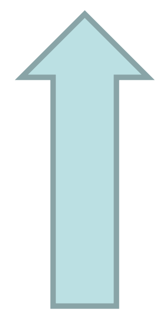
Cluster excitations and Giant resonances

Cluster states in Ex<~15 MeV



For cluster states in 7∼10 MeV energy, strong IS0 trans. because IS0 operator excites radial motion of a cluster
-> IS0 is a good probe

1α excitation

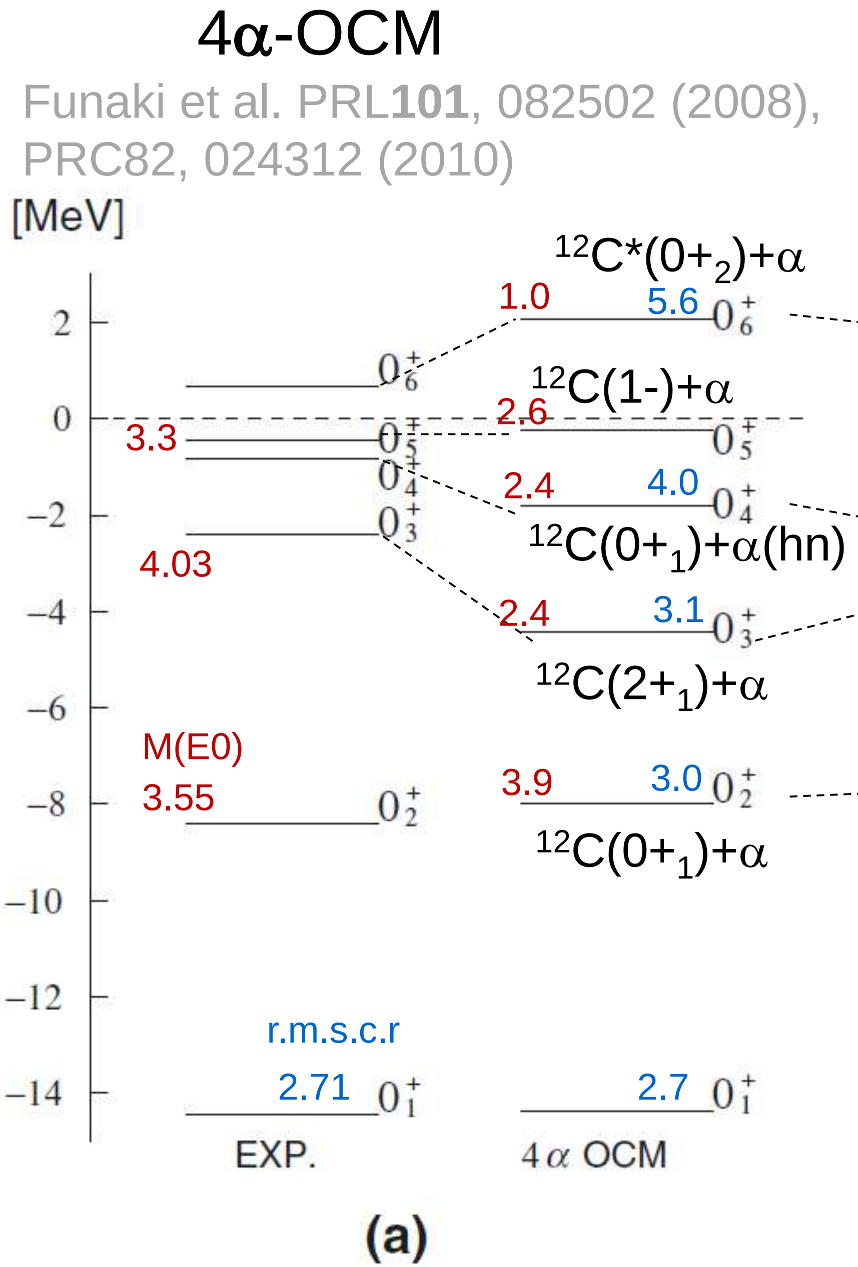


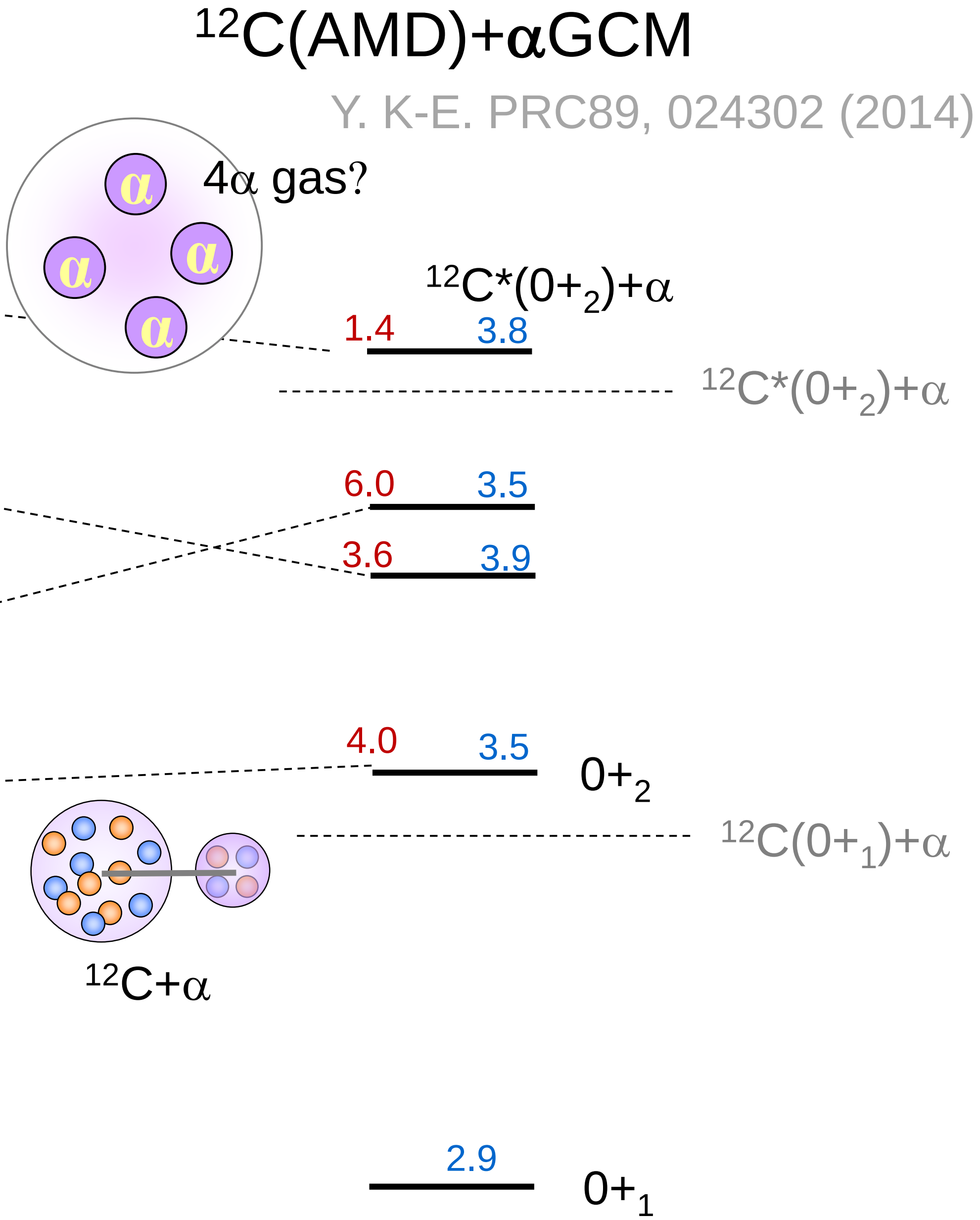
Strong IS0

cluster correlations in g.s. & excited states.

discussed by
Yamada et al.PRC**85**(2012)

Cluster excited states in ^{16}O





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

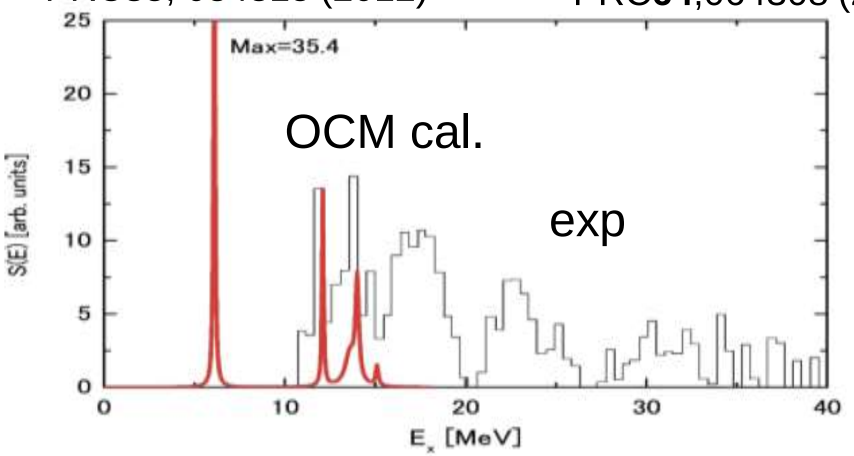
Strong IS0 for cluster states

IS0 operator excites radial motion of cluster.

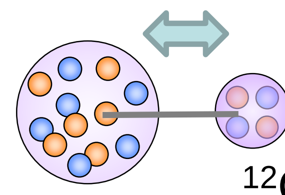
Cluster mode decouples from
collective vibration mode.
GR feeds low-energy strengths.

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

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



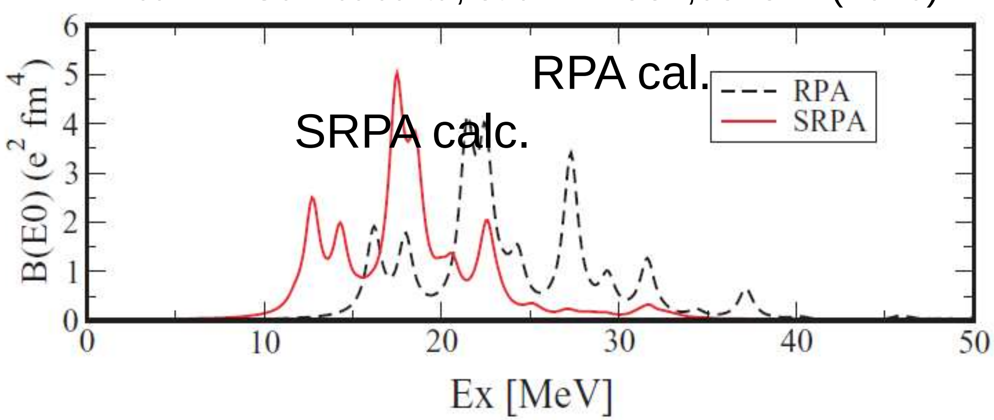
◆ Low-lying IS0 strengths



Cluster mode

^{12}C-α radial motion

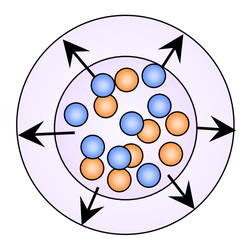
PRA cal. D. Gambacurta, et al. PRC81,054312 (2010).



◆ High-lying IS0 (GMR):

Collective vibration

coherent 1p-1h motion



Breathing mode

LE strengths decoupling from GR＝Decoupling of Scale

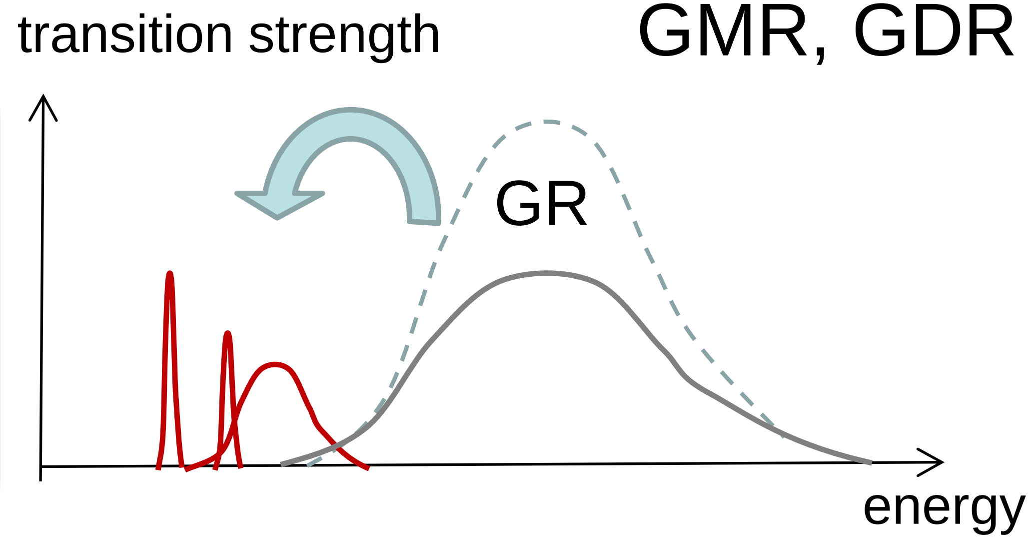
The universal feature

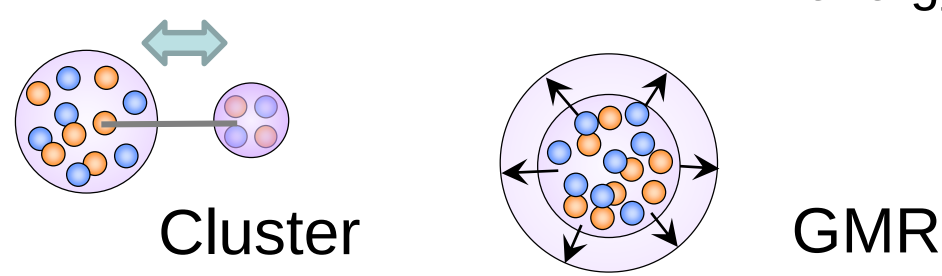
Decoupling of scale（energy)

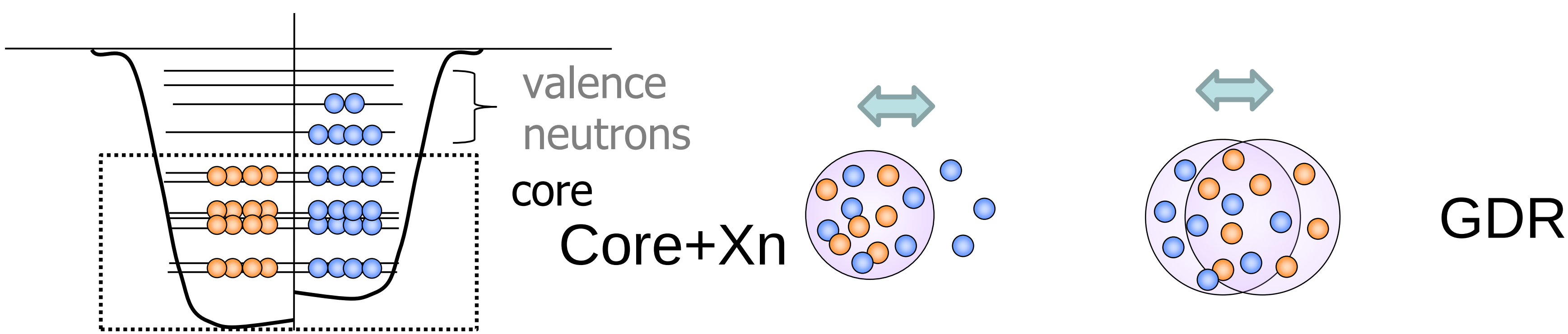
⇩

New excitation modes

GMR, GDR



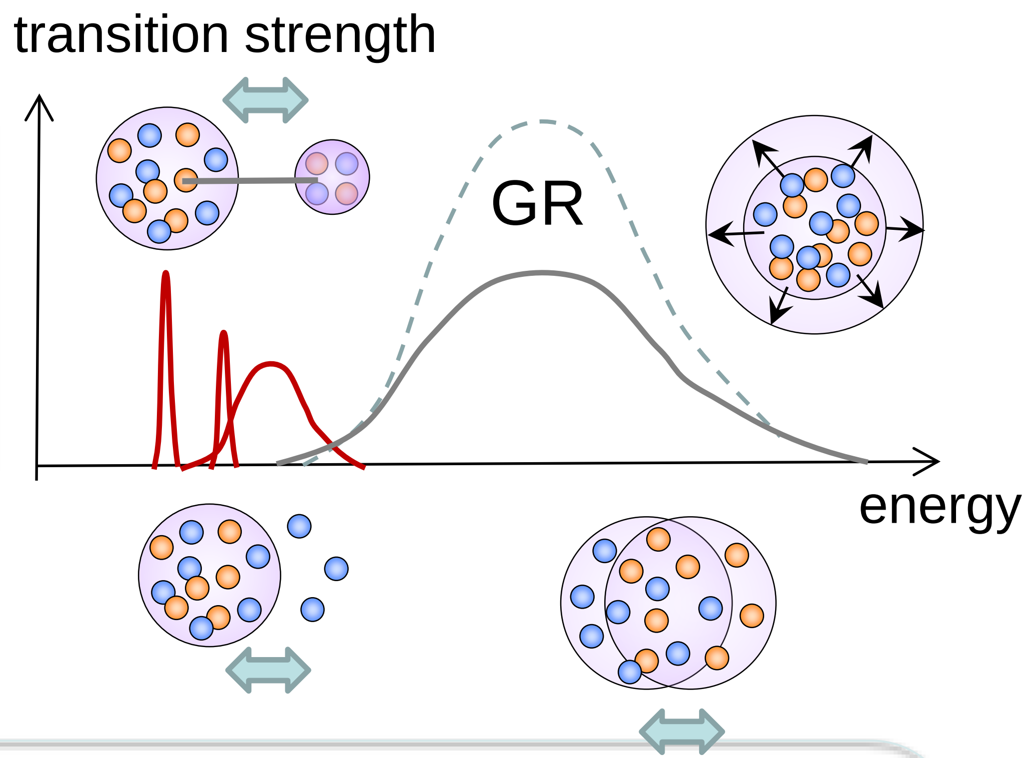




LE strengths decoupling from GR＝Decoupling of Scale

Decoupling of scale（energy)

New excitation modes



Aim:to study LE and GR strengths

Theoretical model describes both 1p-1h excitation (collective vibration) and cluster excitations

Present method: shifted AMD+cluster GCM

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

2. Formulation of shifted AMD+cluster GCM

Formulation of AMD

A approach to study coexistence of cluster and mean-field natures

AMD wave function

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

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

Slater det.

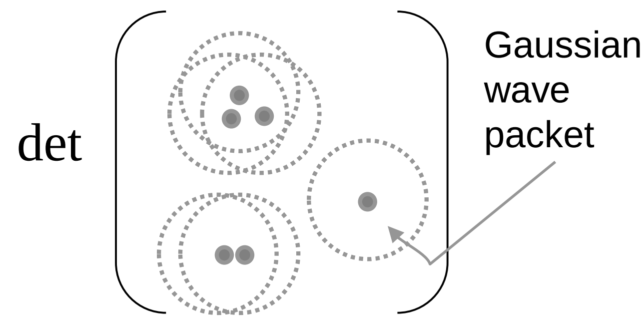
Gaussian

$$\varphi_{\mathbf{i}} = \phi_{\mathbf{Z_i}} \chi_{\mathbf{i}} \begin{cases} \phi_{\mathbf{Z_i}}(\mathbf{r_j}) \propto \exp\left[-\nu\left(\mathbf{r} - \frac{\mathbf{Z_i}}{\sqrt{\nu}}\right)^2\right] & \text{spatial} \\ \chi_{\mathbf{i}} = \begin{pmatrix} \frac{1}{2} + \xi_{\mathbf{i}} \\ \frac{1}{2} - \xi_{\mathbf{i}} \end{pmatrix}_{\text{spin}} \times \; p \text{ or } n \; \text{(isospin)} \end{cases}$$

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

variational parameters

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



Various cluster configurations are contained in the AMD model space

Variation, projection, super position

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

VAP:Variation after spin-parity projection

GCM:β-GCM, α-cluster GCM(αGCM)

sAMD (1p1h excitations)

AMD wave fn. for g.s.

$$\Phi_{\rm AMD}(\mathbf{Z}) = \det\{\varphi_1, \varphi_2, \cdots, \varphi_A\}$$

$$\varphi_{\mathbf{i}} = \phi_{\mathbf{Z_i}} \chi_{\mathbf{i}}$$

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

obtained by VAP

$$\delta \frac{\langle P^{J\pm}_{MK}\Phi_{\rm AMD} | H | P^{J\pm}_{MK}\Phi_{\rm AMD}\rangle}{\langle P^{J\pm}_{MK}\Phi_{\rm AMD} | P^{J\pm}_{MK}\Phi_{\rm AMD}\rangle} = 0$$

⇒ optimized parameters

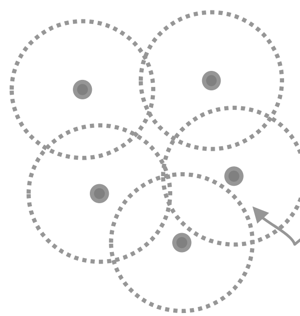
$$\mathbf{Z} = \{\mathbf{Z}_1, \mathbf{Z}_2, \cdots, \mathbf{Z}_A, \xi_1, \cdots, \xi_A\}$$

sAMD small variation of single-particle wave functions

$$\Phi = \det\{\varphi_1, \varphi_2, \cdots, \varphi_A\}$$

$$+ \sum_i c_i \det\{\varphi_1, \cdots, \varphi_i + \delta\varphi_i, \cdots, \varphi_A\}$$

$$\varphi_i + \delta\varphi_i = \phi_{\mathbf{Z_i}+\delta\mathbf{Z_i}} \chi_{\mathbf{i}}$$



Gaussian center

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

small shift of spatial part

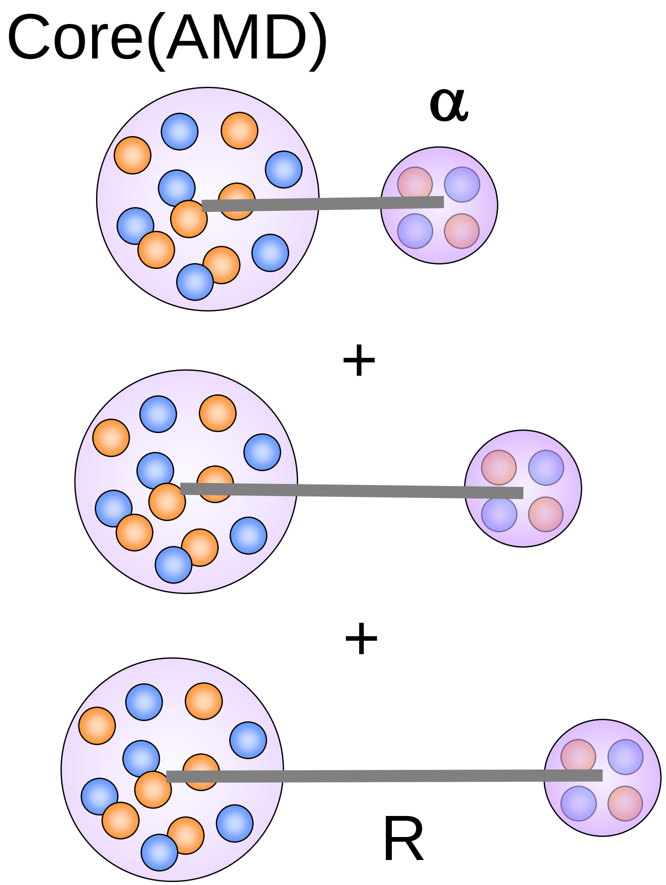
Linear combination of 1p1h excitations from the g.s. configuration
(small amplitude oscillation within shifts of Gaussians)

describes monopole, dipole excitations

(applicable to GT, M1, SD etc.)

AMD+αGCM

Core(AMD)+alpha **=AMD+αGCM**



Generator coordinate: R

Large amplitude cluster mode

sAMD+GCM(cluster)

sAMD+GCM superposing spin-parity projected states of all wave functions (shifted AMD, and cluster wave functions.)

- ground state: VAP describes g.s.cluster correlations
- sAMD describes small amplitude oscillation (1p1h)
- GCM describes large amplitude cluster mode
- Parity and angular momentum projections describe coupling of intrinsic modes with the rotation

RPA: only small amplitude oscillation (->higher: SRPA)
no projections

QRPA: pairing correlation but no cluster correlation
no projections

Time-dependent AMD: large amplitude oscillation
but not quantized
no projections

Monopole and dipole exciations

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

Isovector dipole (E1):

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

Translational mode

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

3. Results

1. ^{16}O: sAMD+ GCM($^{12}C+\alpha$) for B(IS0)
2. ^{12}C: sAMD+ GCM(3α) for B(IS0) & B(ISD)
3. $^{9,10}Be$:sAMD+GCM($^{5,6}He+\alpha$) for B(E1) & B(ISD)

Effective interactions

Phenomenological effective two-body and three-body interactions

Central force

Modified Volkov force:finite range two-body +zero-range three-body

Spin-orbit force

finite range two-body

Coulomb

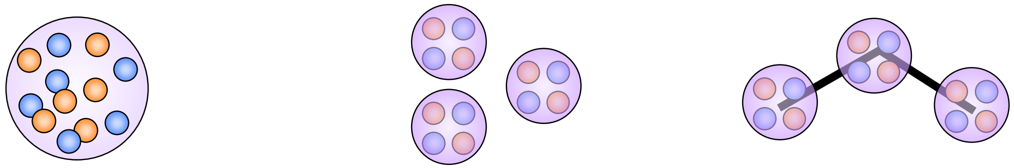
Present parameter set reproduce energy spectra of 12C.

3-1. B(IS0) in ^{16}O

Y. K-E. PRC89, 024302 (2014)

^{16}O(sAMD)+GCM(^{12}C(AMD)+α)

$$^{12}C(\mathrm{AMD}) = \left|\Phi_{AMD}(^{12}C:0_1^+)\right\rangle, \left|\Phi_{AMD}(^{12}C:0_2^+)\right\rangle, \left|\Phi_{AMD}(^{12}C:1_1^-)\right\rangle$$



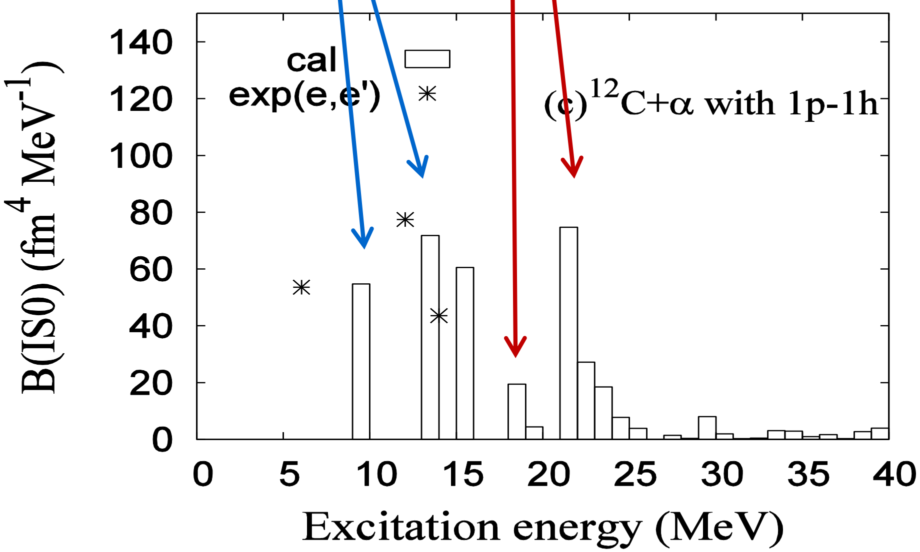
Three states with AMD+VAP

B(IS0) in ^{16}O

sAMD+αGCM

^{12}C(gs)+α

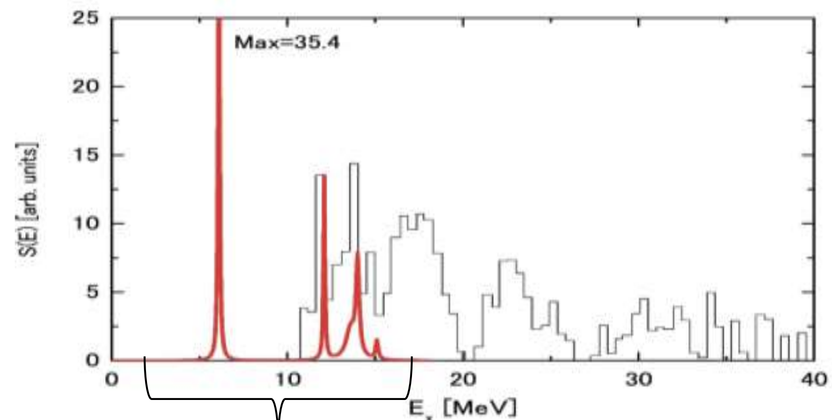
4α gas



LE cluster mode

GMR

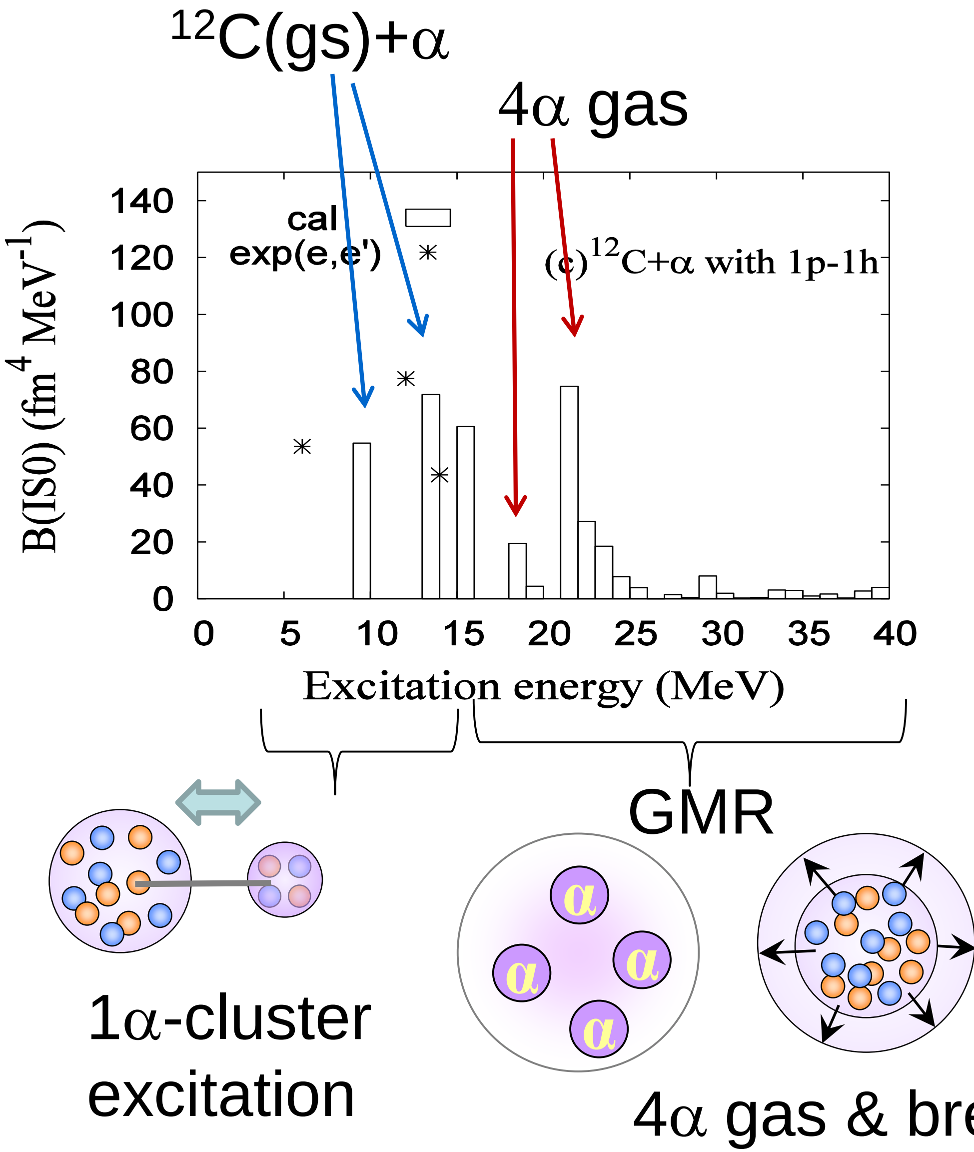
Yamada et al.



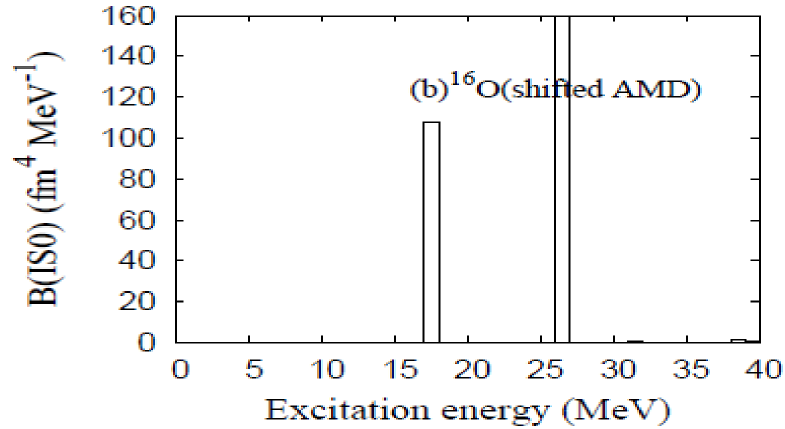
4a-OCM: EWSR(E<16)∼20%

exp.EWSR(E<40)=50%

sAMD+αGCM



sAMD (only 1p1h)



✓ 12C-α mode decouple from GMR: low-energy IS0 strength.

✓ 4α cluster gas does not decouple From GMR, contributes to GMR. Isotropic radial excitation coupling with collective breathing mode.

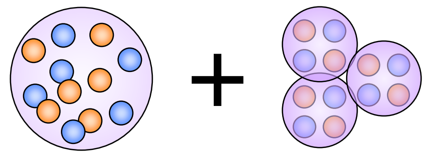
3-2. B(IS0) & B(ISD) in ^{12}C

^{12}C(sAMD)+GCM(3α)

sAMD+αGCM for ^{12}C

^{12}C(sAMD)+GCM(3α)

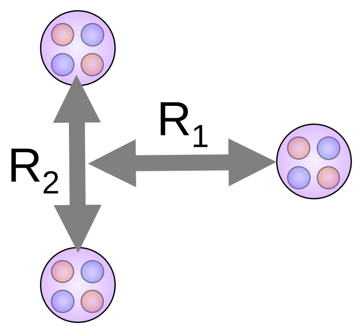
^{12}C(g.s.)=



VAP result contains
the g.s. cluster correlation

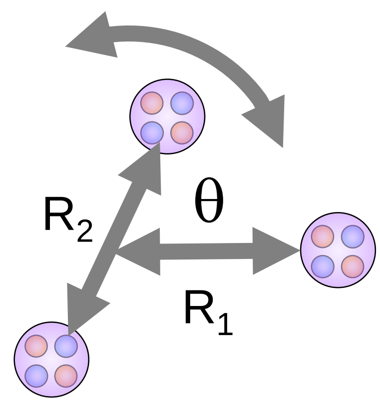
^{12}C(sAMD): 1p1h excitations on g.s.

GCM(3α)



(A) radial mode

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

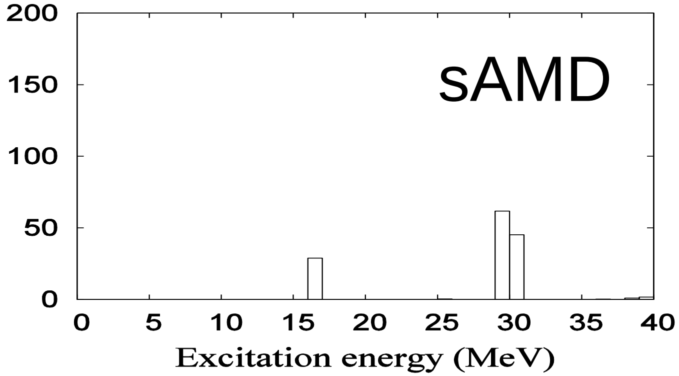


(B) radial & angular mode

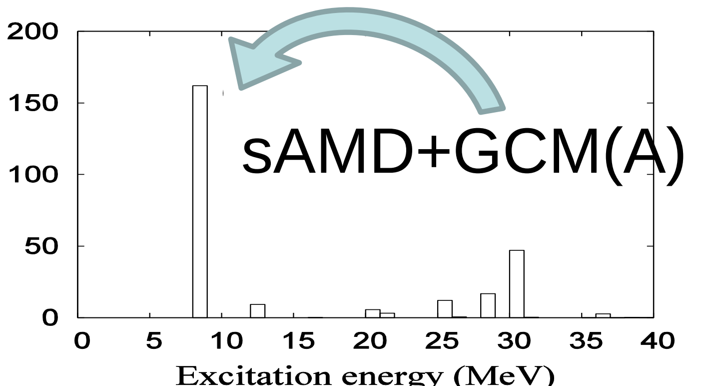
$^{12}C(0^+_3)$

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

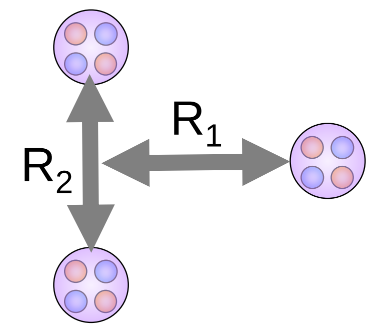
B(IS0) of ^{12}C



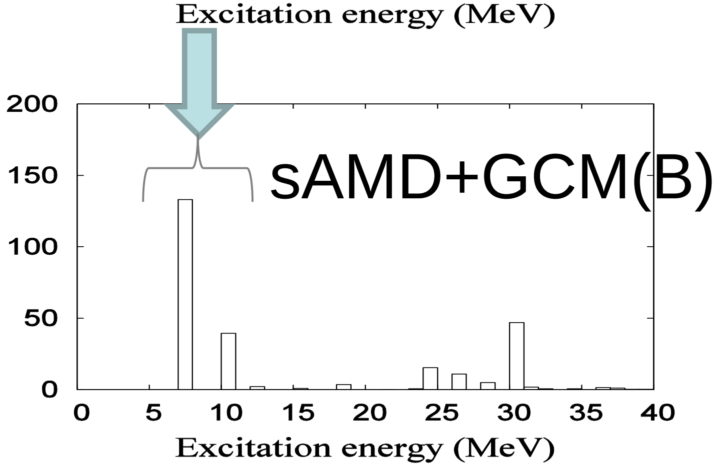
sAMD contains g.s. cluster corr.
LE cluster mode & GMR



(A) 3α radial mode

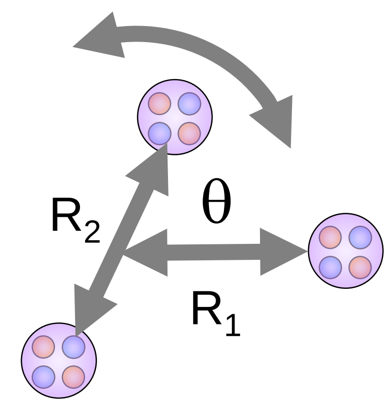


GMR feeds
strength of LE cluster mode

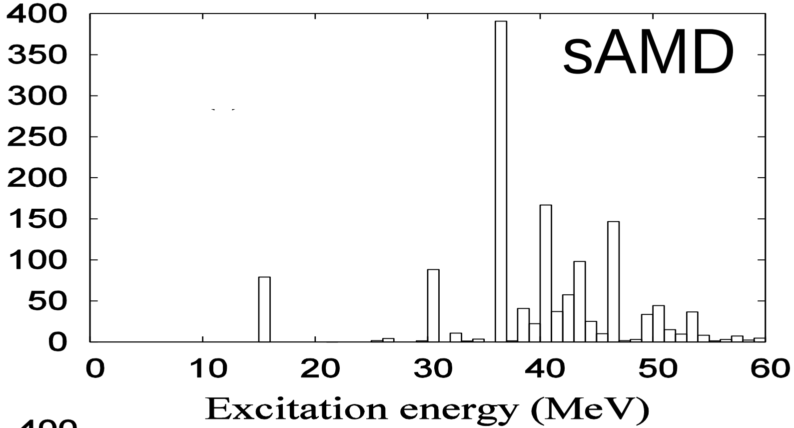


(B) 3α angular mode

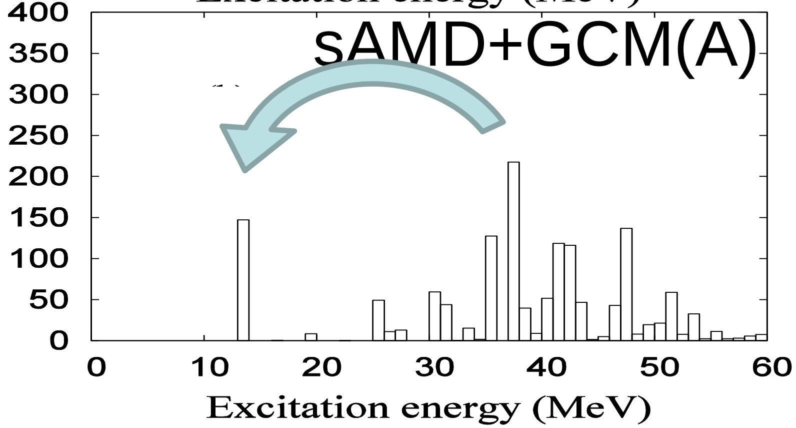
Split IS0 of
LE cluster mode



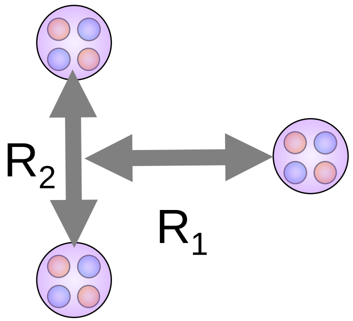
B(ISD) of ^{12}C



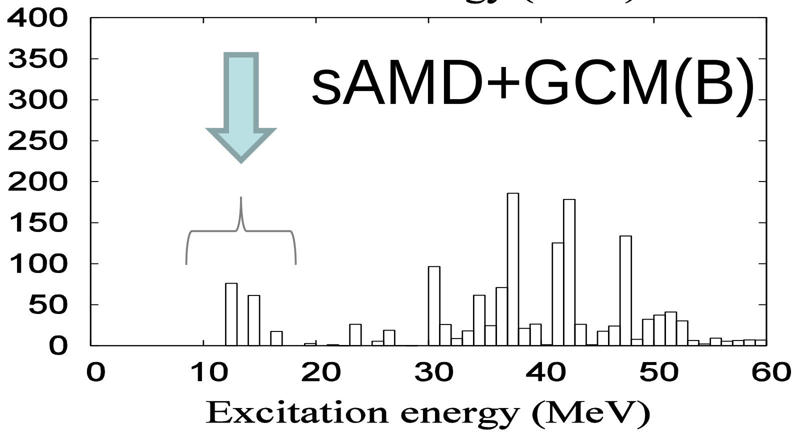
sAMD contains g.s. cluster corr.
LE cluster mode & GR



(A) 3α radial mode

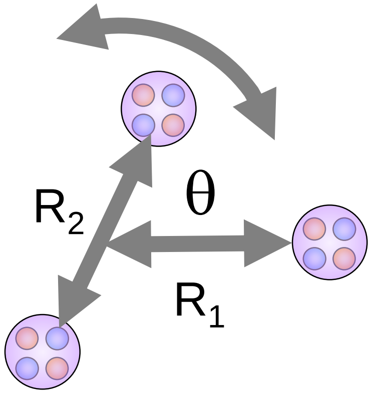


GR feeds
strength of LE cluster mode

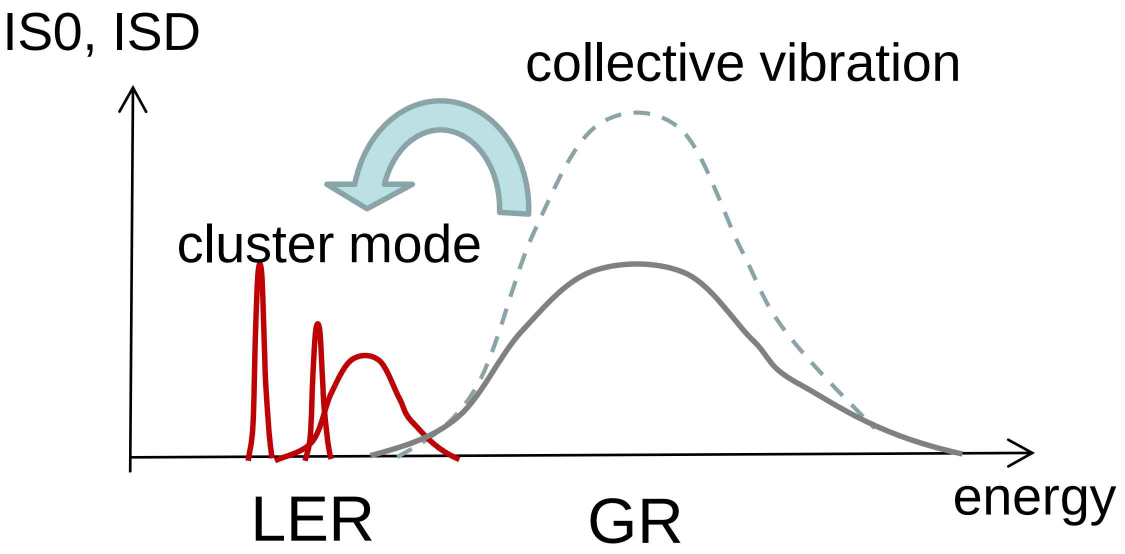


(B) 3α angular mode

Split IS0 of
LE cluster mode



general trend of IS0 and ISD



✓ Cluster modes decouple from the collective vibration mode

✓ Low-energy strengths appears decoupling from the GR.

3-3. B(E1)&B(ISD) in ^{9,10}Be

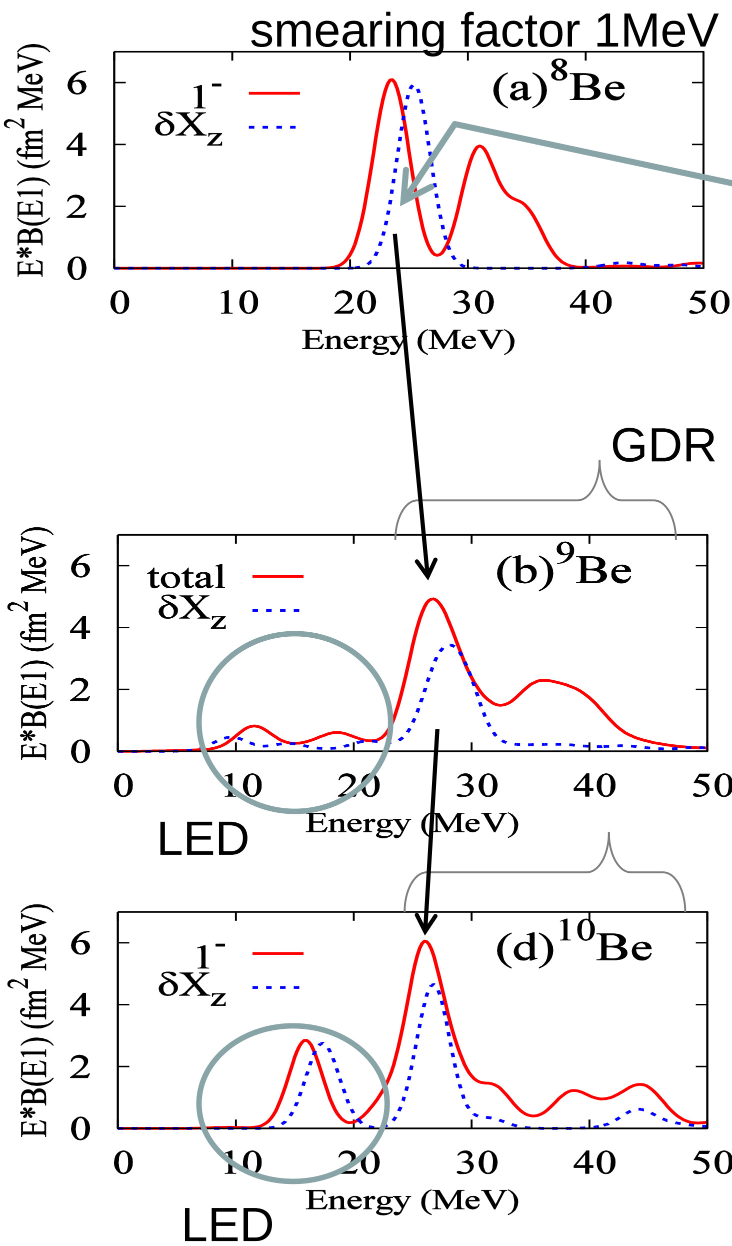
sAMD+αGCM

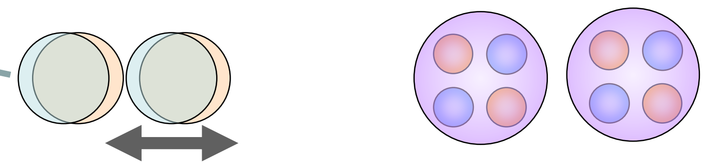
$rY_{1\mu}$ E1: translational mode

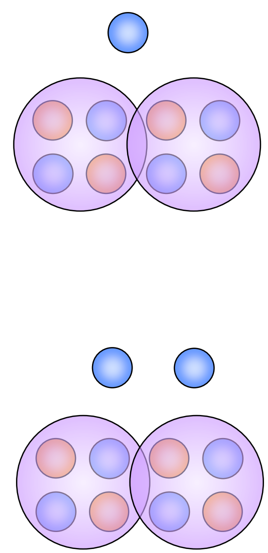
$r^3Y_{1\mu}$ ISD: compressive mode, radial excitation
sensitive to coupling with cluster mode

B(E1) of Be isotopes obtained by sAMD calc.

E1 on prolatele deformed state







LE dipole strengths:
valence neutrons

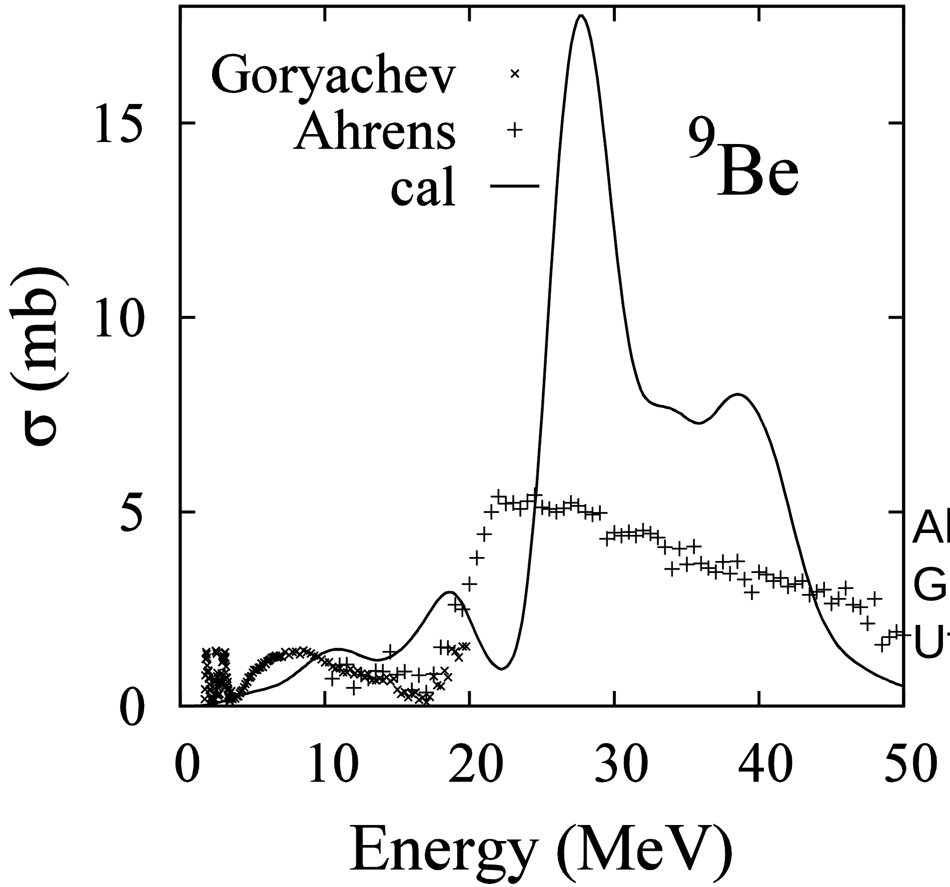
GDR:
^{8}Be core

contribution of valence neutrons

- ✓ LE dipole strengths
- ✓ broadening higher peak of GDR

B(E1) exp. of 9Be

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

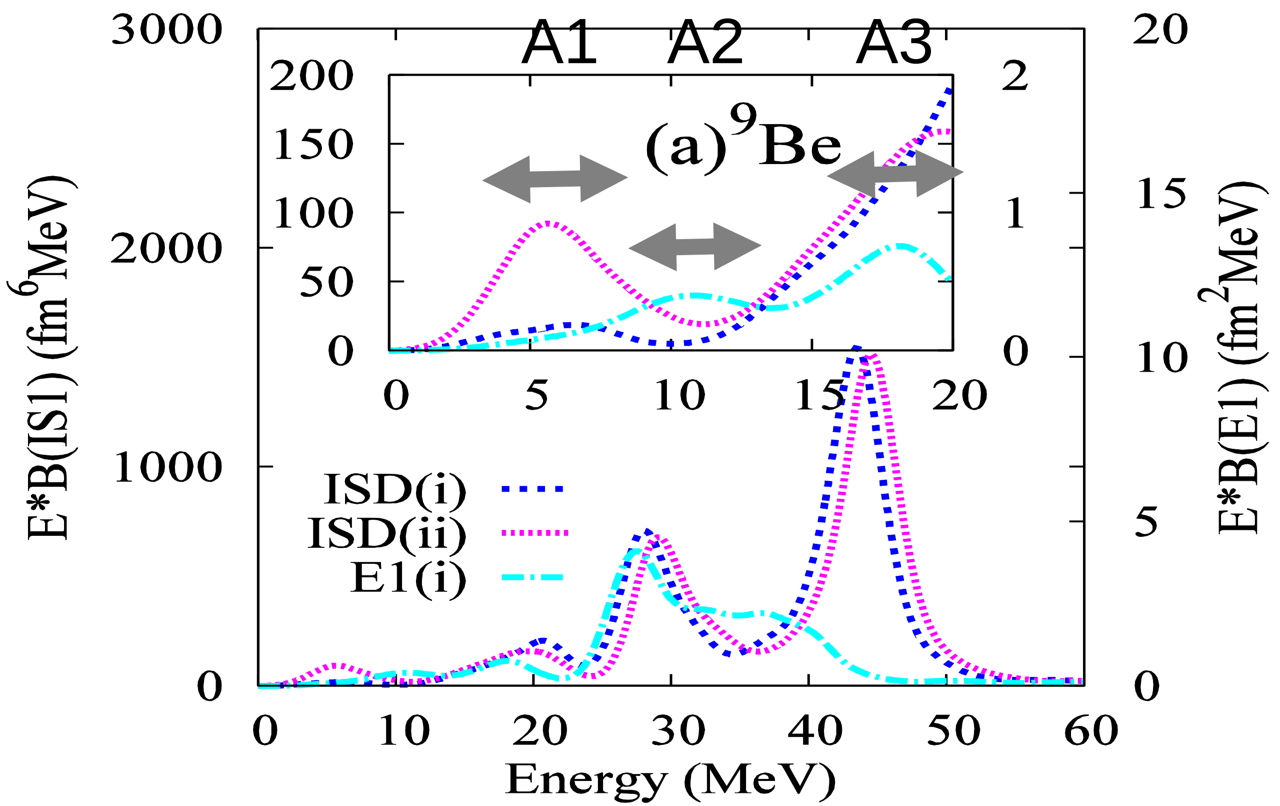


Ahrens et al.(1975)
Goryachev et al. (1992)
Utsunomiya et al.,(2015)

sAMD+αGCM

^{9}Be

LE dipole excitations

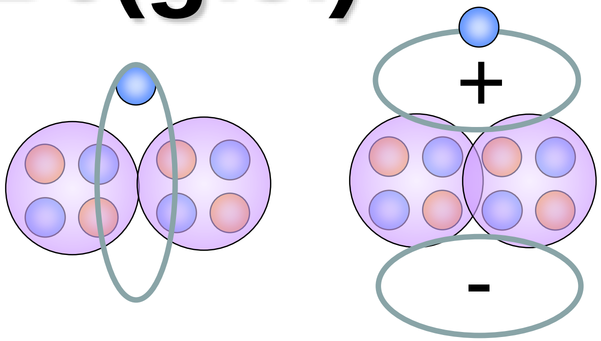


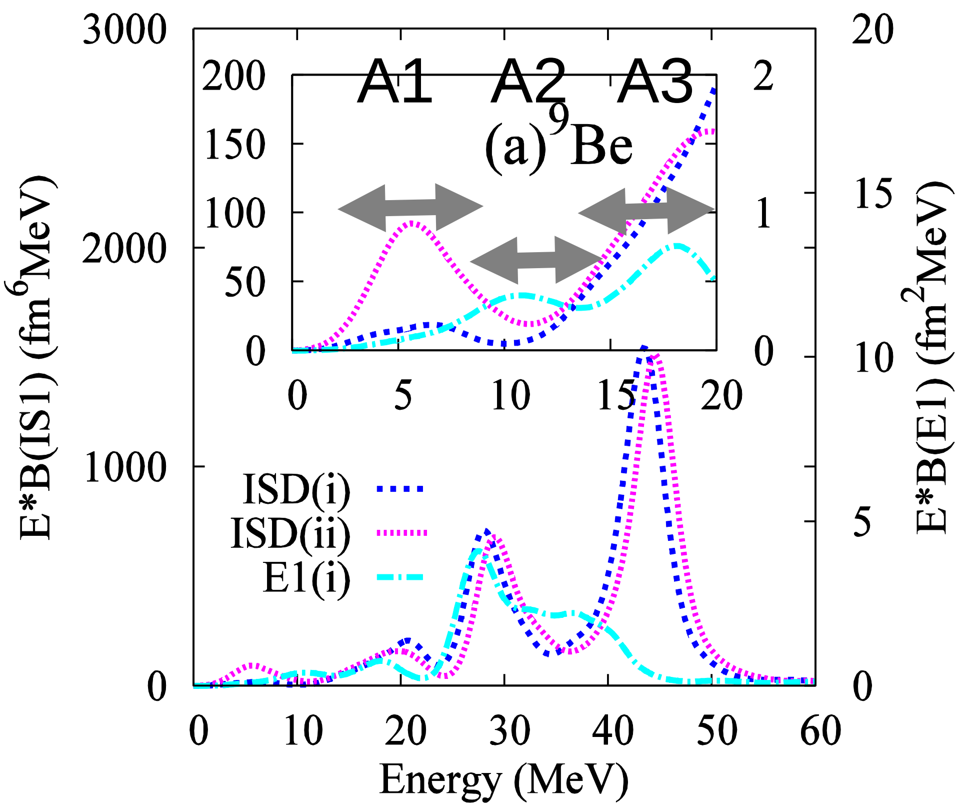
A1: ISD enhanced by α-cluster mode

A2: weak ISD, weak coupling with cluster mode

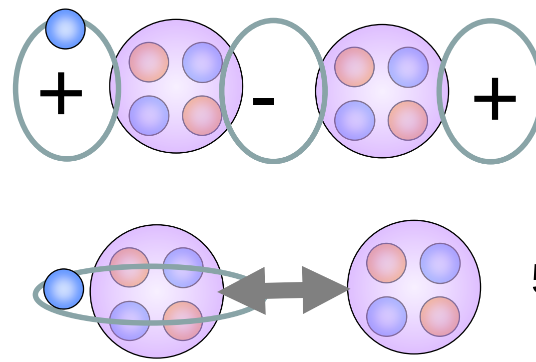
B(E1) & B(ISD) of 9Be

^{9}Be(g.s.)



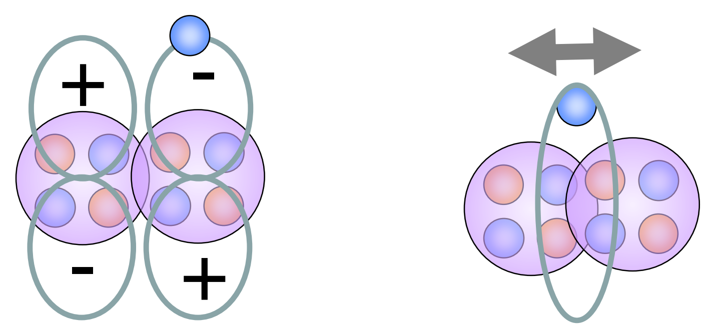


A1 ISD enhanced by α-cluster mode



^{5}He+α enhances ISD

A2 weak ISD, weak coupling with cluster



not radial excitation

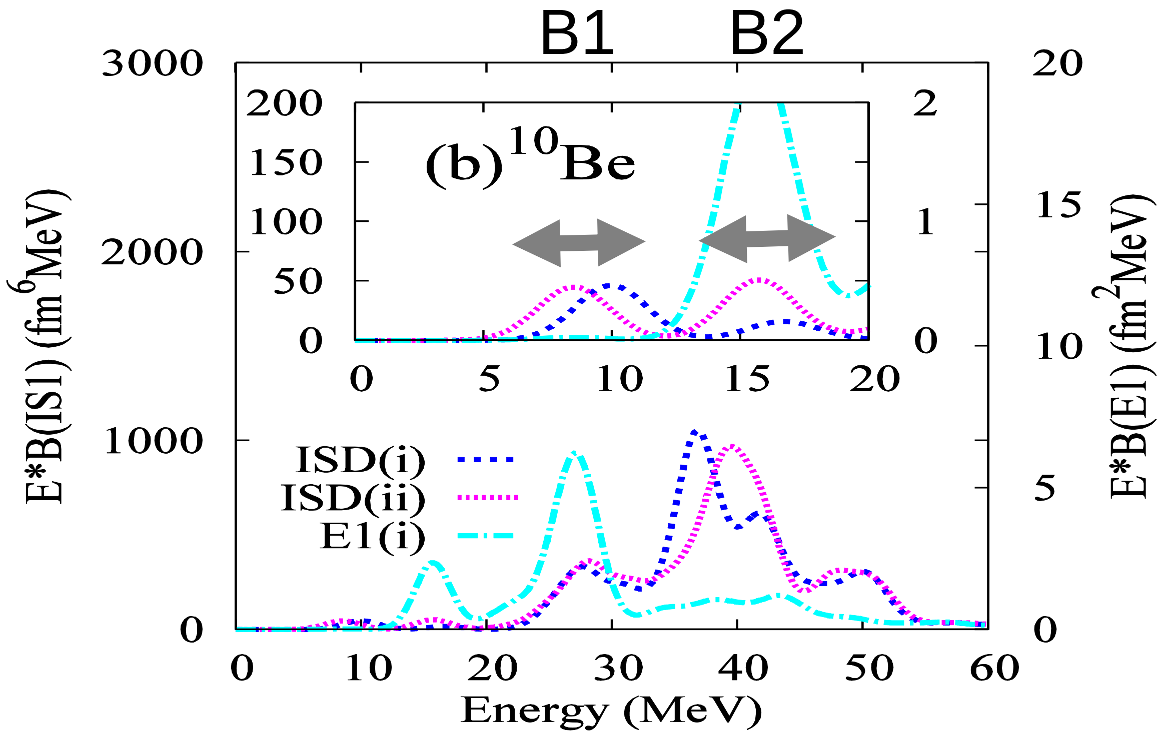
B(E1) & B(ISD) of 10Be

sAMD+αGCM

^{10}Be

sAMD

LE dipole excitations

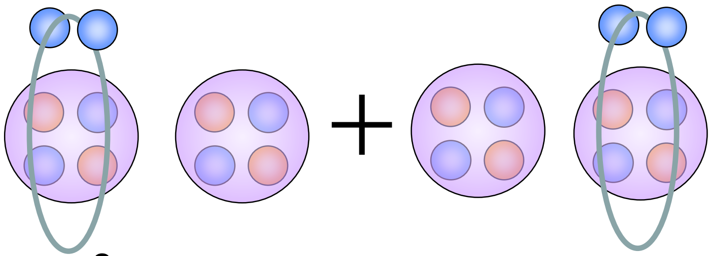


B1: weak E1, weak coupling with cluster mode

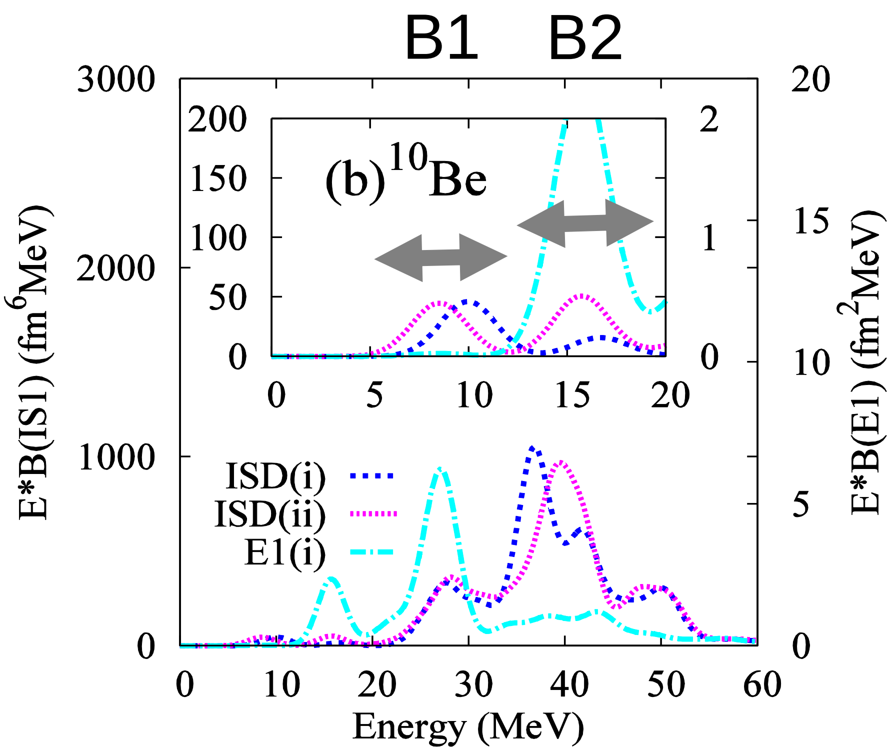
B2: significant E1, ISD enhanced by α-cluster mode

B(E1) & B(ISD) of 10Be

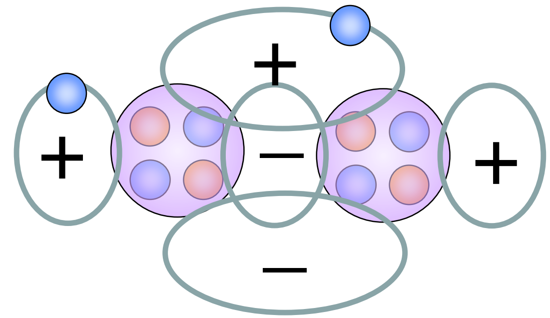
^{10}Be(g.s.)



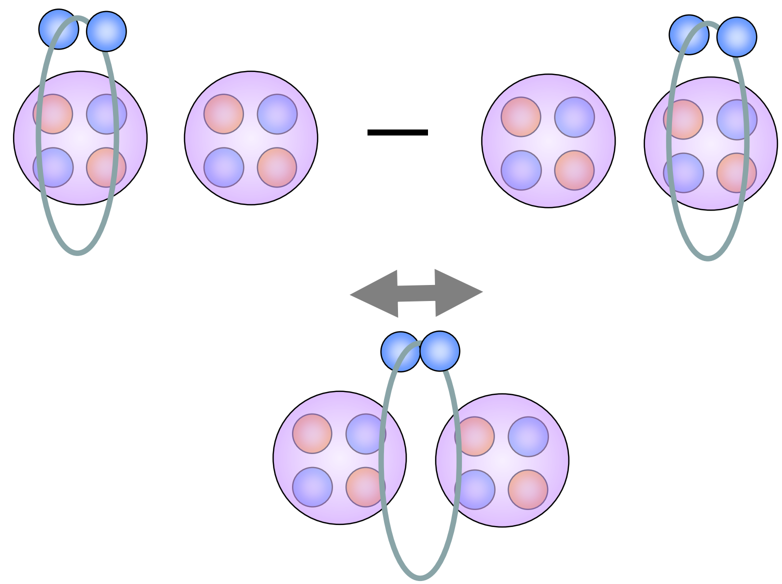
^{6}He+α



B1 weak E1,
weak coupling with cluster mode



B2 significant E1,
ISD enhanced by α-cluster mode



5. Summary

Summary

- sAMD+GCM

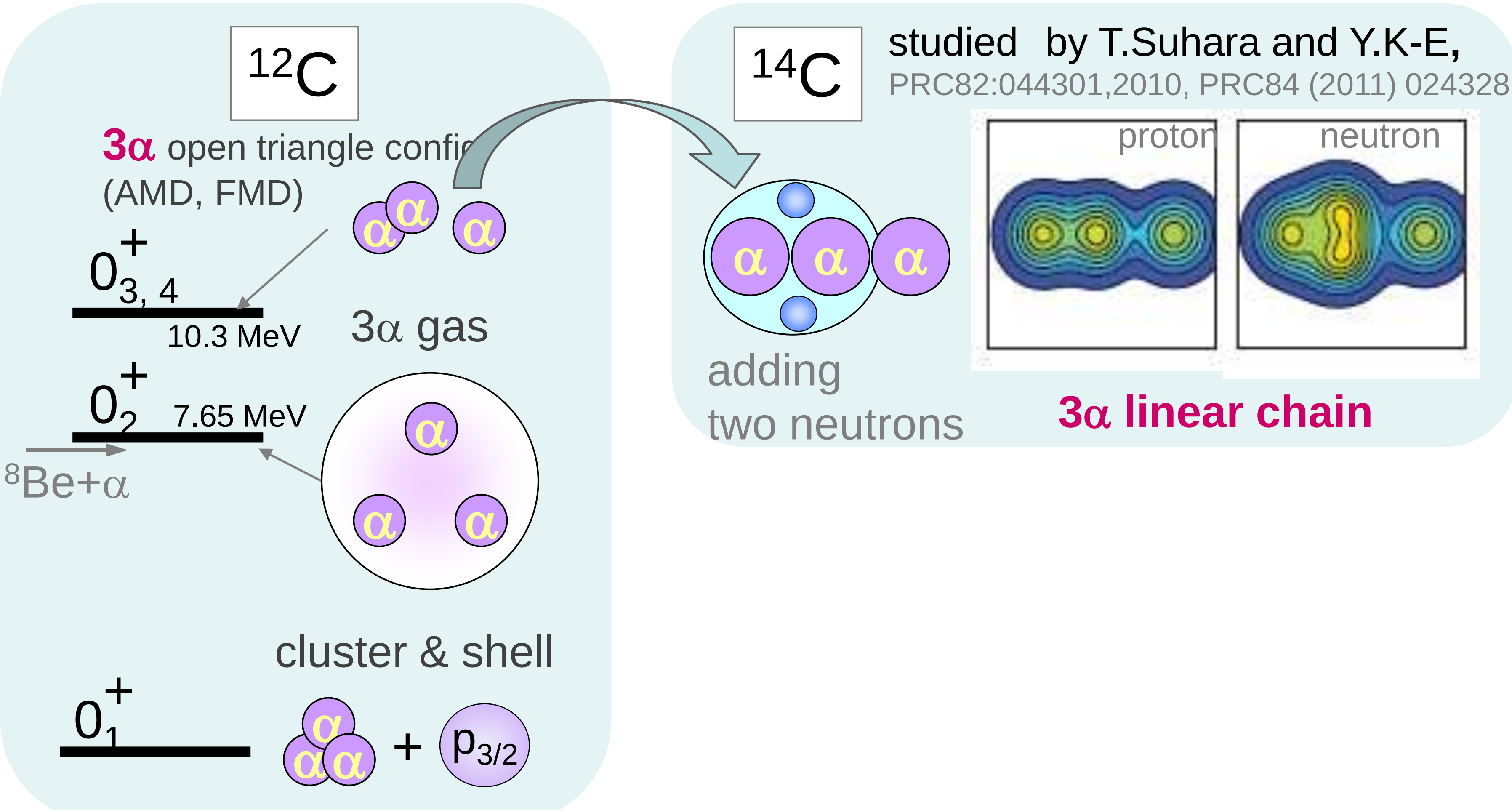
  1p1h+cluster excitations, Jπ-projections
- Monopole & Dipole excitations
- Monopole excitations in 16O
- Monopole and ISD in 12C
- Dipole excitations in Be isotopes
- IS0 & ISD enhahced by coupling with cluster modes
- Low-energy excitations decoupling from GR

  LE IS0 & ISD in 12C: cluster mode

  LE E1 in 9,10Be: valence neutron mode

  LE ISD in 9. 10Be: cluster mode

6. What is shape ?
of bound and resonance states

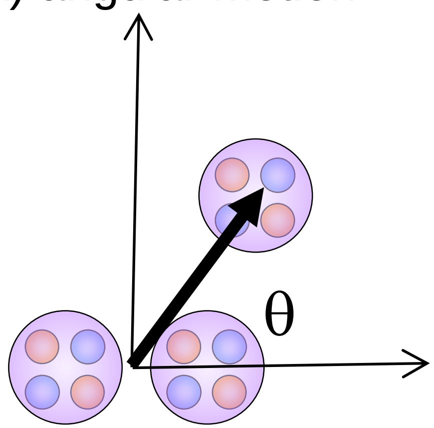


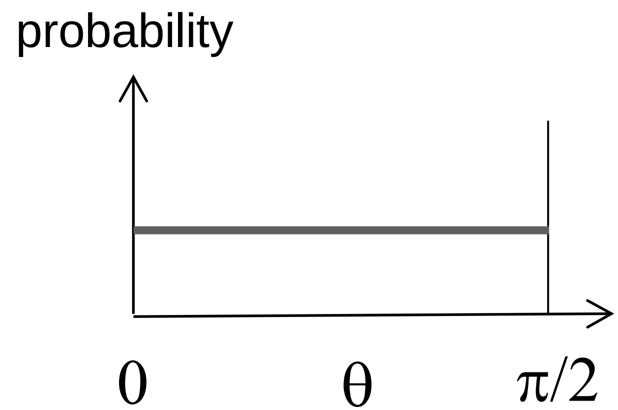
Shape of quantum system

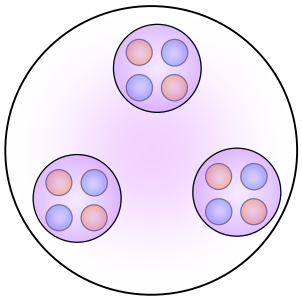
Localization in probability distribution -> shape

A state dominantly contains a certain configuration (classical interpretation)

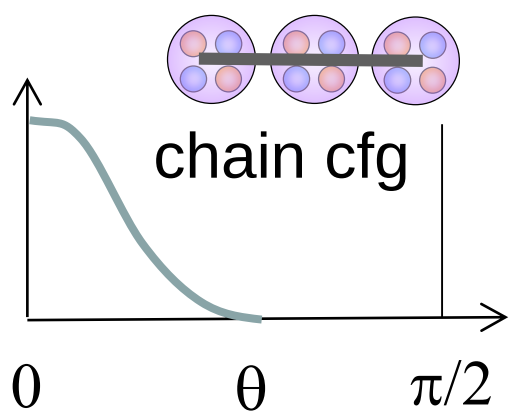
Ex) angular motion

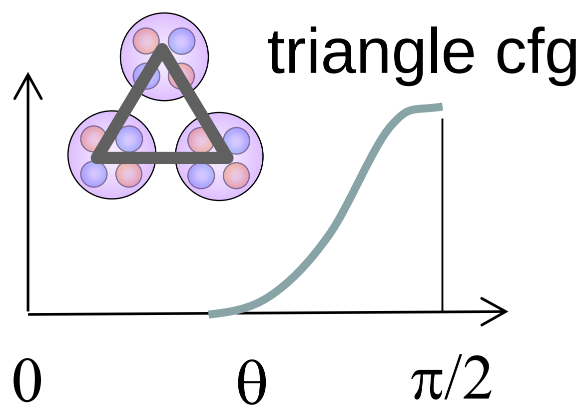




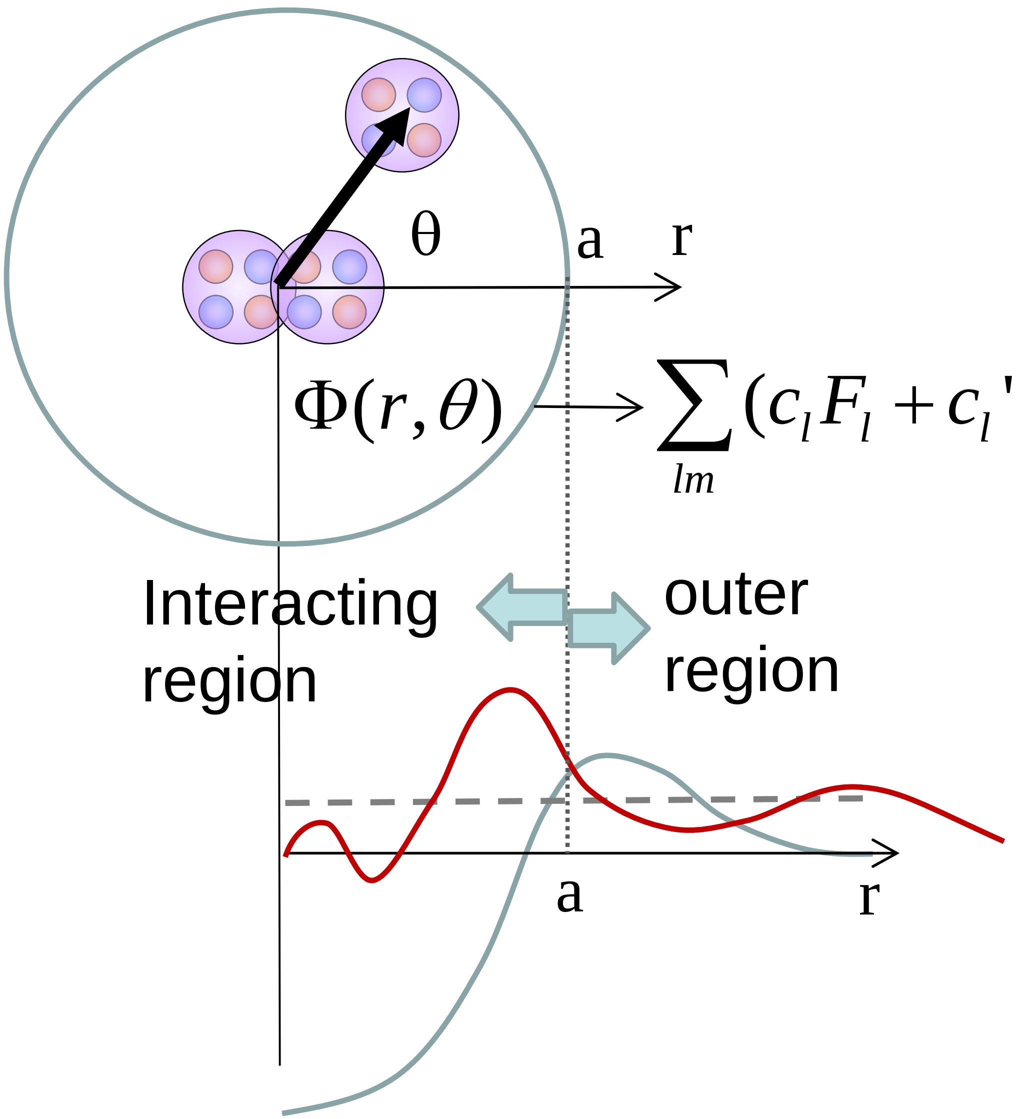


cluster gas





Shape of resonance

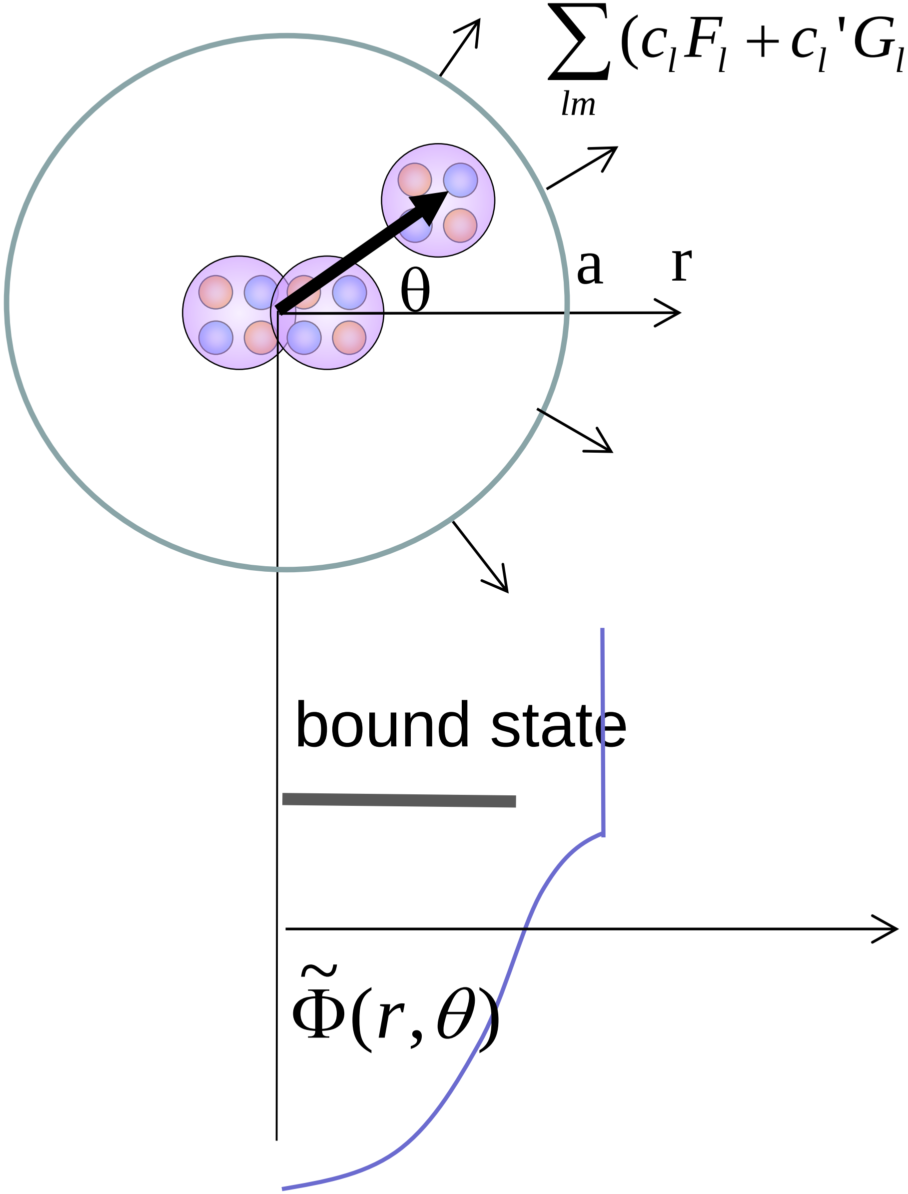


$$\Phi(r,\theta) \rightarrow \sum_{lm} (c_l F_l + c_l' G_l) Y_{lm}$$ observable

Inner: region of interest
(3-body dynamics)
Outer: observable
2b(3b) asymptotic
reflects angular distribution
in the inner region $\Phi(r,\theta)$
through coefficients c_l

Bound state approximation

$$\sum_{lm}(c_l F_l + c_l' G_l)Y_{lm}$$

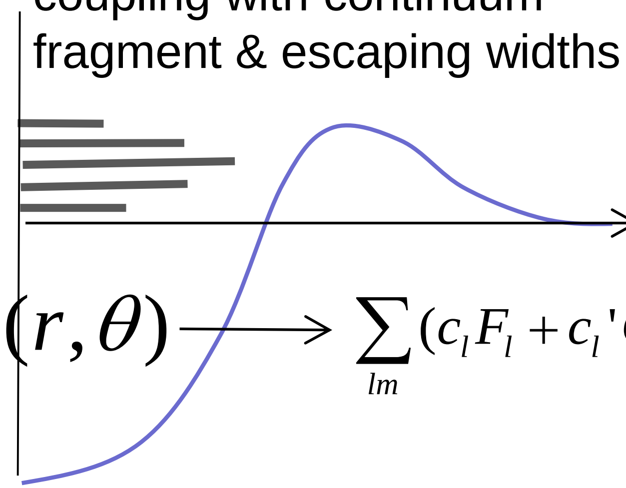


Case of linear chain state

Resonance $\tilde{\Phi} \approx \Phi$

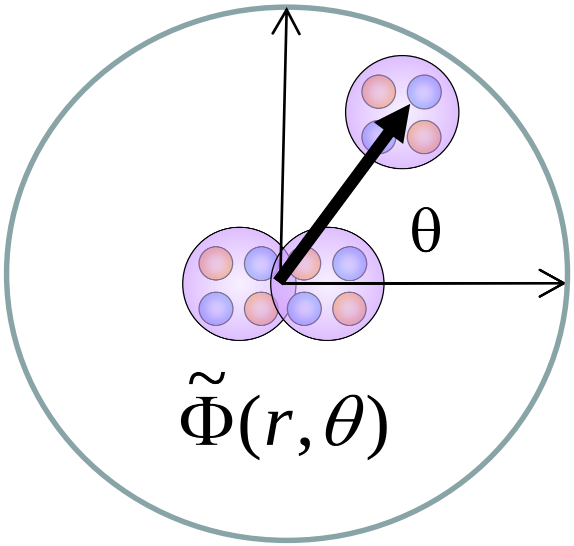
- ✓ quasi bound state (complex E)
  linear chain state decaying to s+d+g… channels (mixed waves).
- ✓ Scattering state (real E)
  head-on scattering

coupling with continuum
fragment & escaping widths



$$\Phi(r,\theta) \longrightarrow \sum_{lm}(c_l F_l + c_l' G_l)Y_{lm}$$

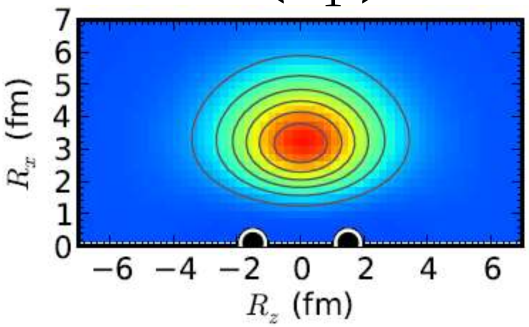
12C 0+ states (bound state approx.)

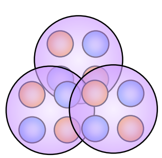


Linear chain state

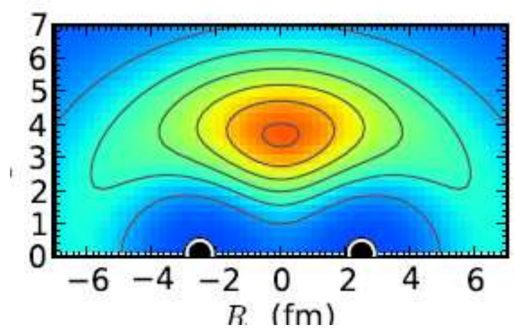
- ✓ localization of amplitude
  large probability of linear chain cfg.
- ✓ head-on scattering
  large mixing of s,d,… waves

$^{12}C(0_1^+)$

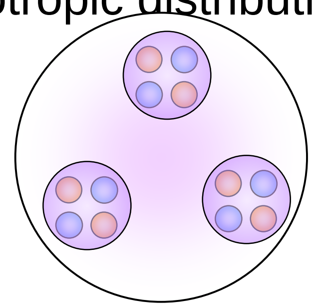




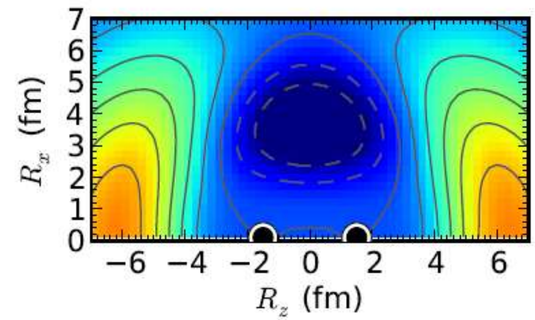
$^{12}C(0_2^+)$



Isotropic distribution



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



Localized distribution
dominant component: