Cluster states probed by alpha (and proton) inelastic scattering

Y. Kanada-En'yo (Kyoto Univ.)

Collaborators:

Y. Shikata, Y. Chiba, Y. Yoshida,

T. Suhara, K. Ogata,

1.Introduction

low-energy (LE)

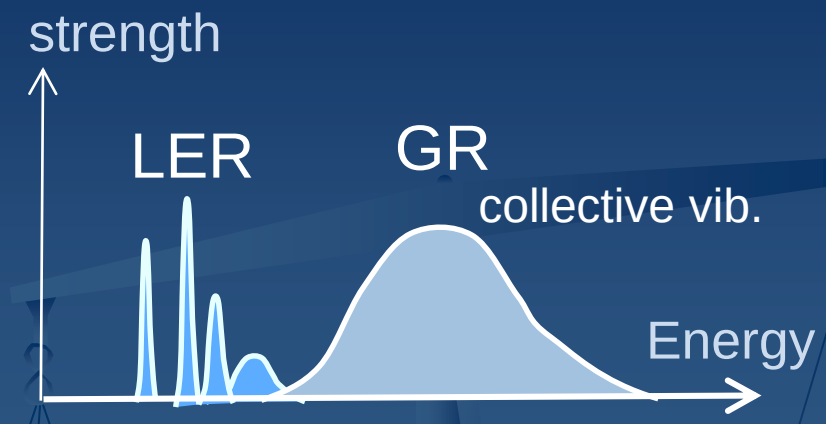
monopole/dipole excitations

&

cluster states

LE-ISM, LE-ISD for cluster states

LE strengths (<15 MeV):
observed by hadron probes
alpha/proton inelastic scattering
What is the origin?
maybe, various LE modes

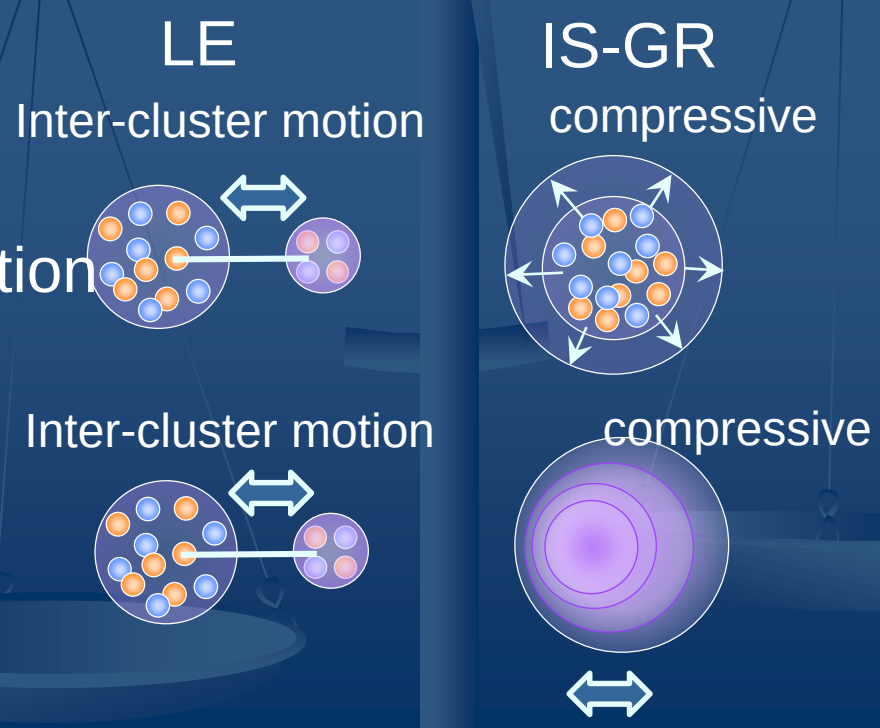


Yamada et al. PRC**85**, 034315 (2012)
Chiba et al. PRC93 (2016) no.3, 034319

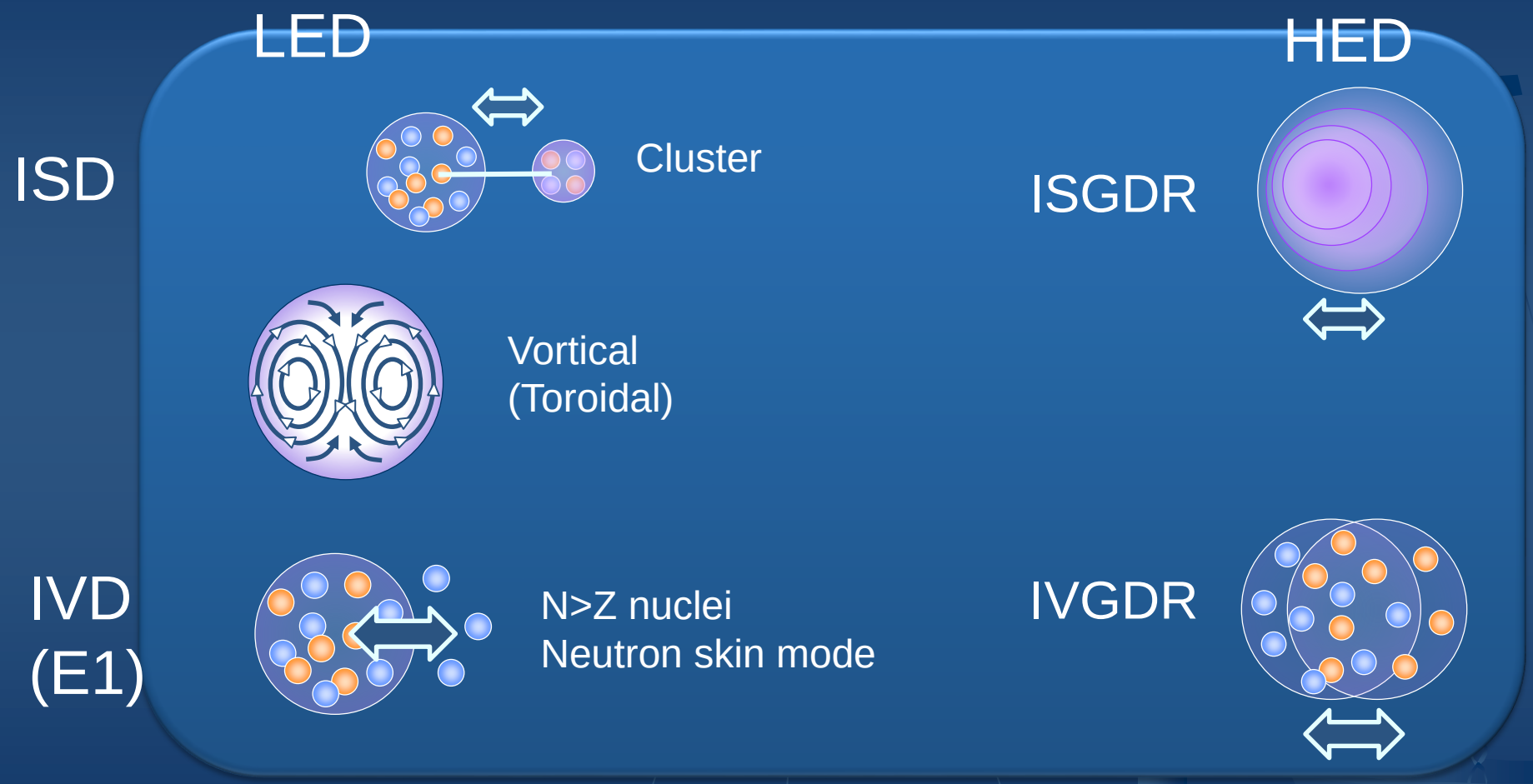
ISM, ISD: compressional operators excite inter-cluster motion

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

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



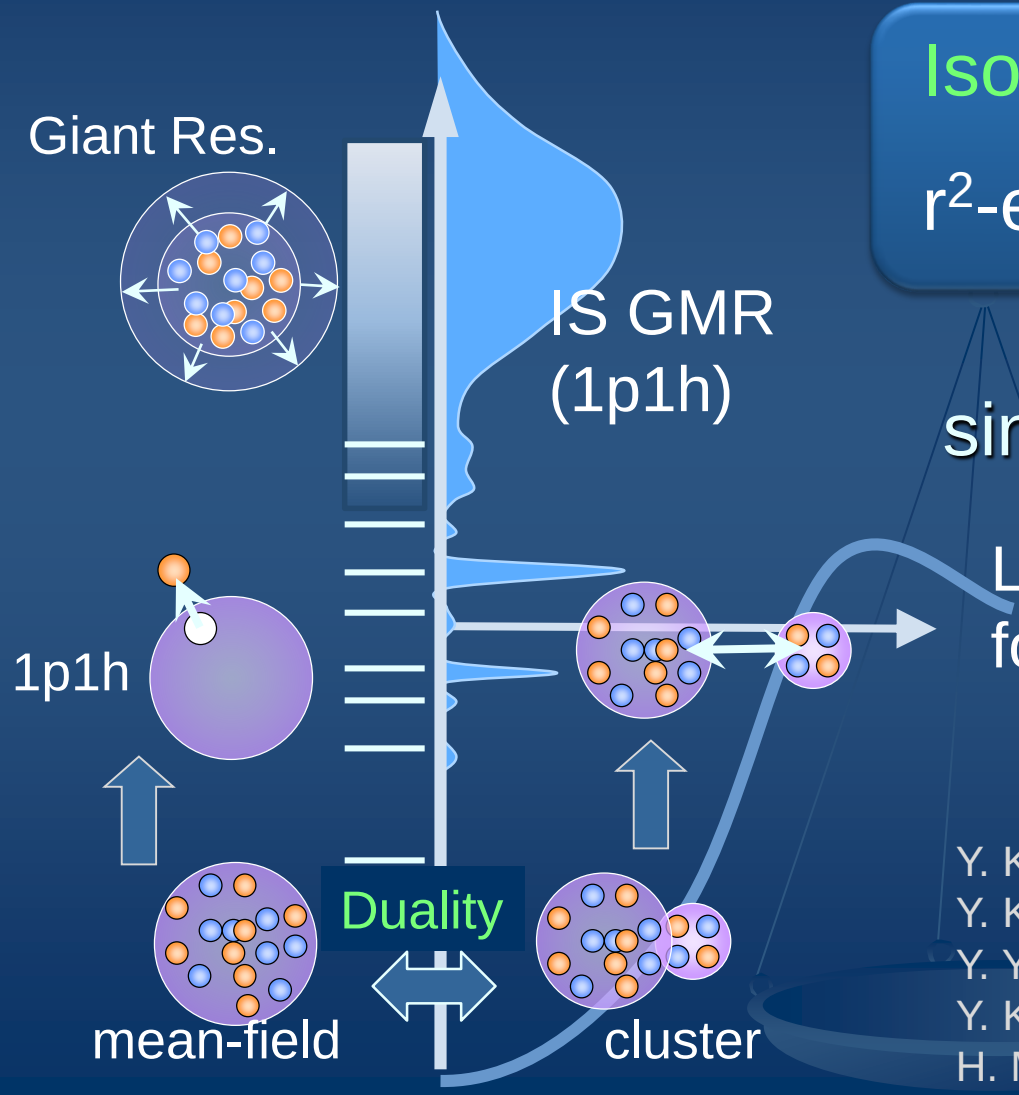
Various modes contribute to LE strengths
ex) case of Dipole



Many modes may arise from various Dof:
1p1h ex, cluster, nuclear currents etc.

Isoscalar monopole (dipole) excitations

Various modes arise from various Dof:1p1h ex, cluster, nuclear currents etc.



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)

Aims

- To clarify natures and origins of LE modes:
  - How do they decouple from HE GRs.
  - Why do they come down to low energy

Structure calculation with AMD+cl-GCM

cluster, deformation, 1p1h, vib/rot, GR

- How to experimentally probe them

Reaction analysis of alpha inelastic scattering

alpha (and/or proton) inelastic scattering can be good probe

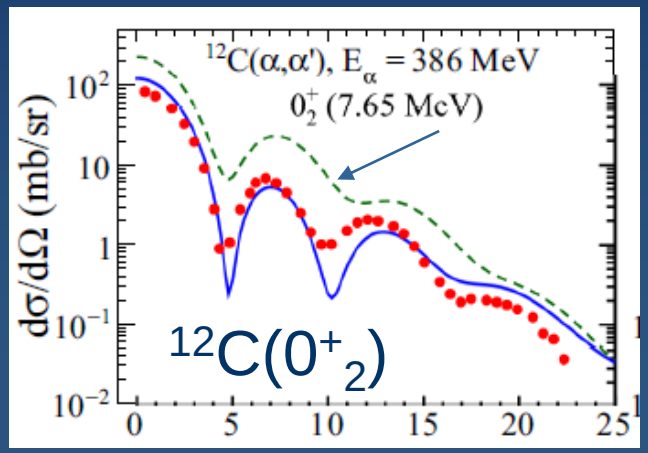
- Isoscaler(and isovector) monopole, dipole excitations
- search for new cluster states

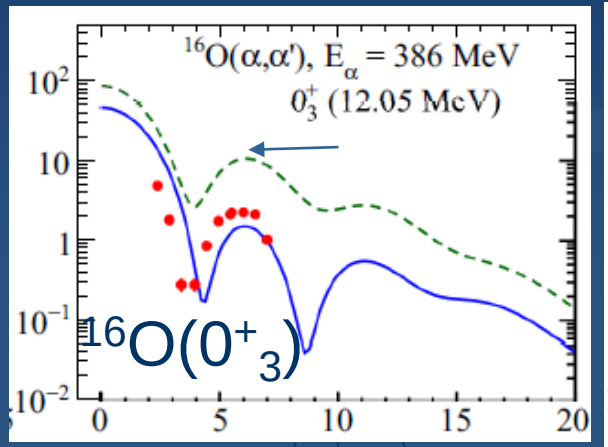
- Determination of B(IS0), B(ISD)?

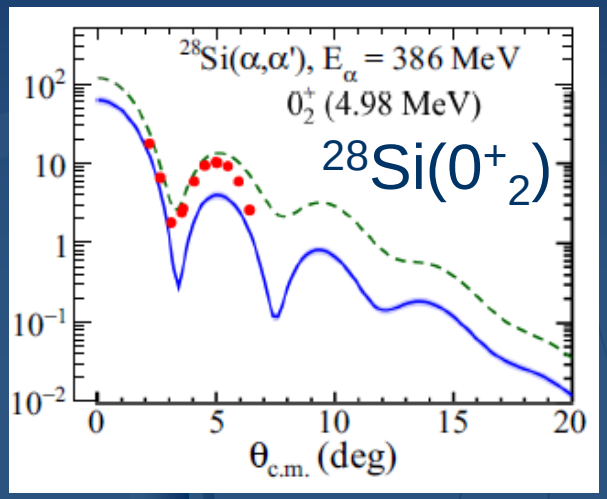
But, ... a problem in reaction calculation:

It largely overestimate cross sections of only 0+ excitations by a factor of 3-5.

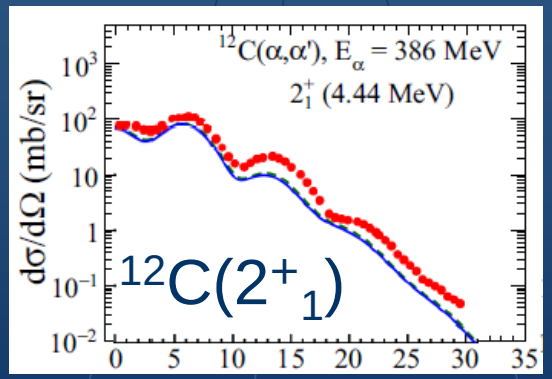
A puzzle: overestimation of monopole cross sections by factors of 3-5

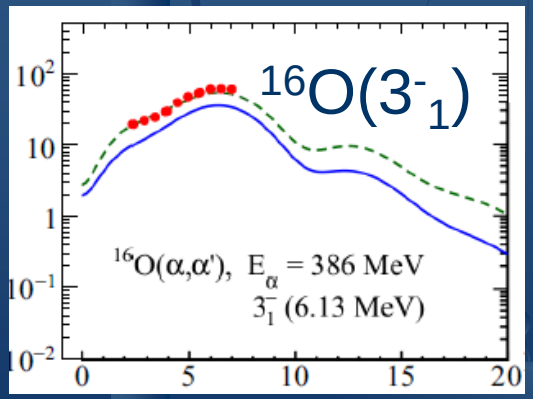






traditional reaction model
no problem in 2+, 3-,
but overshoot
only 0+ cross section
by a factor of 3-5



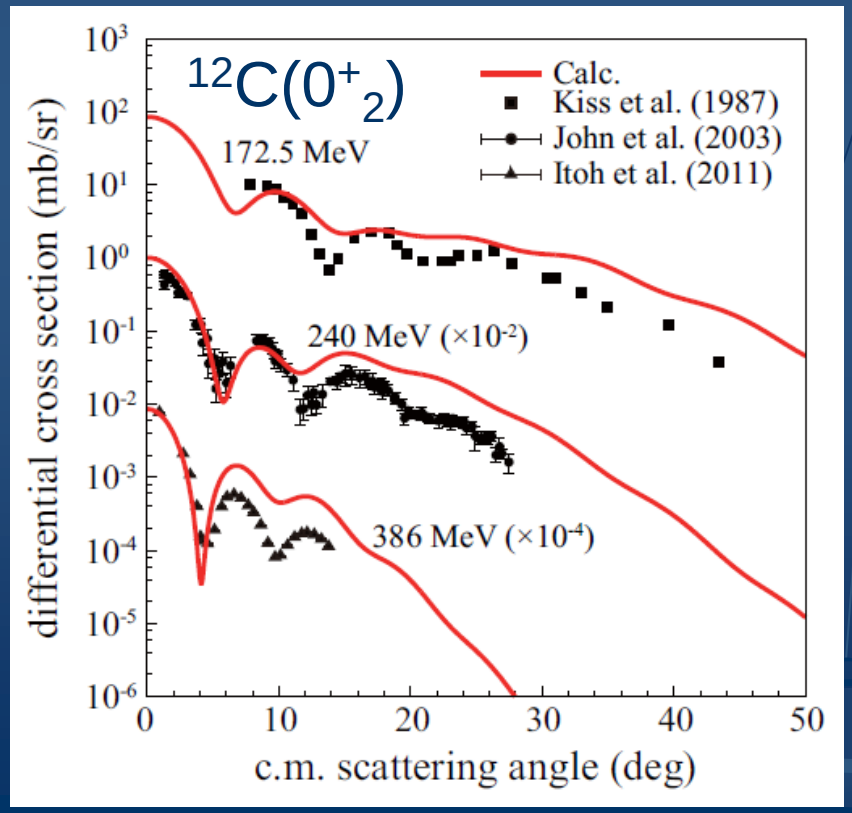


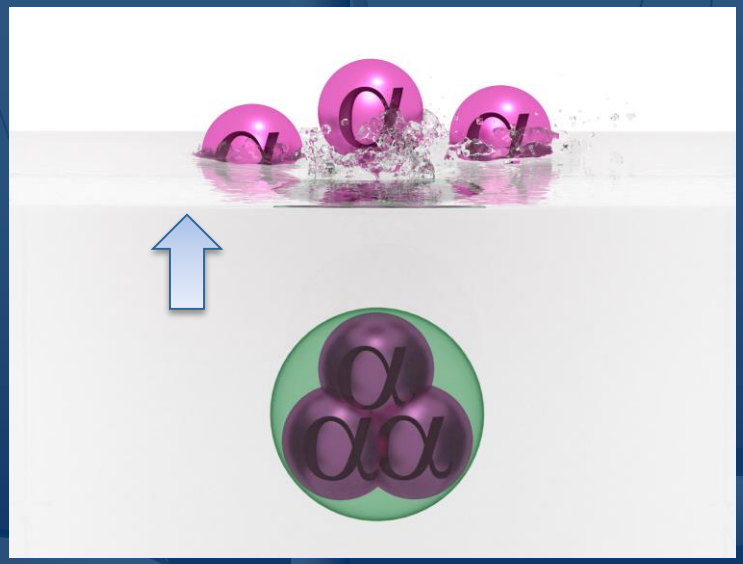
Adachi et al. PRC97,014601(2018)

Success of MCC calc. with g-matrix folding model

- microscopic coupled-channel (MCC)

successful reproduction of $^{12}C(0^+_2)$ cross sections with 3α-RGM density *Minomo et al. C 93, 051601(R) (2016)*





MCC: strategy

Reaction part

bare NN forces
(Bonn-B)

g-matrix theory

Effective NN int.
(Melbourne g-matrix)

double folding

α-nucleus potentials

coupled-channels calc.

(α,α') cross sections

Structure part

micro. structure model

(AMD, Cluster-GCM, RGM)

Matter and transition densities

great merits:
no phenomenological adjustable parameters for real and imaginary potentials.

2.Formulatoion of structure model: sAMD+GCM

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

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

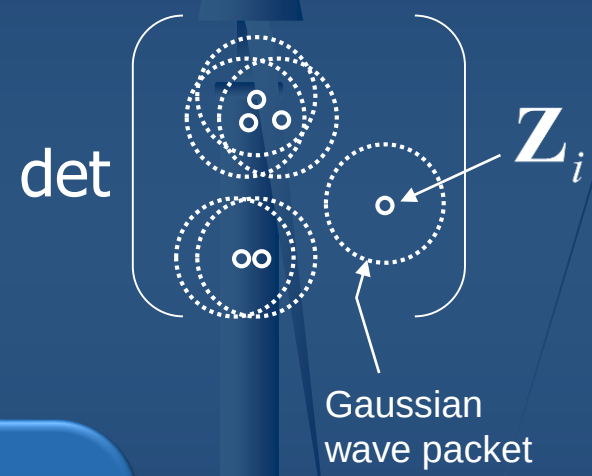
Intrinsic spins

isospin

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

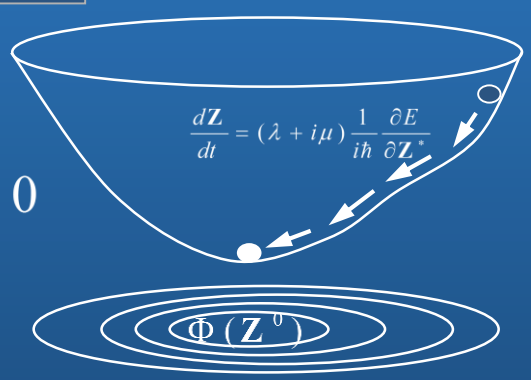
$$\mathbf{Z} = \{\mathbf{Z}_1, \mathbf{Z}_2, \cdots, \mathbf{Z}_A, \xi_1, \cdots, \xi_A\}$$

Variational parameters:
Gauss centers, spin orientations

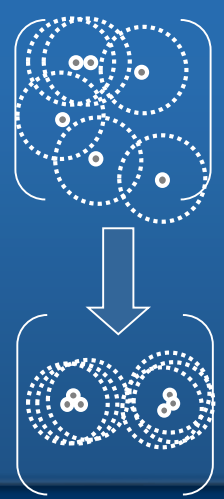


Energy Variation

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



Model space



Initial states

Energy minimum

J^π-VAP

to get the ground state wave function.

Shifted basis AMD (sAMD)

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

Ground st. wave functions

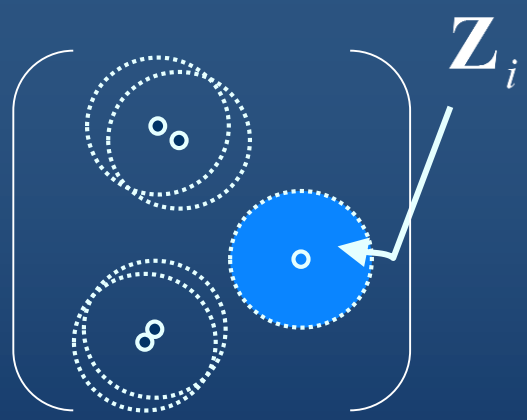
$$\varphi_i + \delta\varphi_i = \phi_{\mathbf{Z_i}+\delta\mathbf{Z_i}}\chi_{\mathbf{i}}$$

small shift of spatial part

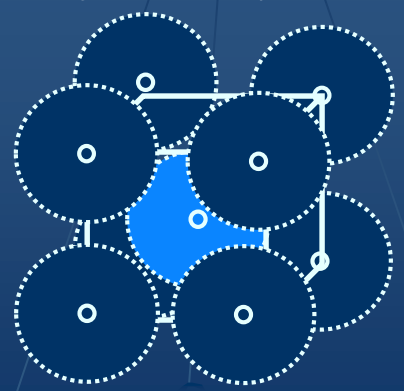
$$\det\{\varphi_1, \cdots, \varphi_i + \delta\varphi_i, \cdots, \varphi_A\}$$

A shifted basis

det



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



Small shift for 8 orientations

(8A basis)

8A basis is enough for IS0,E1,IS1 in 12C and Be

sAMD+GCM

AMD(VAP)
Ground state wave function → g.s. cluster correlation

sAMD
1p1h excitations on g.s. → GRs

GCM various cluster configurations

→ Large amp. cluster motion in LE

sAMD+GCM: all bases are superposed.

Jπ-projection, cm motion are treated microscopically

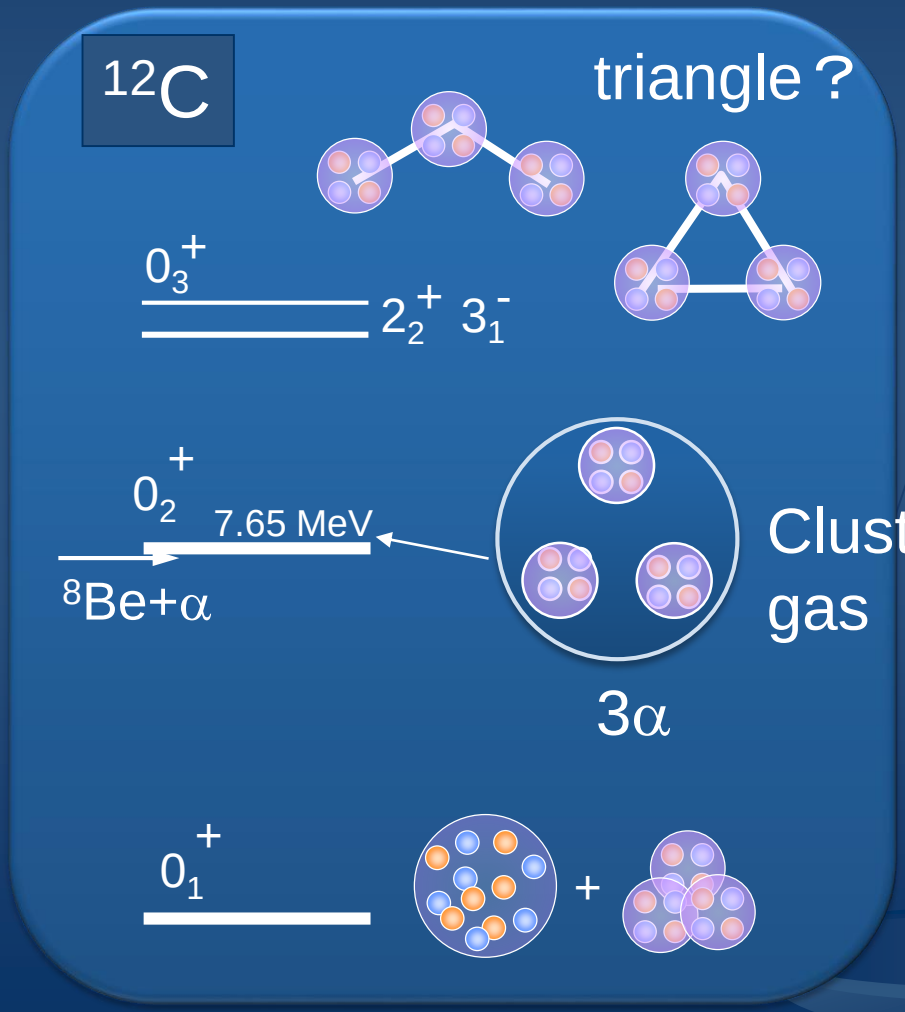
Today's topics

1. cluster states in ^{12}C
2. alpha scattering off ^{12}C, ^{16}O
3. cluster states in ^{14}C

Topic 1

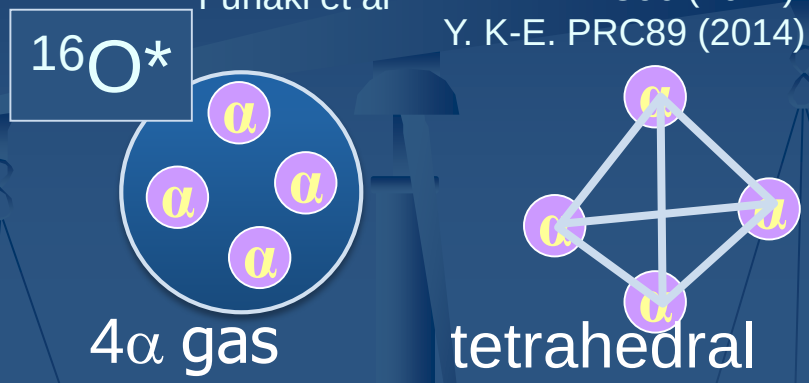
Cluster states in ^{12}C with sAMD+3αGCM

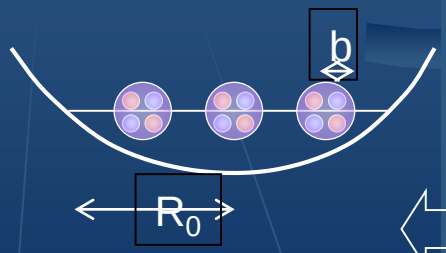
multi-cluster: gas, triangle, linear chain

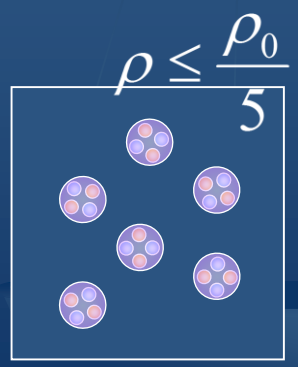


Tohsaki et al., Funaki et al

Yamada et al., Y. K-E PRC96 (2017) Y. K-E. PRC89 (2014)

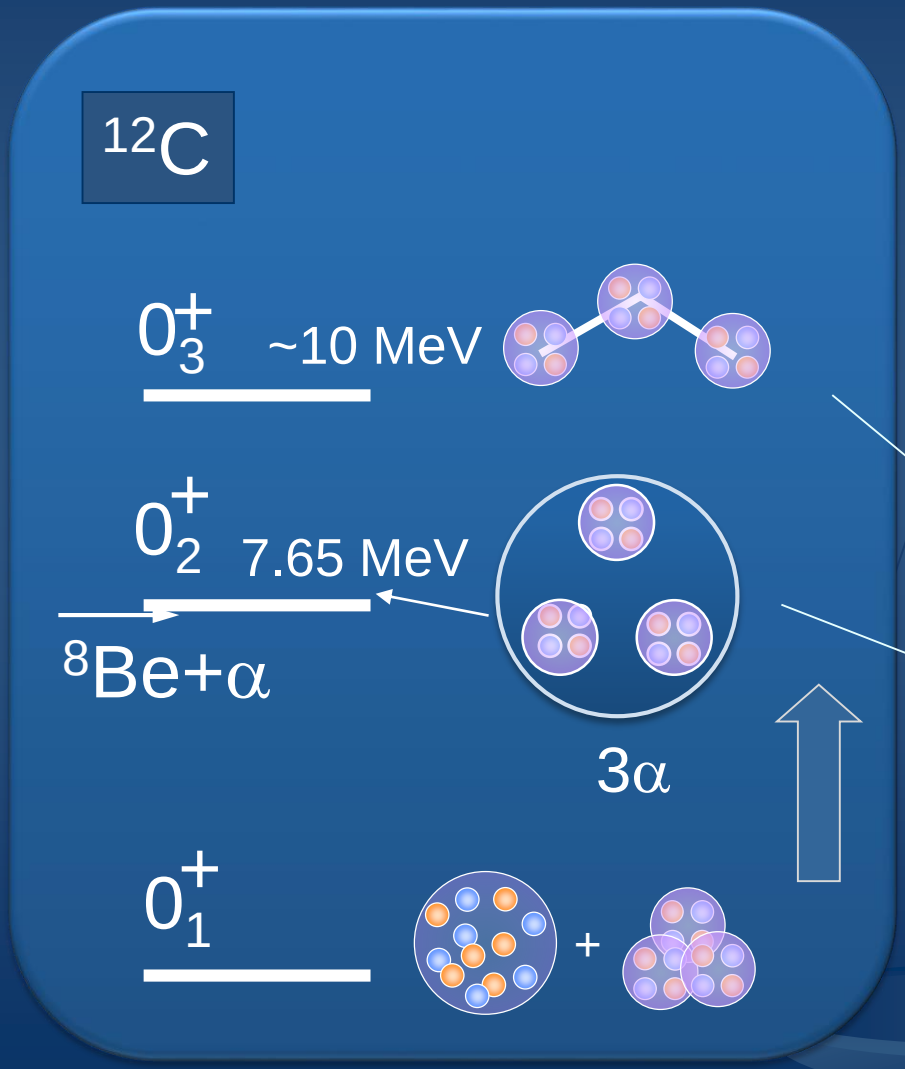


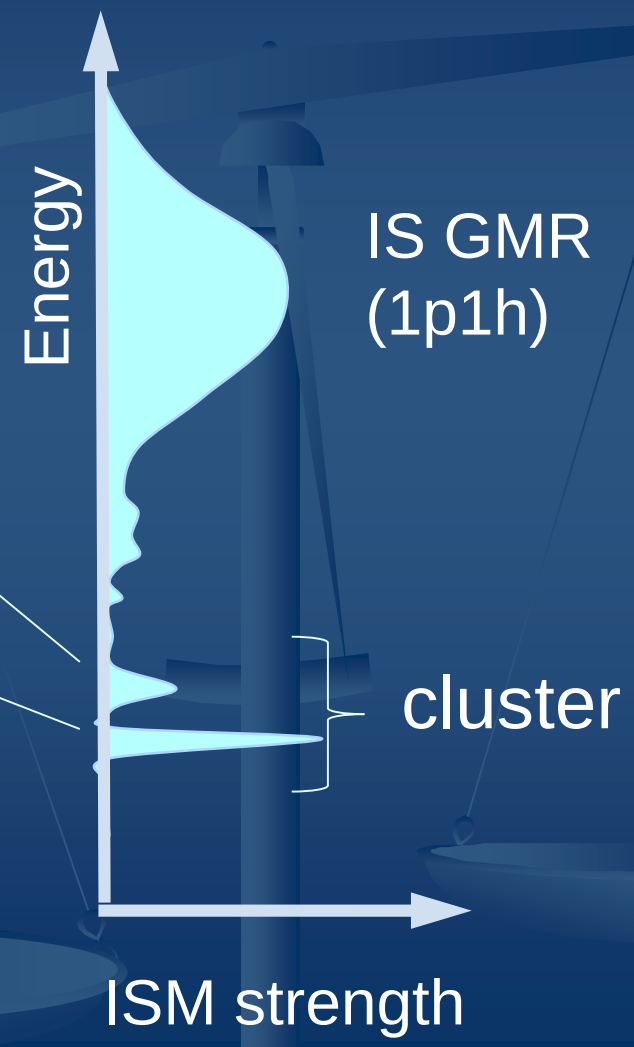




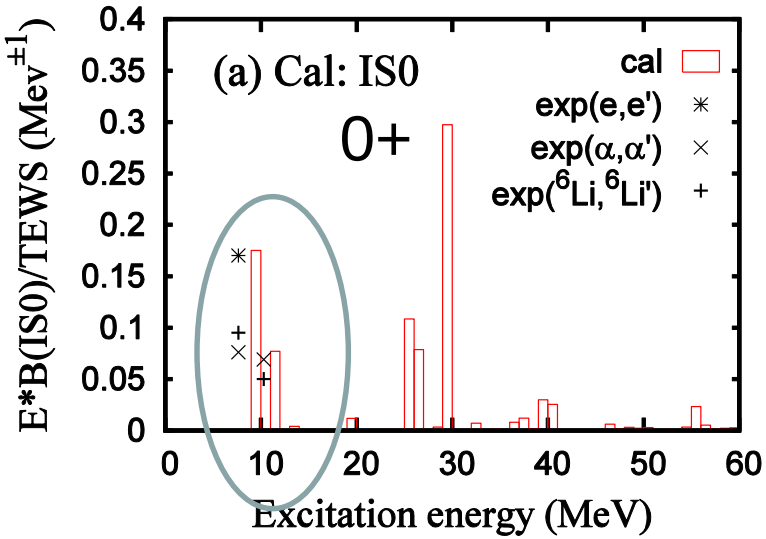
Analogy to BEC in dilute nuclear matter

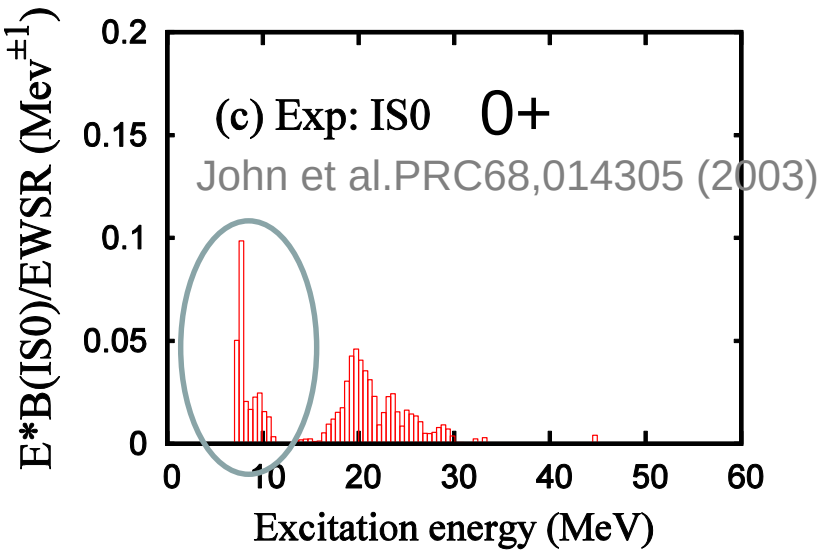
Results of ^{12}C: sAMD+3αGCM for ISM and ISD excitations



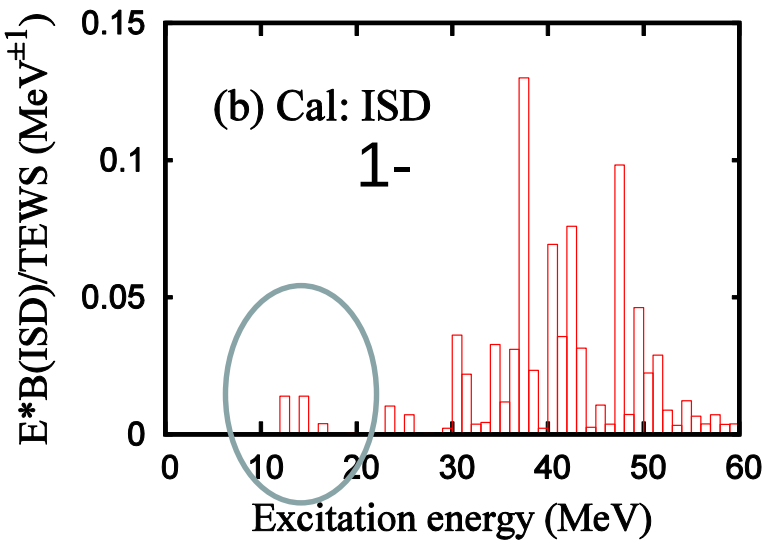


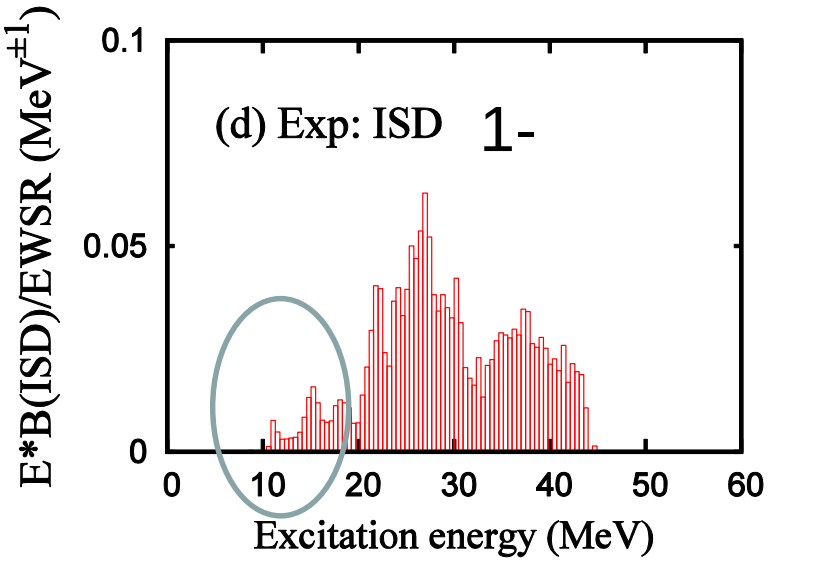
IS Monopole, Dipole strengths in 12C: sAMD+GCM(3α)



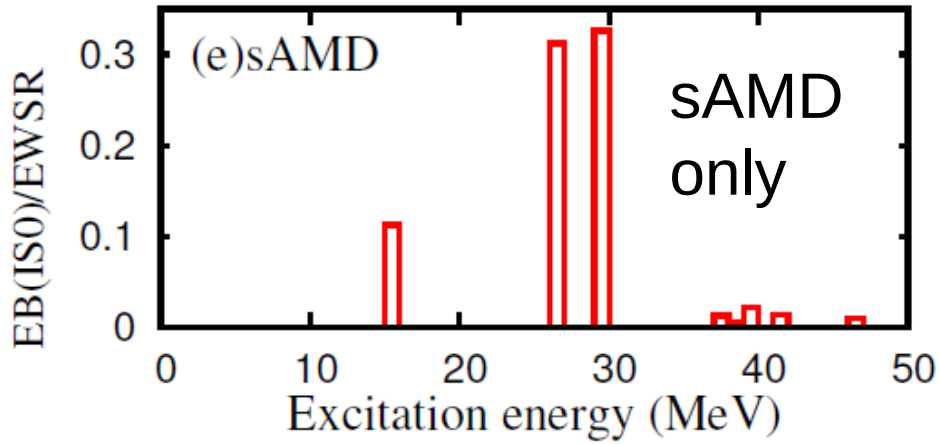


Low-energy strengths for cluster states separately from GRs.
Why the LE strengths are fragmented into a few cluster states?



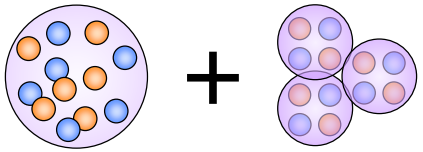


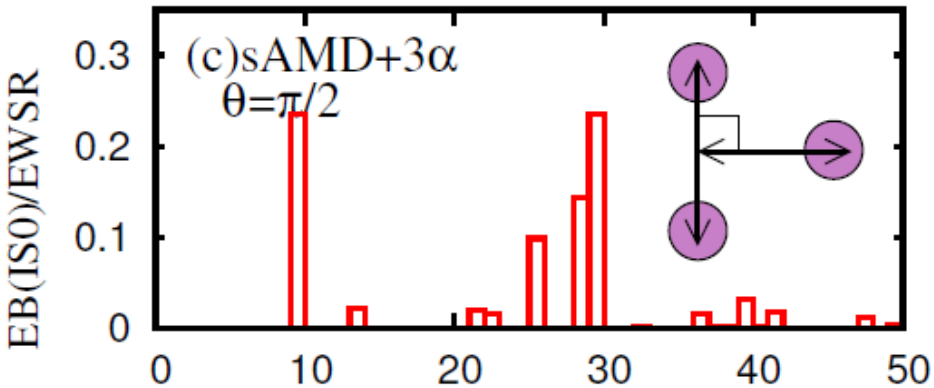
B(ISM) of ^{12}C



sAMD small amp: 1p-1h

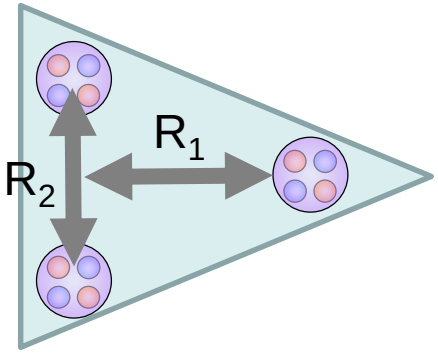
GMR strengths

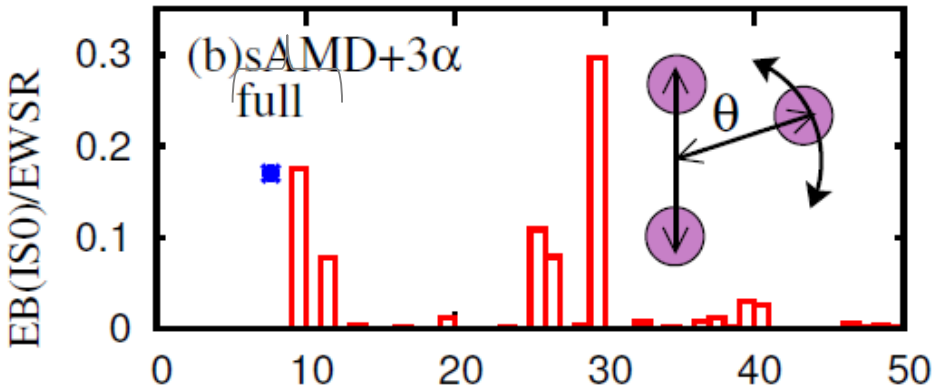




sAMD+3α(π/2)
distance mode

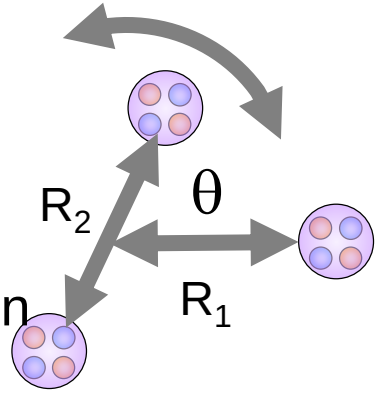
Large amplitude
cluster motion





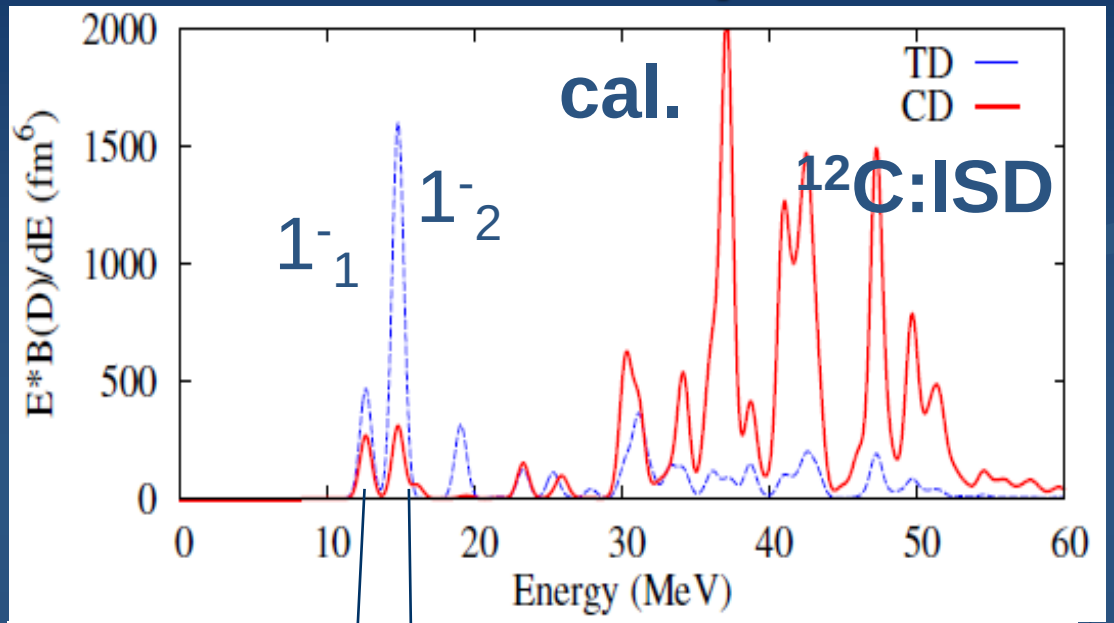
sAMD+3α(full)

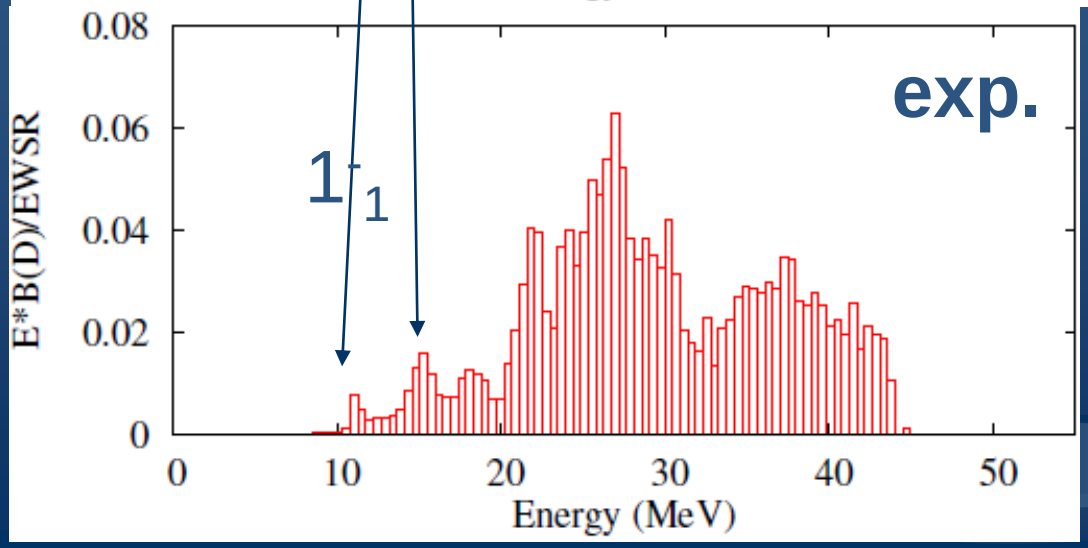
distance& angular



Coupling of 8Be-rotation
splits LE-ISM

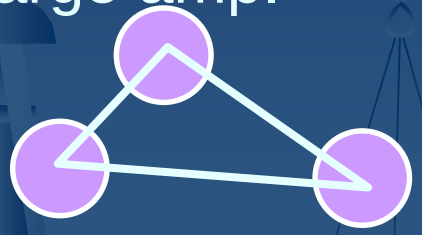
Dipole in ^{12}C





1^-_1 Cluster mode

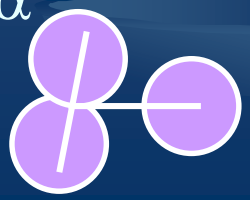
Large amp.



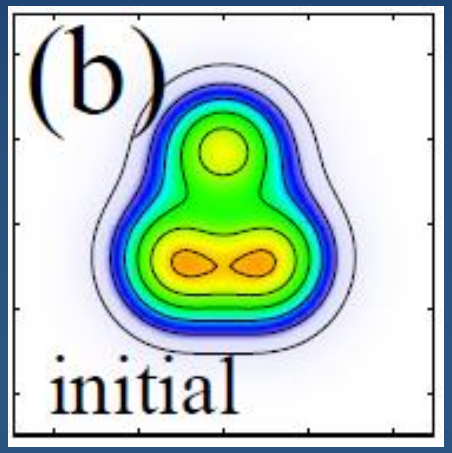
Distorted 3α-triangle
= Uegaki's 3α-GCM

1^-_2 vibration

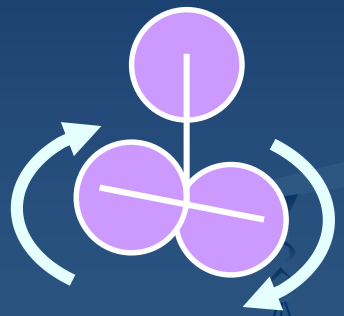
Small amp. 1p1h mode
Compact 3α



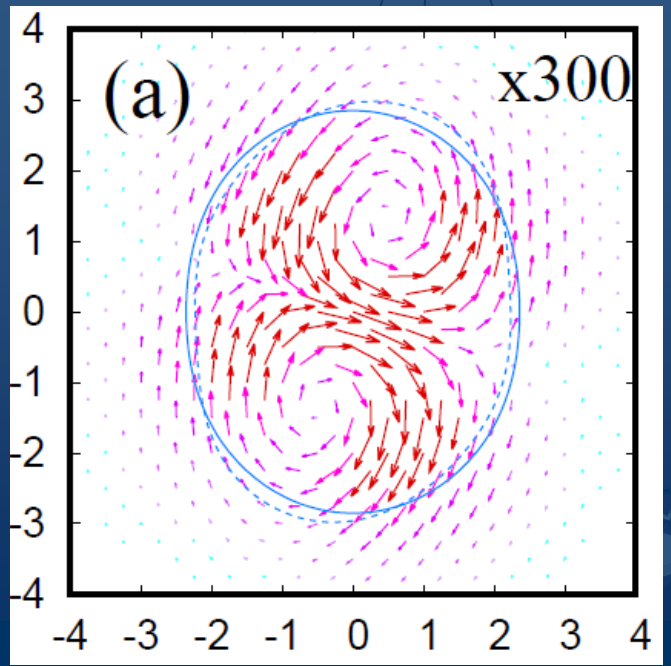
Vortical nature in 0^+_1 to 1^-_2

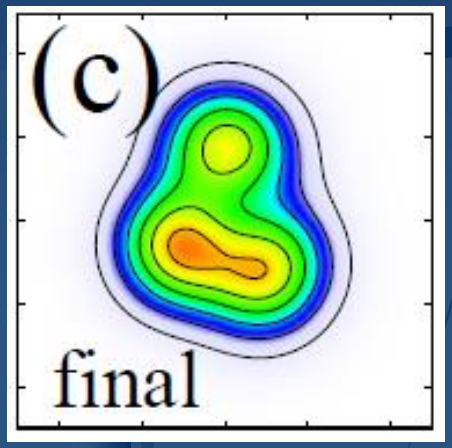


0^+



Transition current density

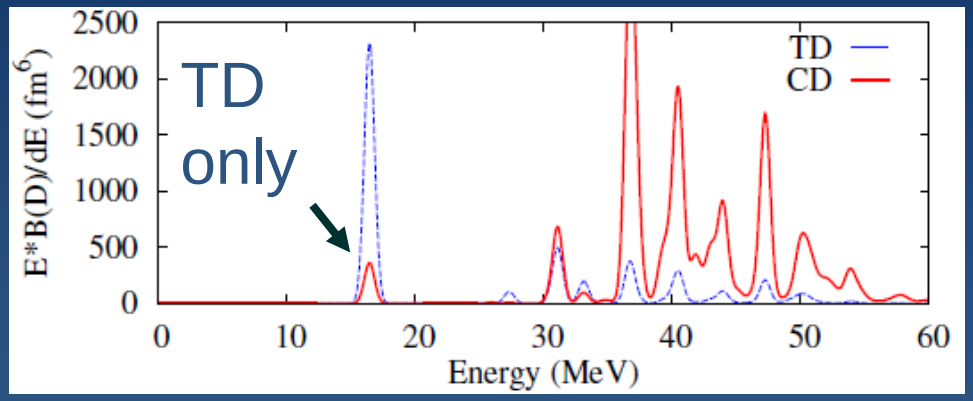


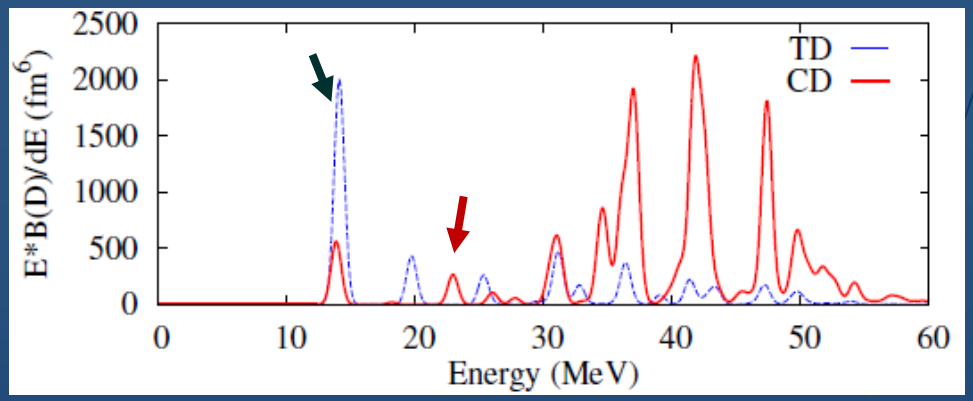


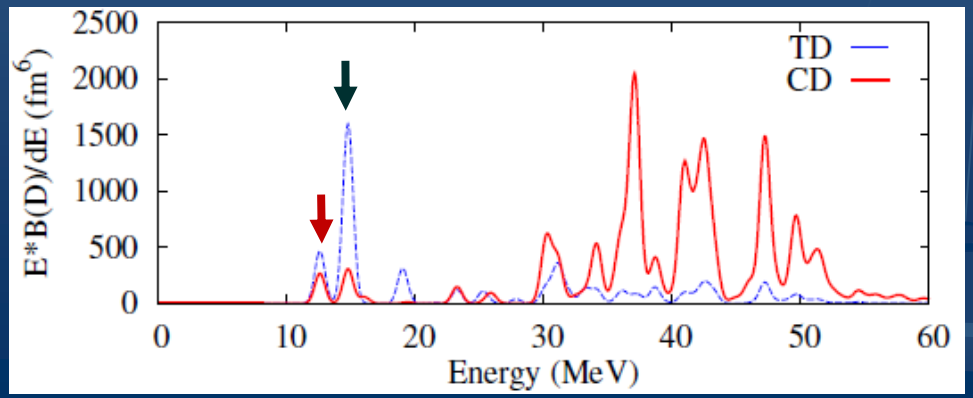
1^-_2

2α-cluster rotation induces vortical (toroidal) current.

Compressive and toroidal dipole strengths





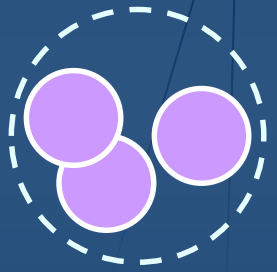


CD:compressive TD:toroidal

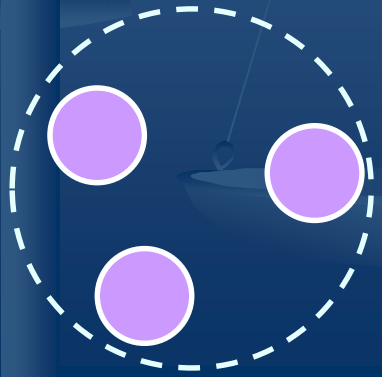
$$(\nabla \cdot \mathbf{j})\, r^3 Y_{1\mu} \qquad (\nabla \times \mathbf{j}) \cdot r^3 \mathbf{Y}_{11\mu}$$

sAMD: small amp.

sAMD
+3α(R<3 fm)



sAMD
+3α(full)



Topic 2

Alpha inelastic scattering with MCC

microscopic reaction calculations with g-matrix folding model

- successful reproduction of $^{12}C(0^+_2)$ cross sections with RGM density by Minomo et al.

Minomo et al. C 93, 051601(R) (2016)

No overshooting problem of 0+ cross sections

Reliable reaction approach:
There is no phenomenological adjustable parameters in the reaction part

MCC

Minomo et al. PRC93 (2016)
K-E, Ogata PRC99 (2019)
K-E. Ogata ORC99 (2019)

Reaction part

bare NN forces
(Bonn-B)

g-matrix theory

Effective NN int.
(Melbourne g-matrix)

double folding

α-nucleus potentials

coupled-channels calc.

(α,α') cross sections

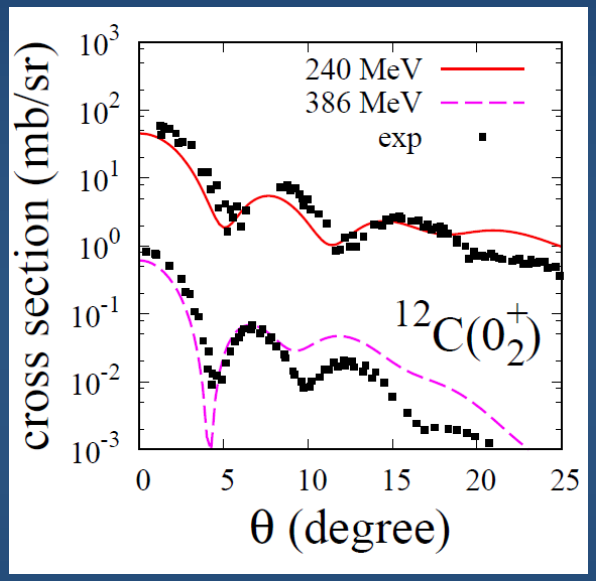
Structure part

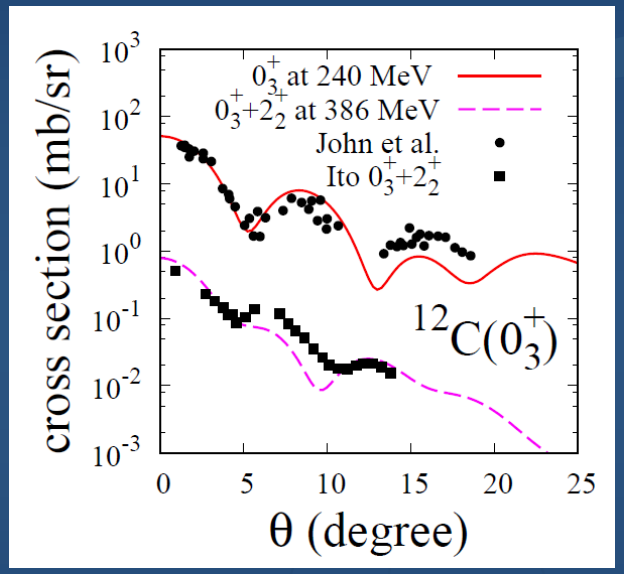
micro. structure model
(AMD, Cluster-GCM, RGM)
1p1h, cluster, vib/rot, vortical, GR

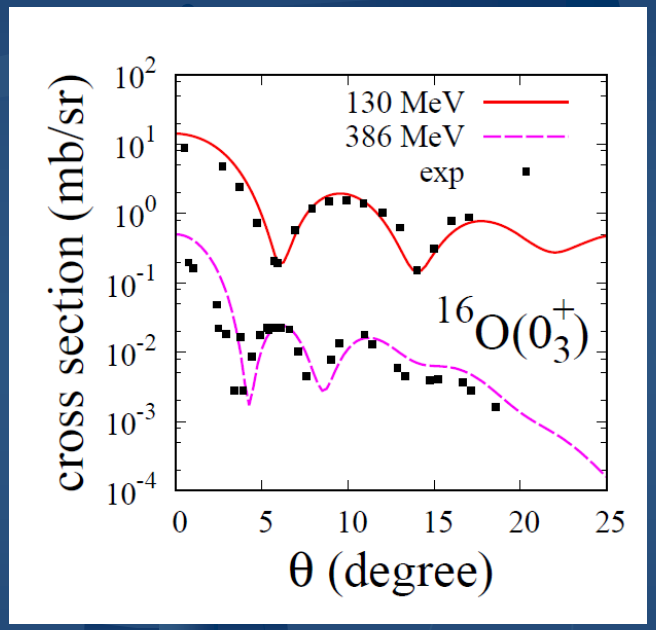
Matter and transition densities

great merits:
no phenomenological adjustable parameters for real and imaginary potentials.

Results of $^{12}C(\alpha,\alpha')$ and $^{16}O(\alpha,\alpha')$ MCC with AMD densities





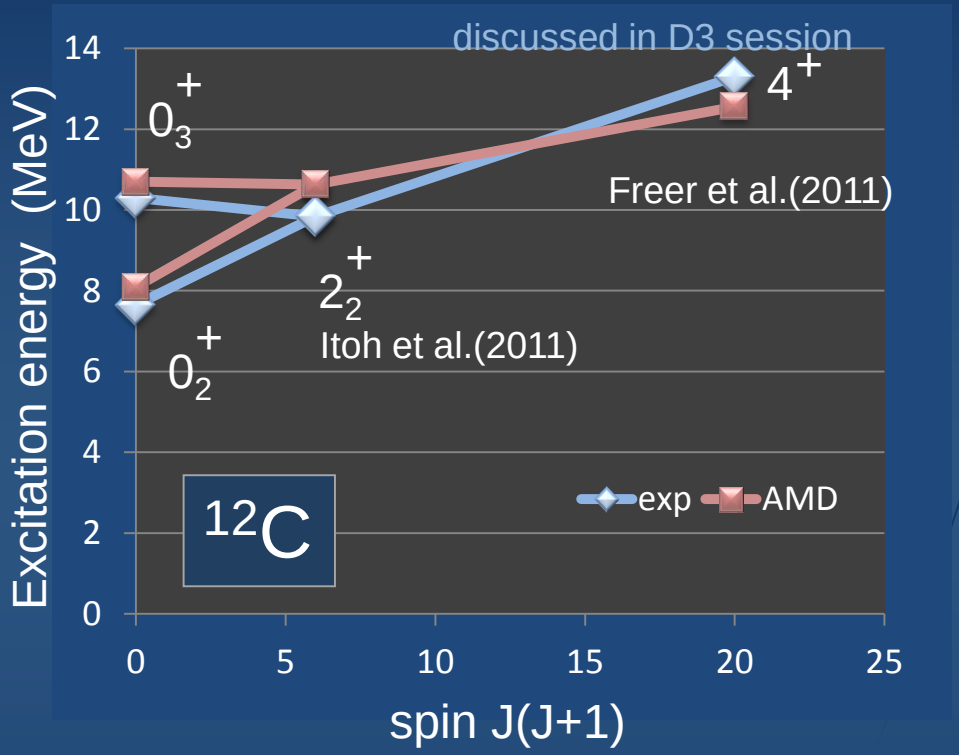


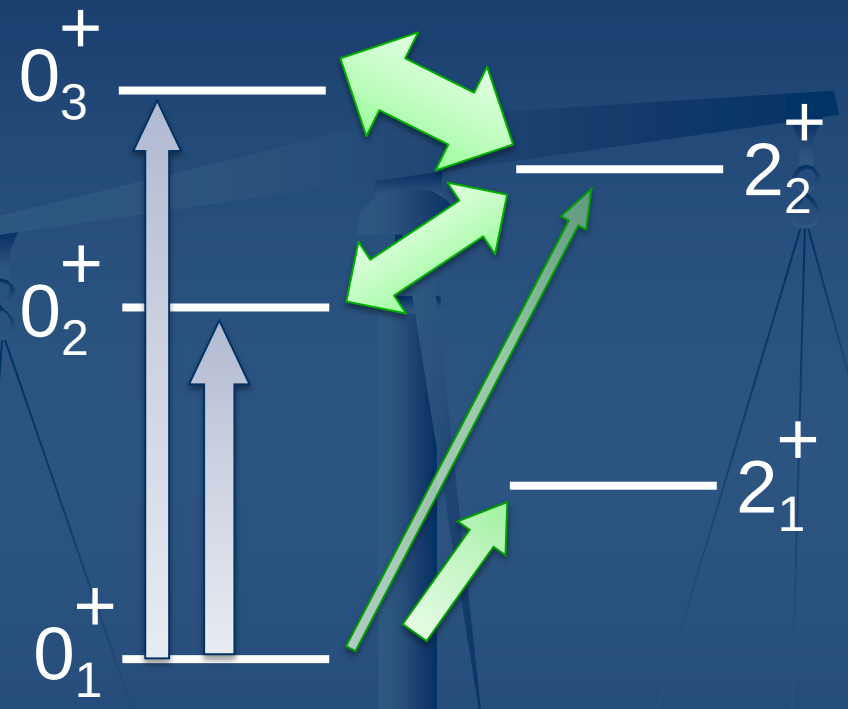
Cross sections are successfully described:
Alpha inelastic scattering can be a good probe for searching new cluster states

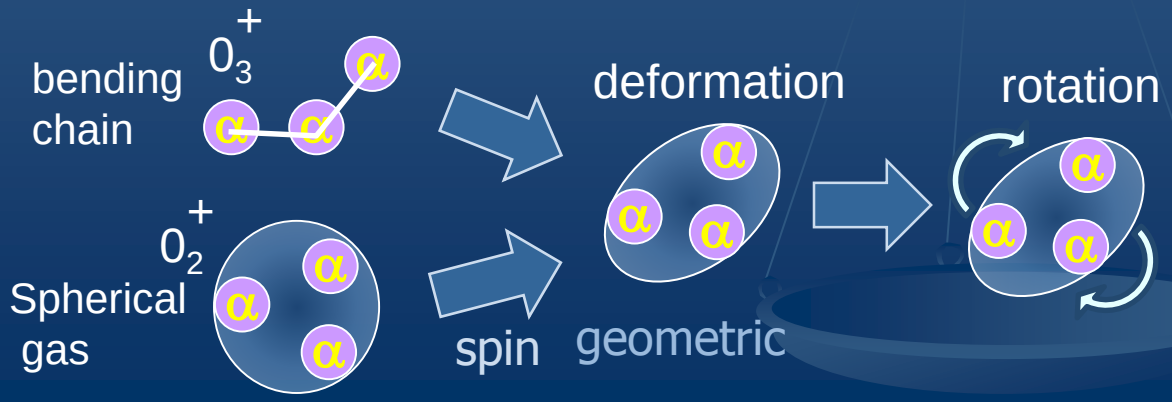
What we can learn from α,α' scattering?

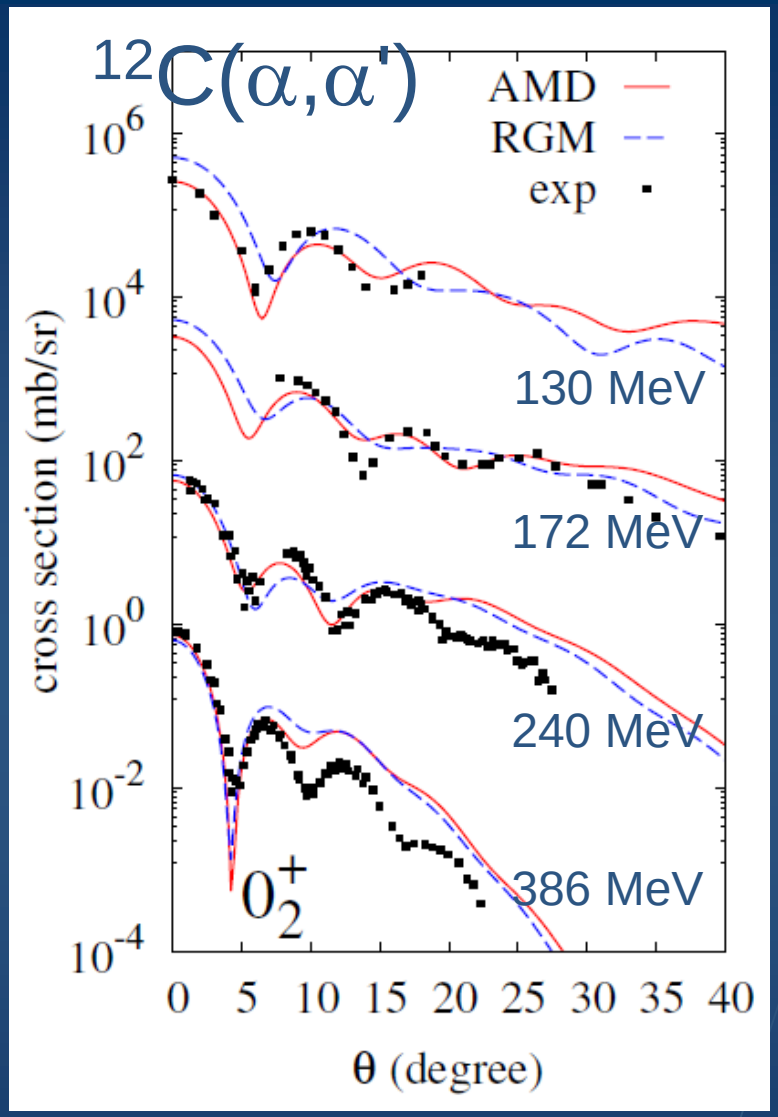
- Search for new cluster states
- Determination of B(IS0) and B(IS1)
- Information of transitions between excited states

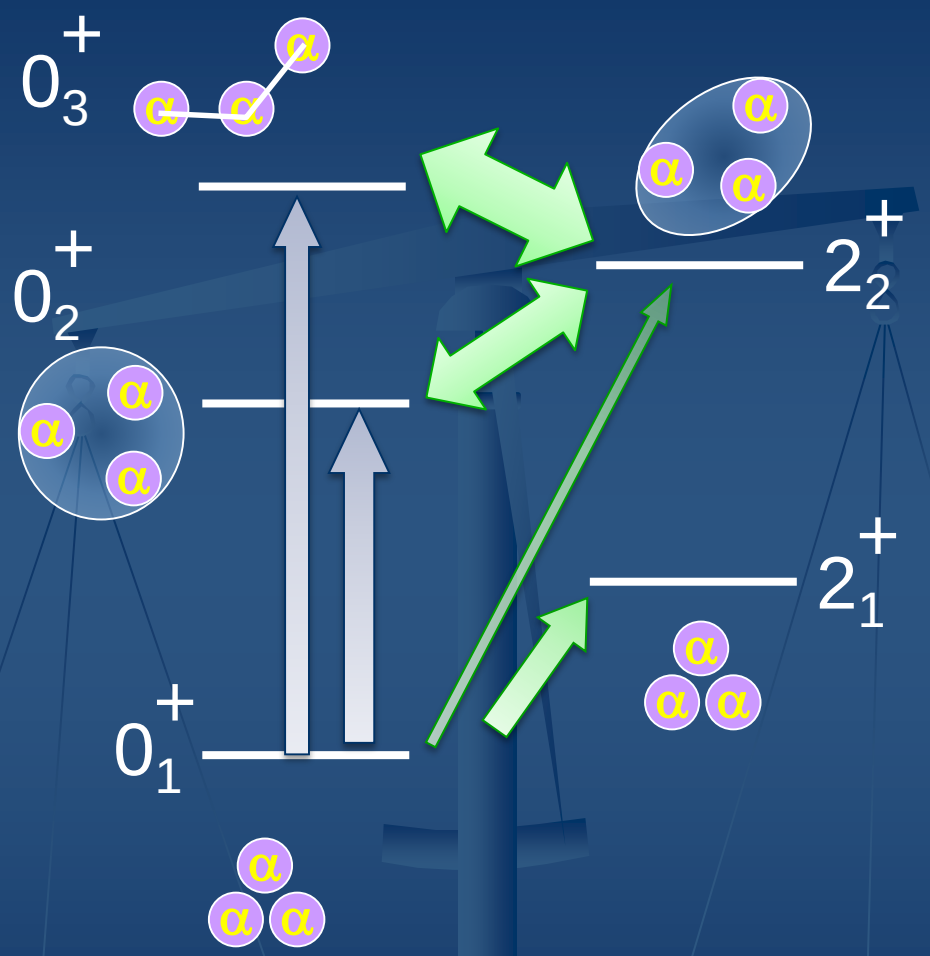
Rotational band from cluster gas





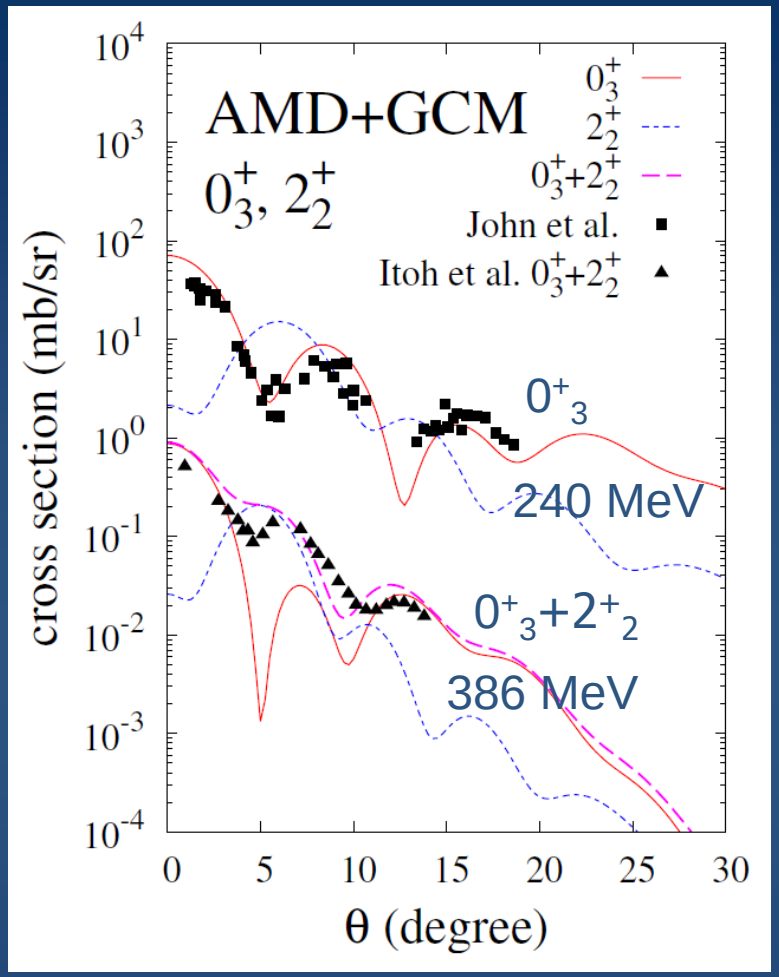


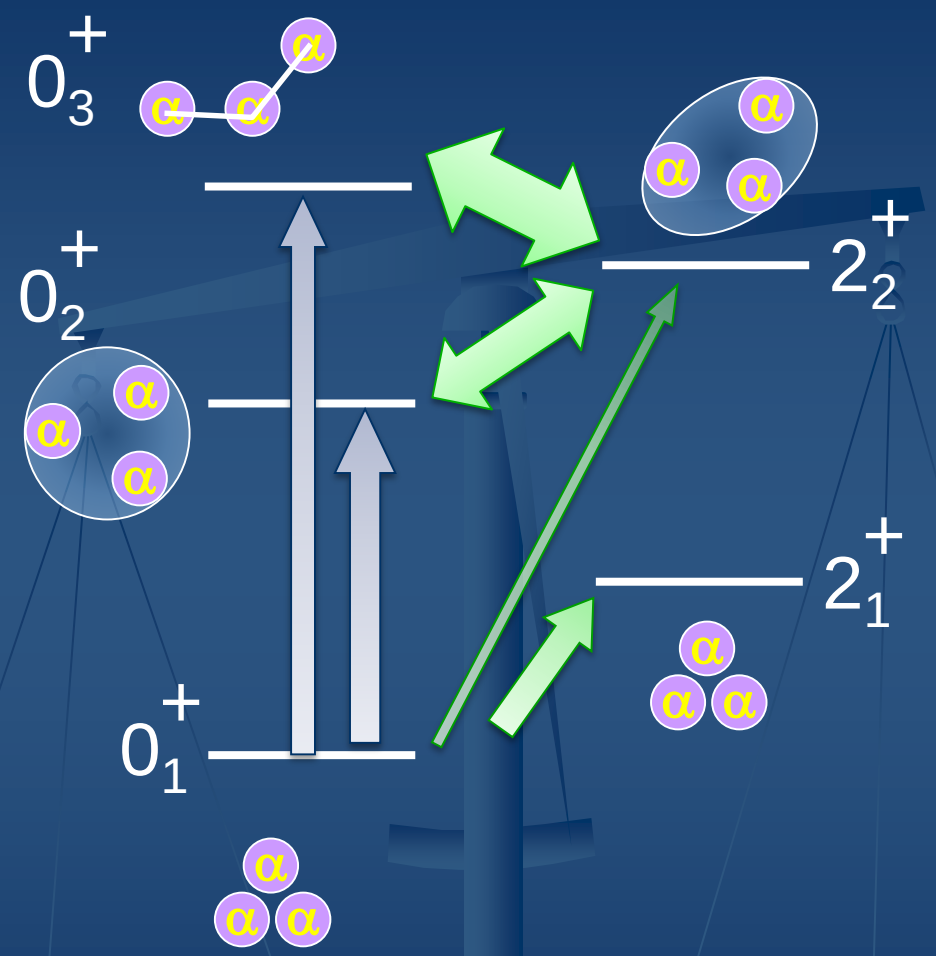




AMD is better

RGM: too strong coupling with 2^+_2

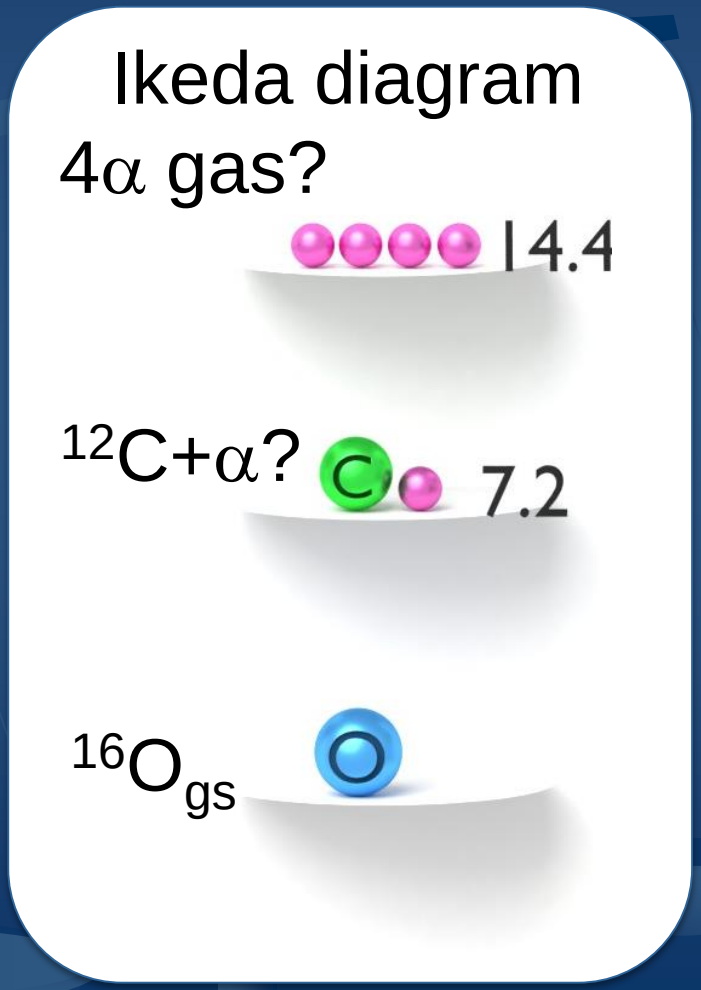




- Determination of B(E0) for 0^+_3
- Experimental discovery of 2^+_2 by Itoh

Topic 2-2

Cluster states in ^{16}O with sAMD+GCM



Band structures of ^{16}O

large amplitude cluster states

$^{12}C(0+_1)+\alpha$ bands

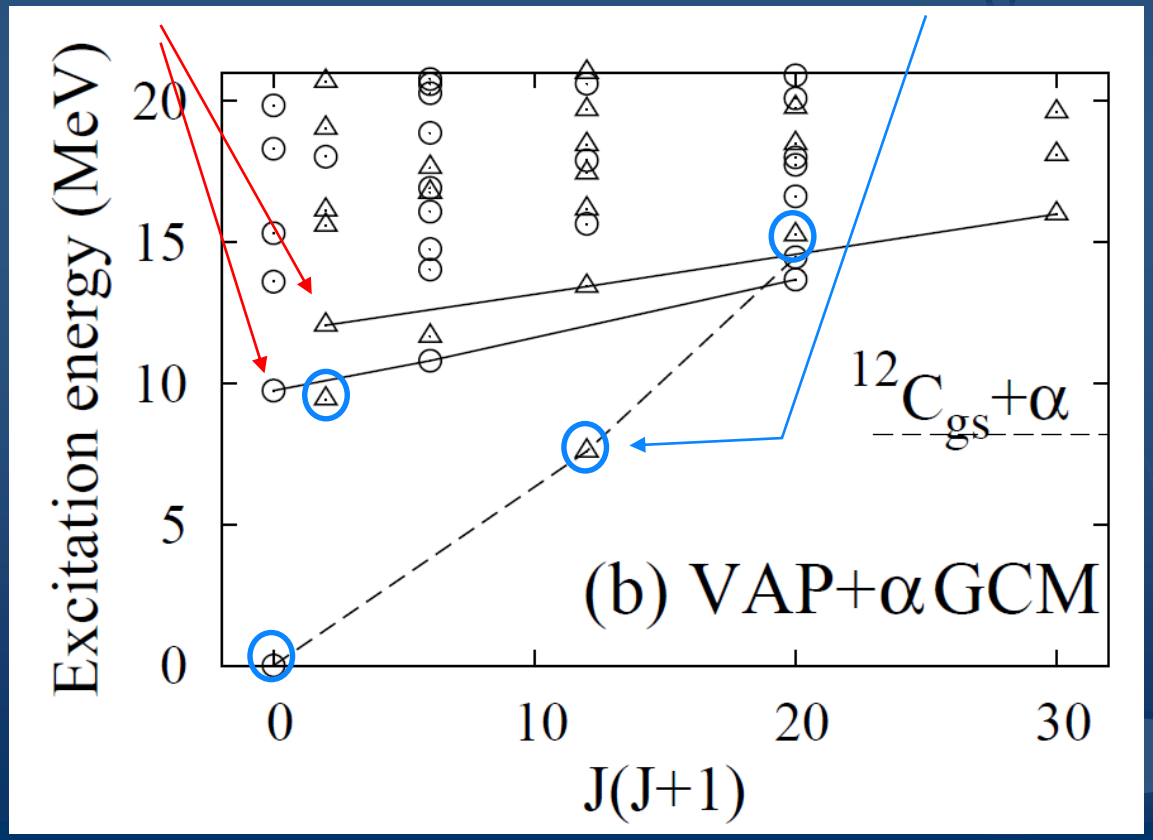
K=0+ (0^+_1, 2^+_1, 4^+_1),

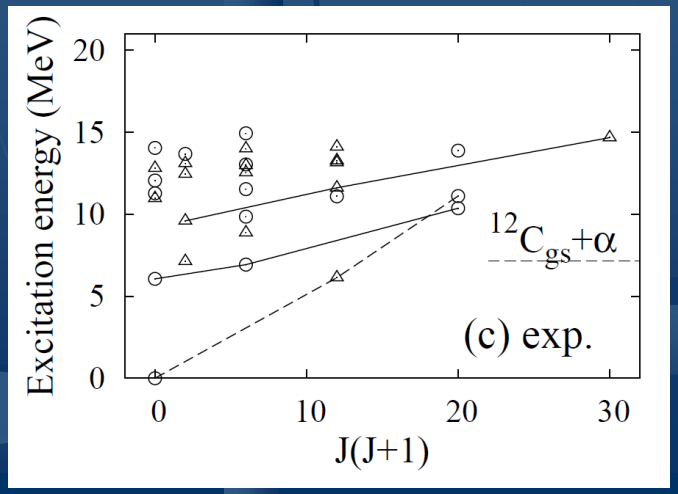
K=0- (1^-_2, 3^-_2, 5^-_1)

small amplitude modes

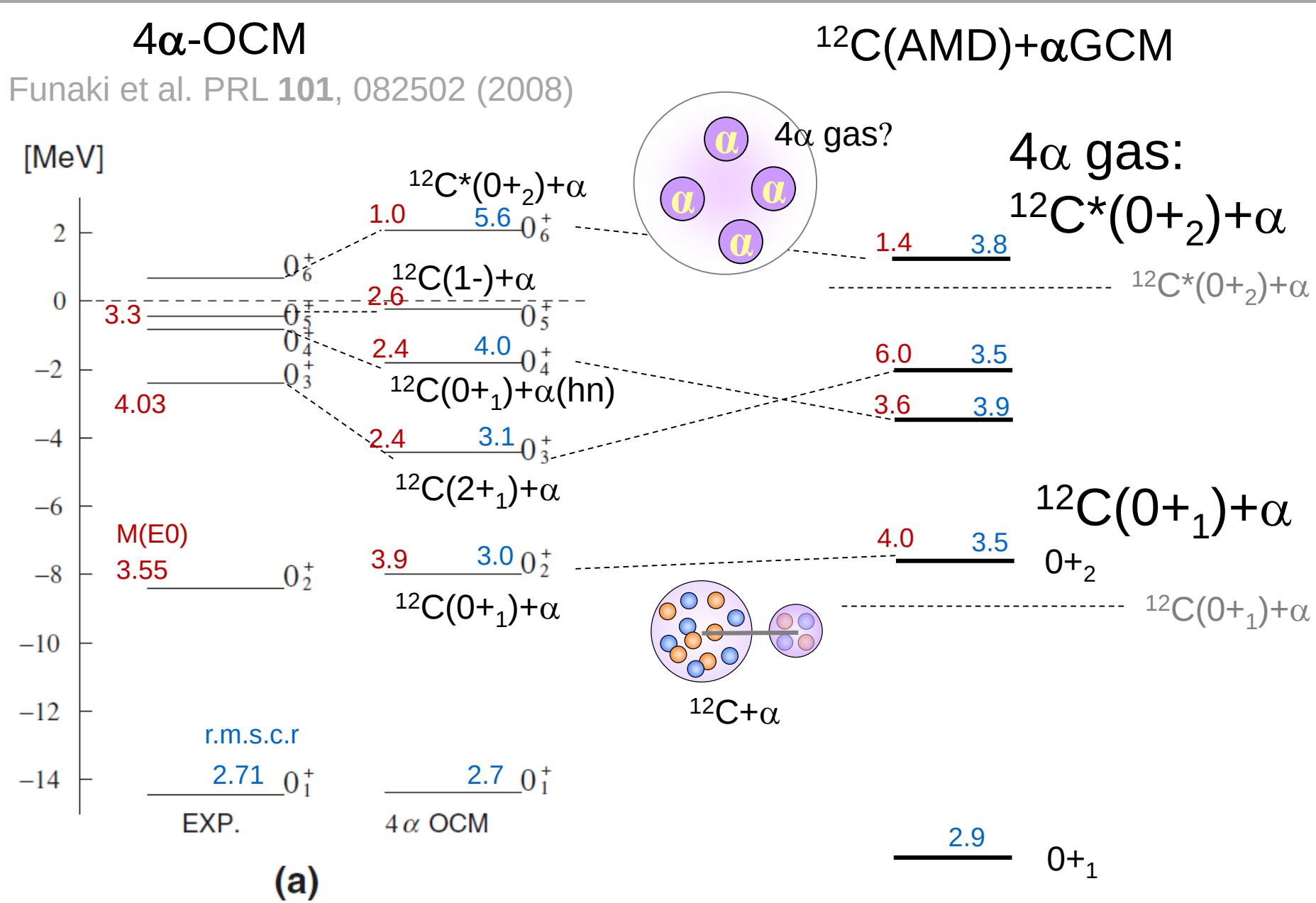
Ground band(0^+_1, 3^-_1, 4^+_2) ,

vib(TD) 1^-_1

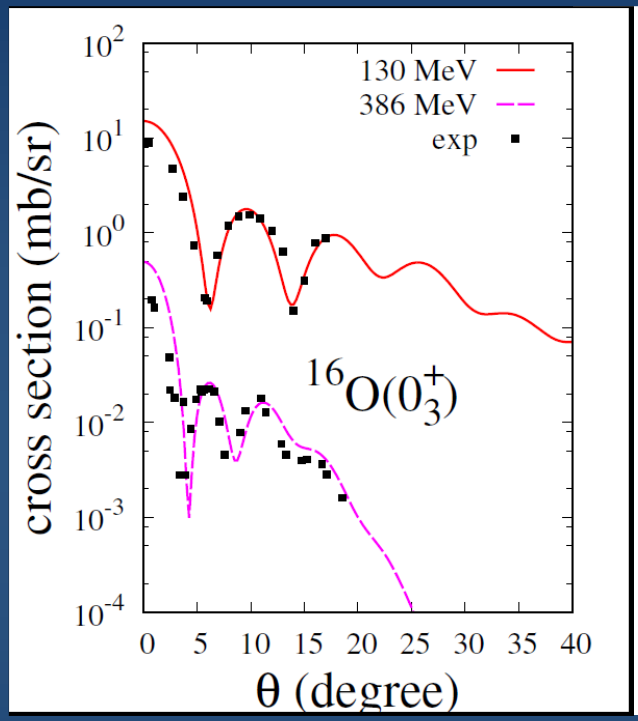


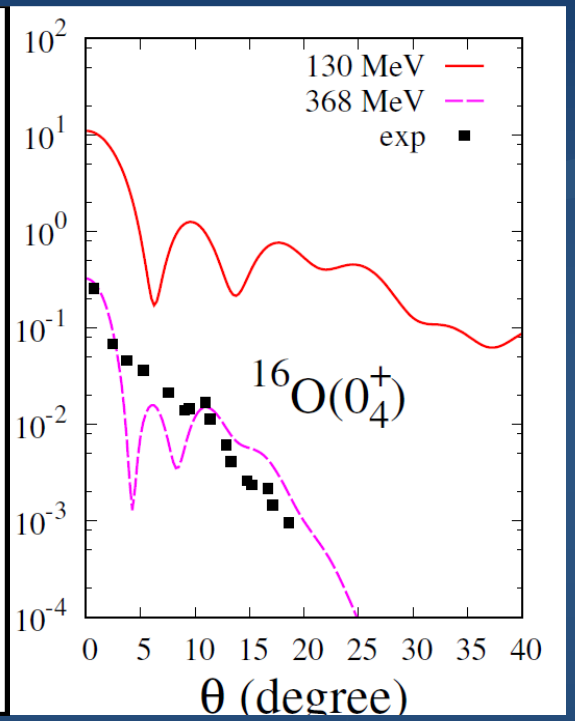


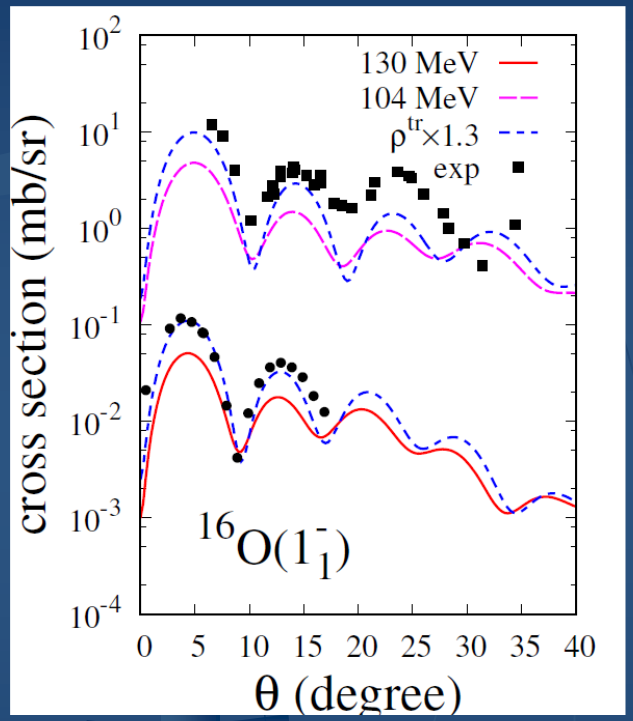
Monopole excitations in ^{16}O



α scattering off ^{16}O (first MCC calc.)







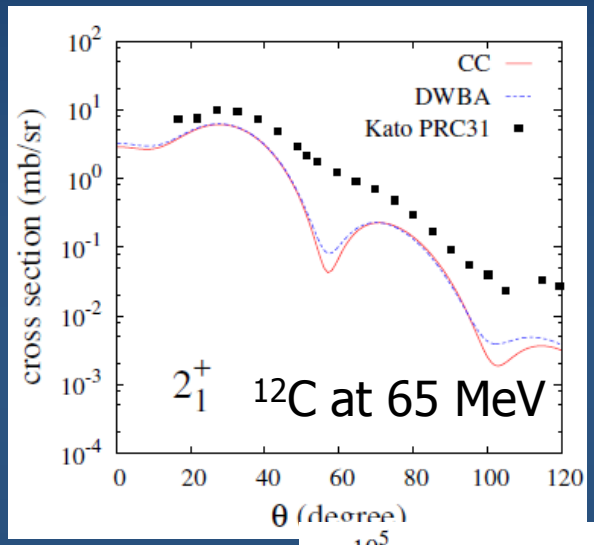
0+ states: large amp. cluster modes
successfully reproduces 0+ cross sections

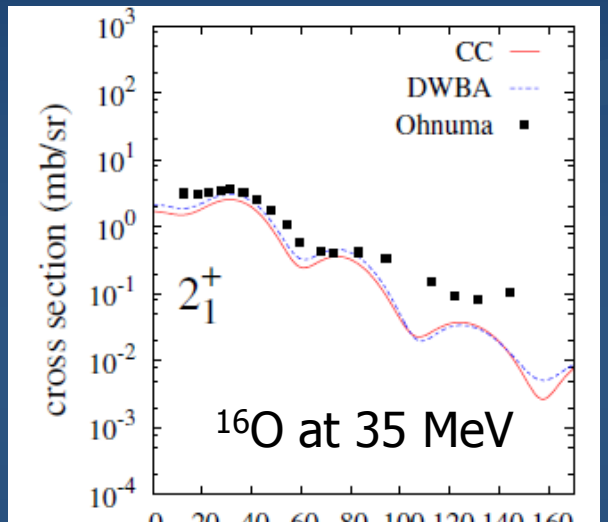
1- state: small amp. mode
Larger B(IS1) by a factor of 1.3 is favored

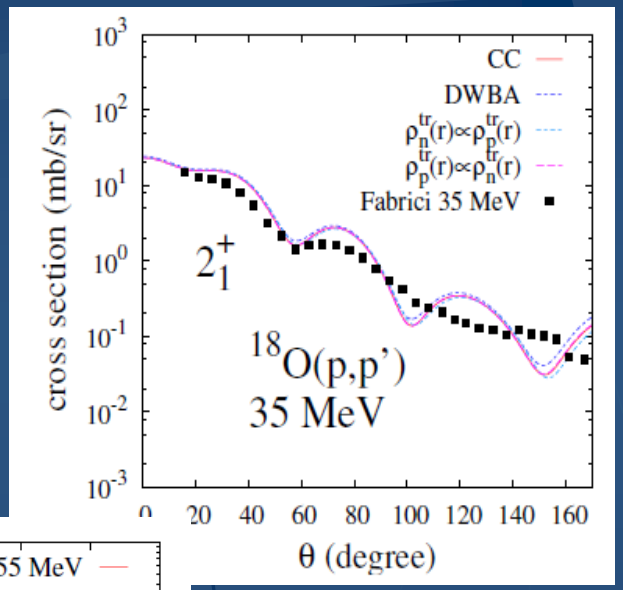
Application to unstable nuclei
(p,p') scattering for 2^+_1 transitions

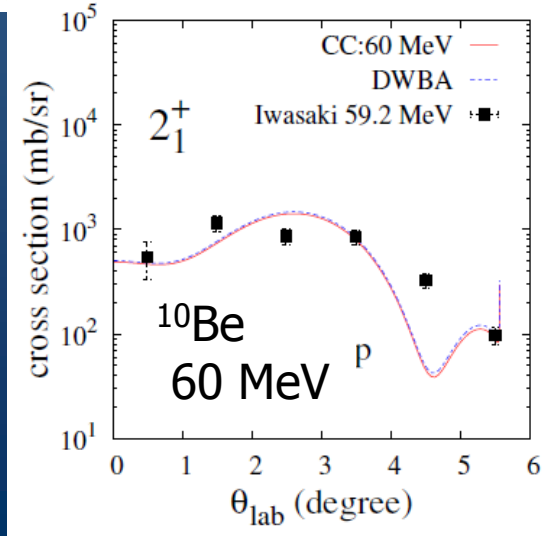
to measure quadrupole deformation

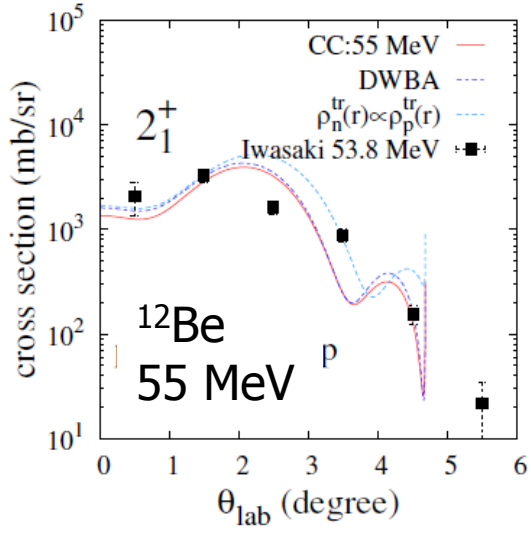
Proton/neutron differences (Mn/Mp ratio) can be discussed











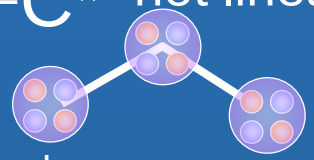
Topic 3

Cluster states in ^{14}C with AMD+(3α+nn)GCM

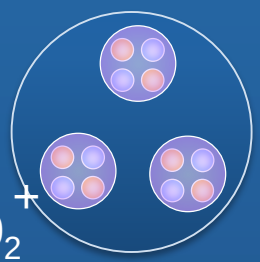
Triangle / Linear states in $^{14}C^*$

^{12}C — Excess neutron — $^{14,16}C$

$^{12}C^*$ not linear

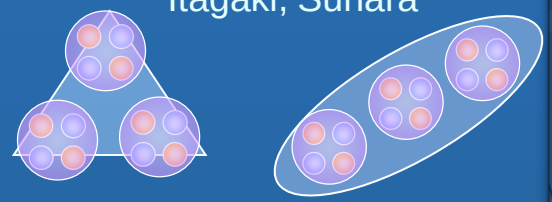


0_3^+ Y.K-E.et al., T. Neff et al.



0_2^+ Tohsaki et al., Funaki et al.

Itagaki, Suhara



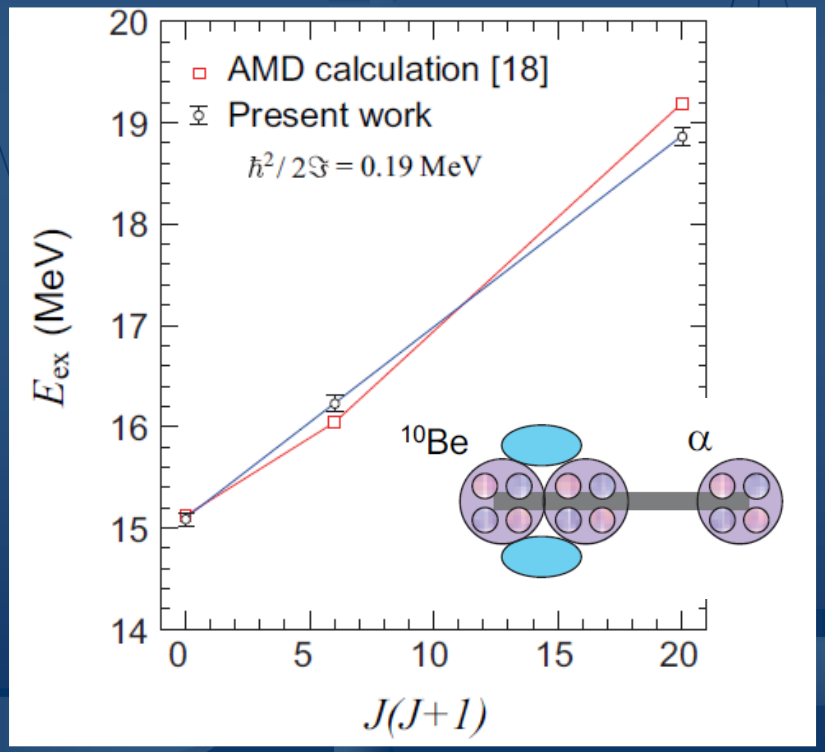
Triangle, linear α-hain

von Oertzen ZPA354(96) EPJA21(04),PR 432(06)
Itagaki PRC64(01)
Suhara PRC82(10)
Maruhn NPA833(10)
Baba PRC90(14).

^{12}C g.s. ^{14}C g.s.

^{14}C 3α linear chain

theor. Suhara.Y.K-E, PRC82 (2010)
exp. Yamaguchi et al, PLB766(2017)

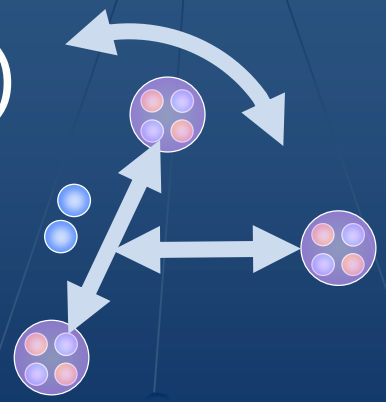


^{14}C:AMD+(3α+nn)GCM

AMD $^{14}C(0^+_{1,2}, 2^+_{1,2})$

combined with cluster config.

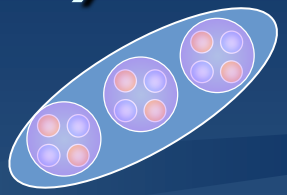
GCM(3**a+nn**)

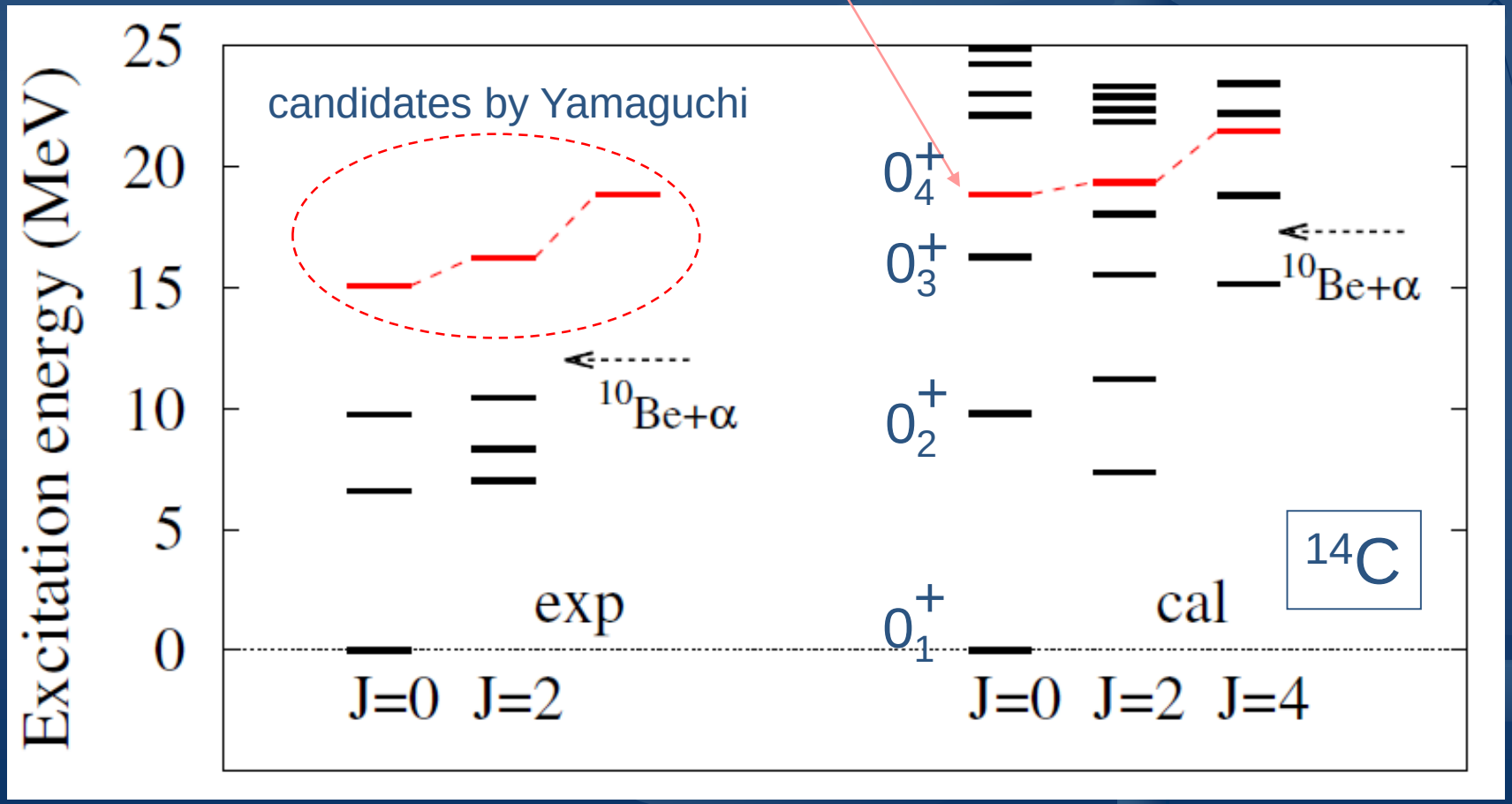


3-alpha dynamics with nn

^{14}C results : AMD+(3α+nn)GCM

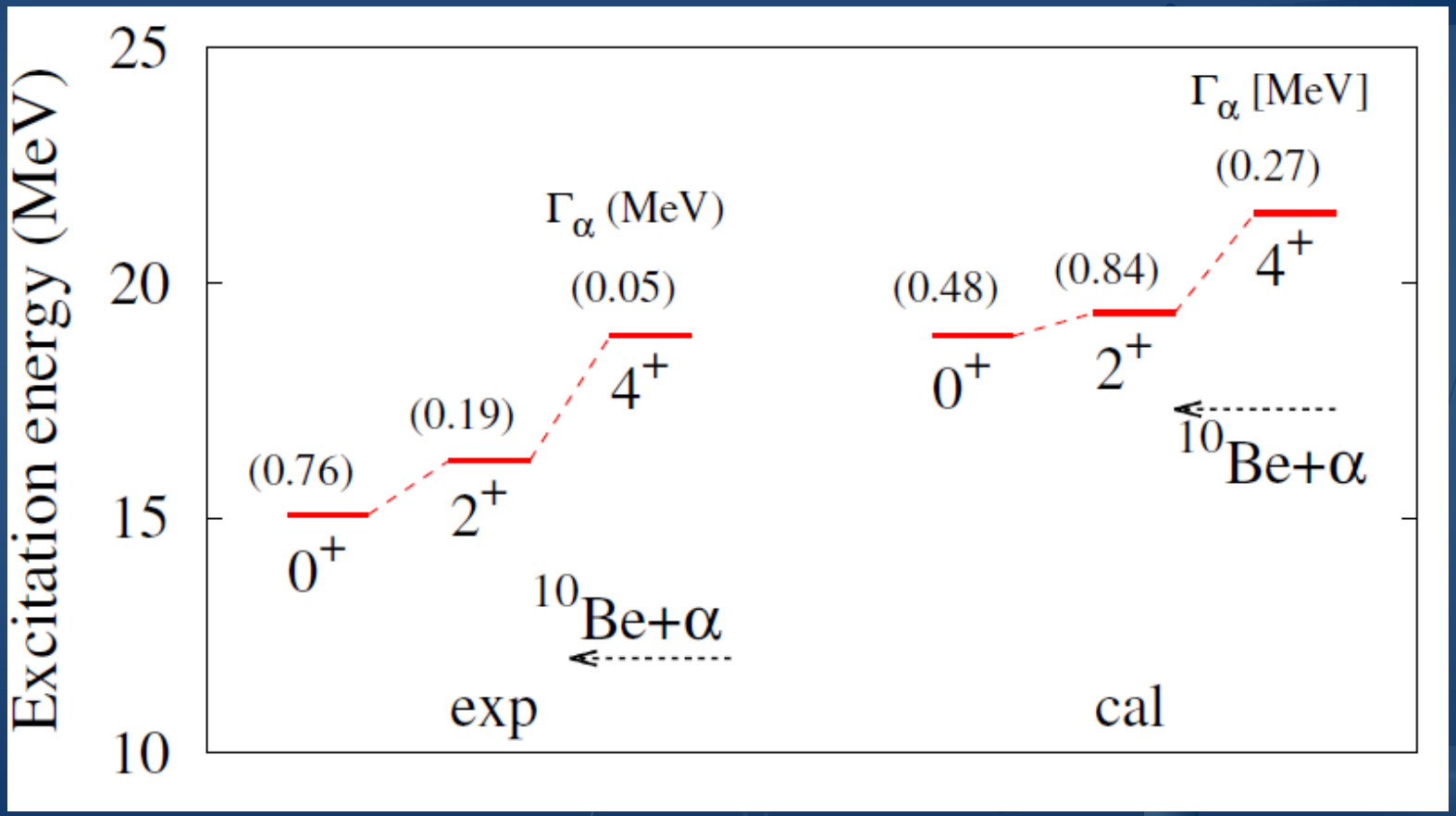
3α linear chain





^{14}C : linear chain states

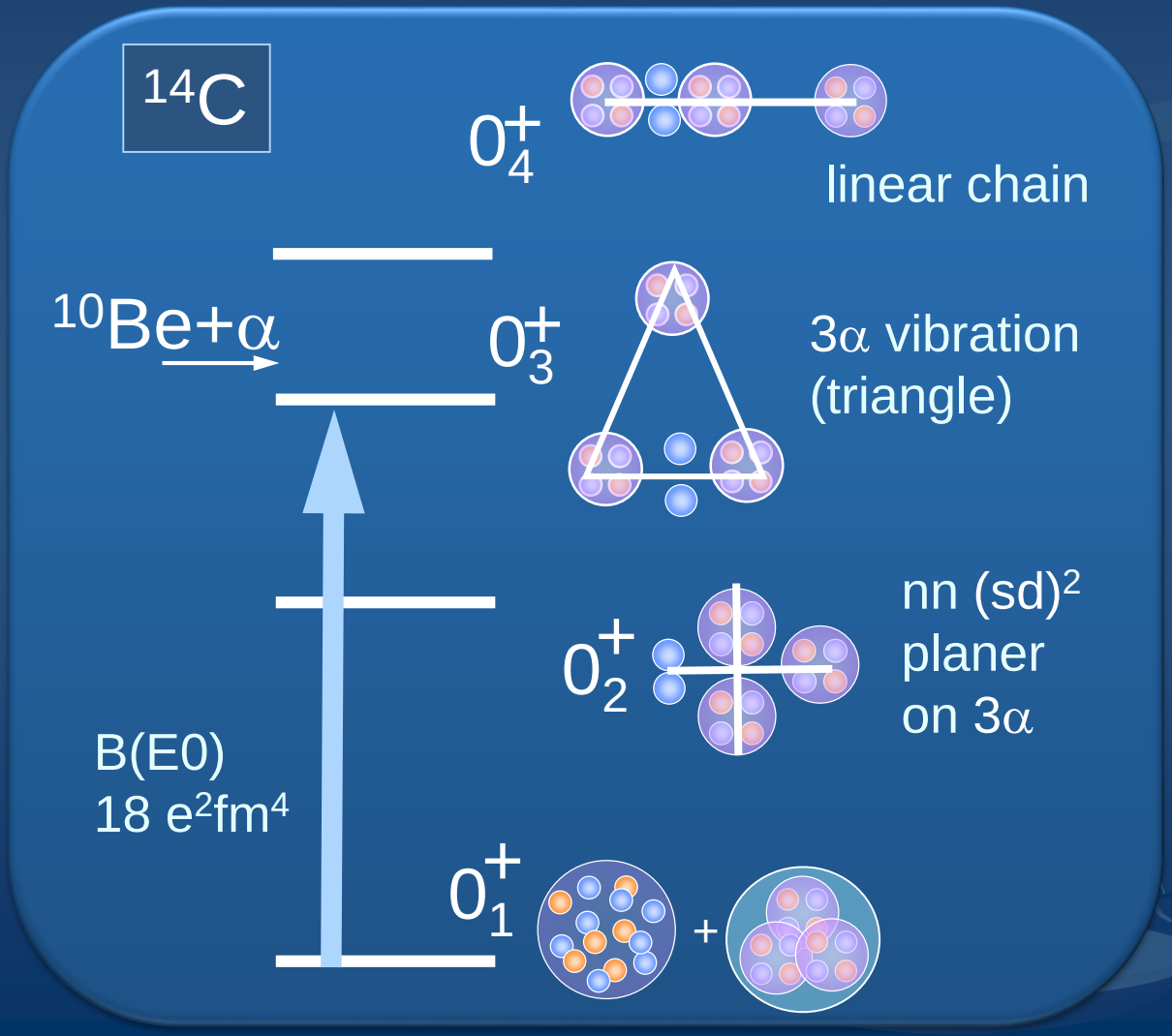
comparison with obsevation



exp: Yamaguchi et al
PLB766(2017)

0+: monopole excitations in ^{14}C

3α dynamics with nn: some differences



- 2α bonded by nn
- new configurations because of nn

^{14}C

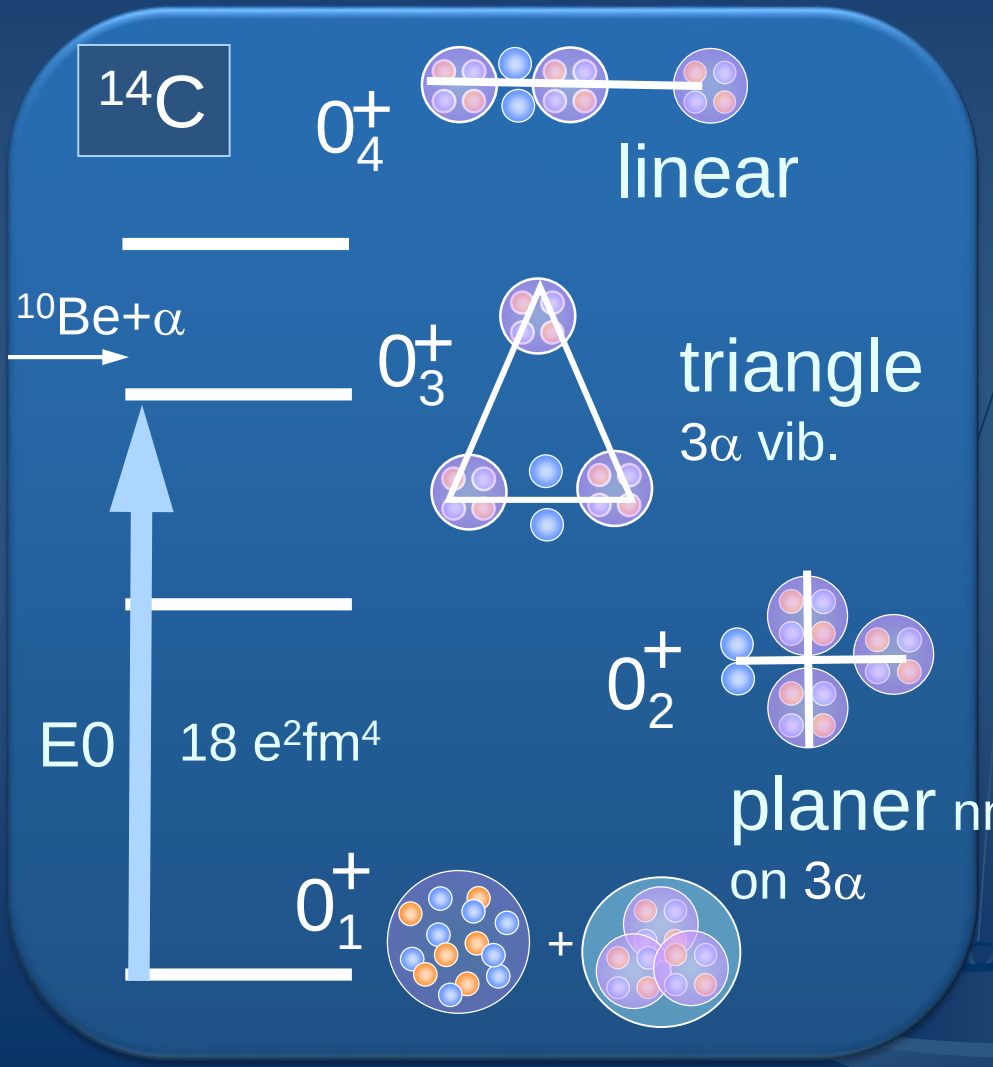
⇕

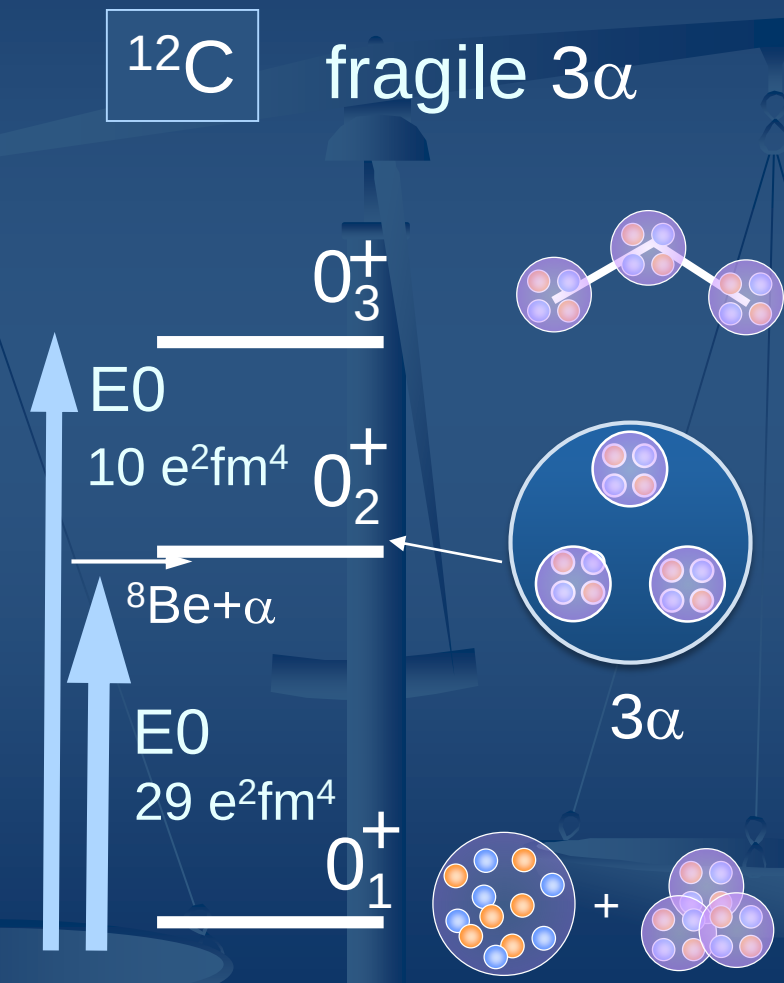
^{12}C

fragile 3α

monopole excitations in ^{14}C,^{12}C

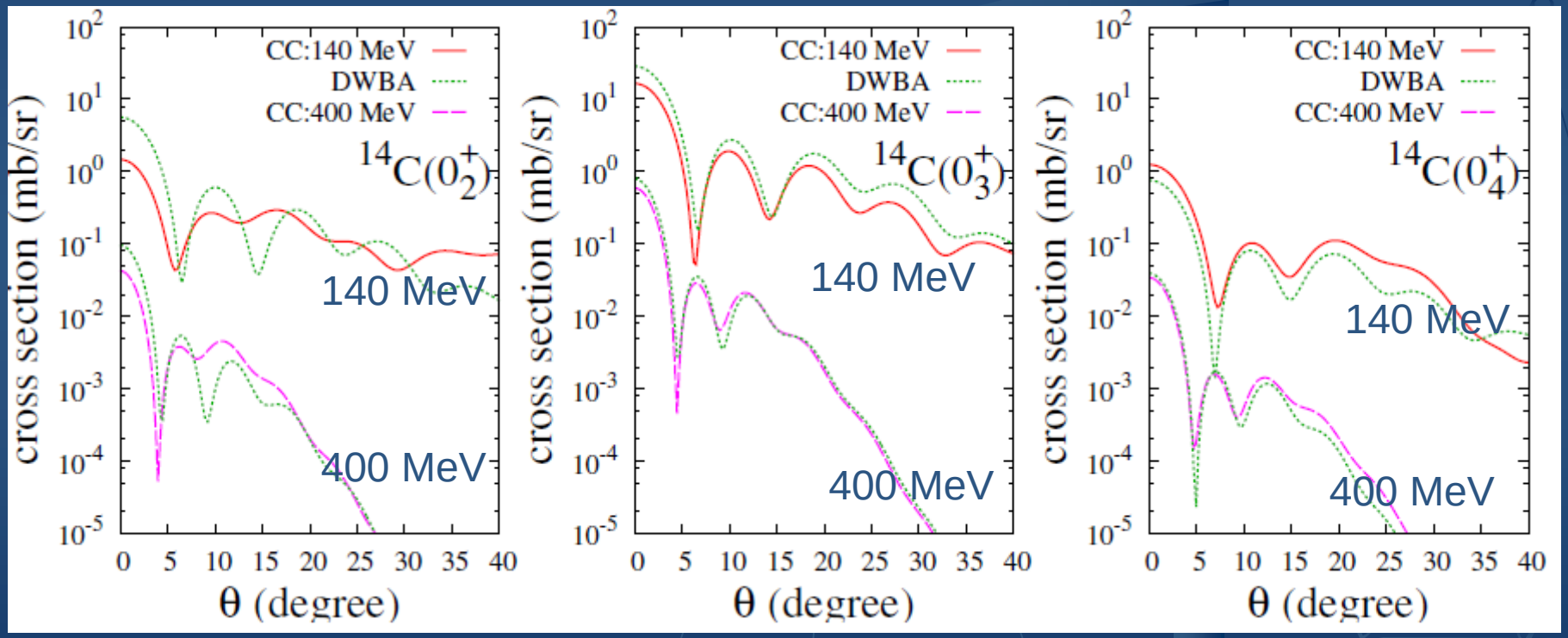
3α dynamics with and w/o nn: differences





$^{14}C(\alpha,\alpha')$

- E_α=140 MeV and 400 MeV



$^{14}C(0^+_3)$ can be observed by (α,α')

Summary

- (s)AMD+GCM was applied to monopole&dipole excitations in ^{12}C, ^{16}O, and ^{10}Be
- Various LE modes: cluster, vib, vortical modes
- alpha inelastic scattering
- cluster states in ^{14}C: Triangle vib., linear-chain 3a

Various modes arises in monopole & dipole excitations

Physics behind:

small amplitude modes & large amplitude cluster dynamics in nuclear phenomena

References

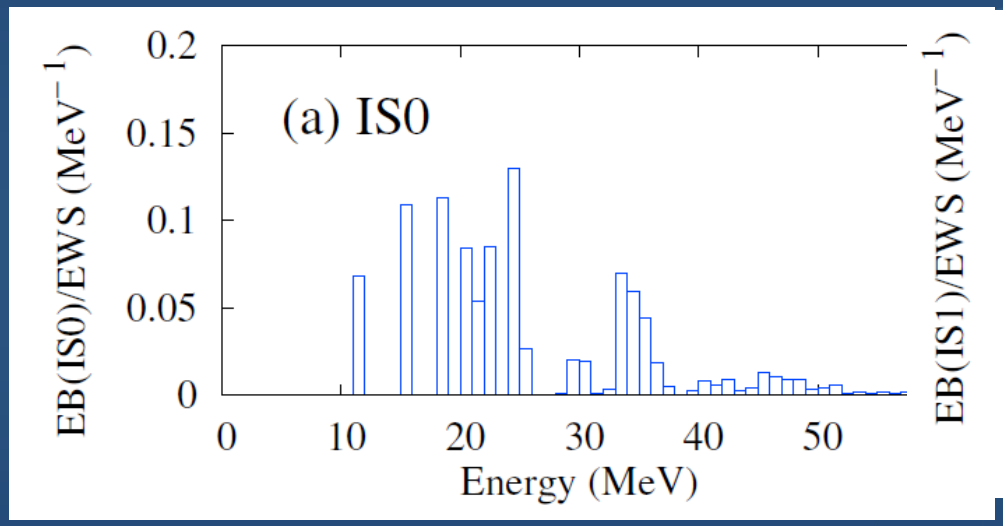
- (p,p’) arXiv:1908.03
- (a,a’) off 16O Phys.Rev. C99 (2019) no.6, 064608
- (a,a’) off 12C Phys.Rev. C99 (2019) no.6, 064601
- monpole&dipole in 16O

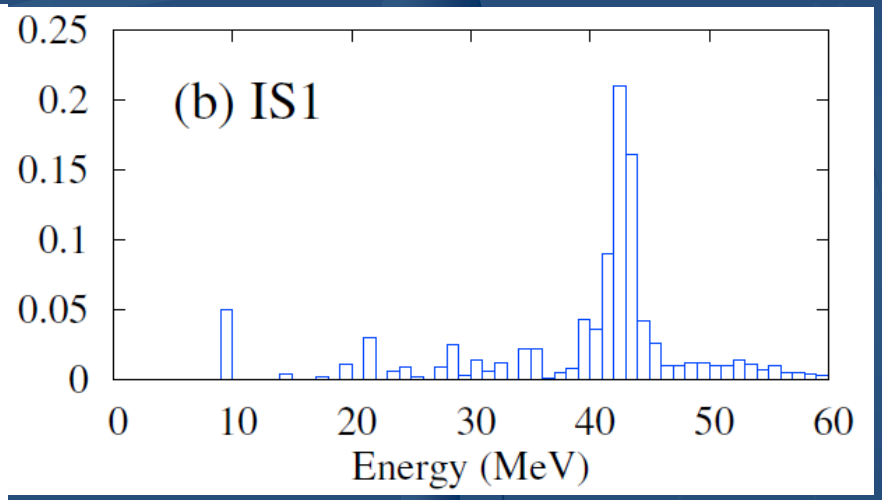
  Phys.Rev. C89 (2014) 024302, Phys.Rev. C100 (2019) 014301
- monpole&dipole in 12C

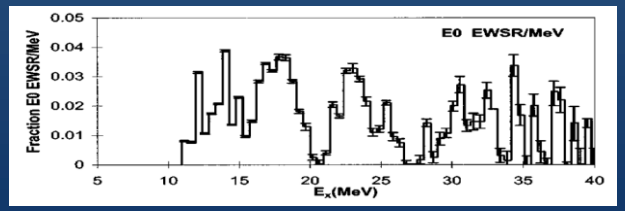
  Phys.Rev. C97 (2018) no.1, 014303, Phys.Rev. C93 (2016) no.5, 054307

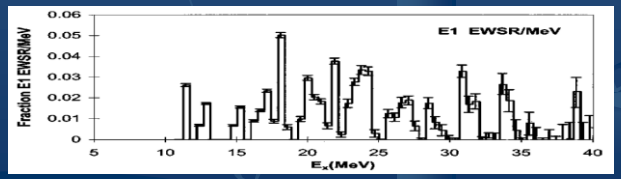
EB(IS0,IS1) in ^{16}O

- sAMD+GCM





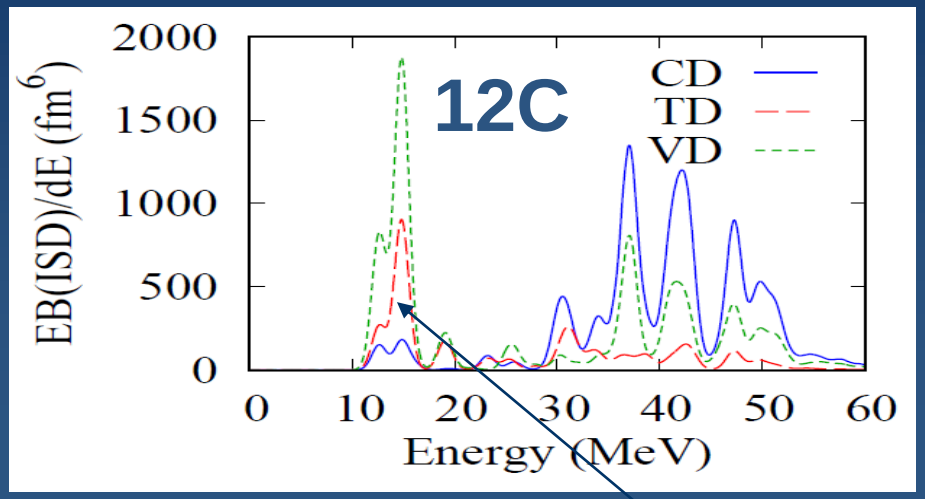




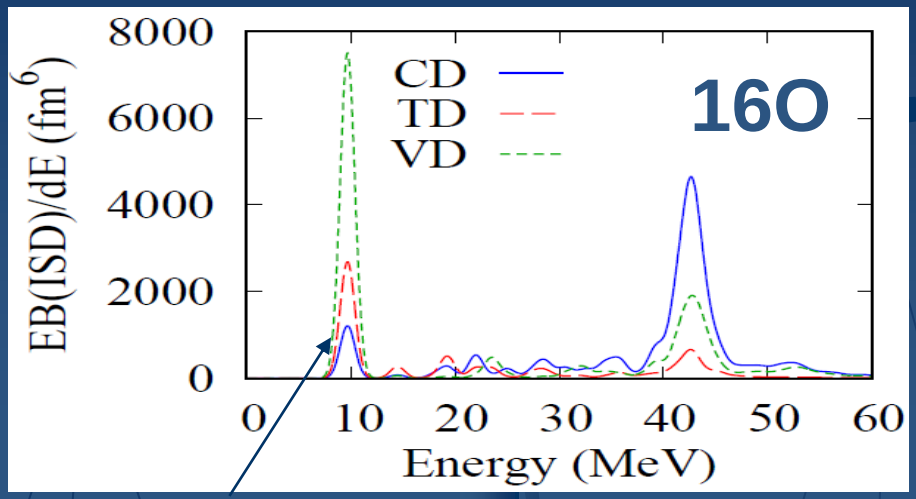
(a,a') exp: Lui et al. PRC64(2001)

IS-LED in ^{12}C, ^{16}O

3% of EWSR



5% of EWSR

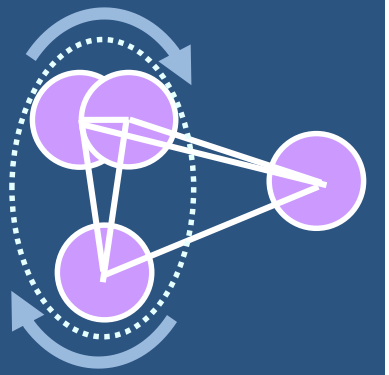


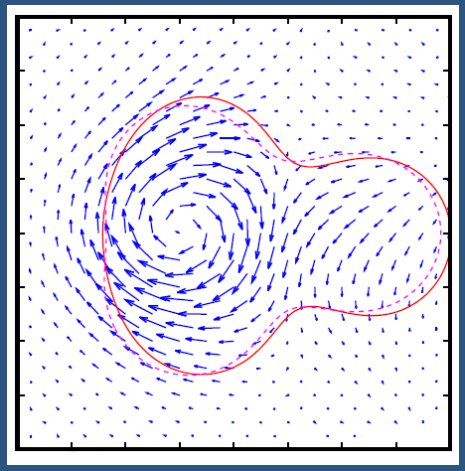
$^{12}C(1^-_1)$
$^{16}O(1^-_2)$
Developed Clustering:
3α, $^{12}C+\alpha$

TD dominant LED !

$^{12}C(1^-_2)$
$^{16}O(1^-_1)$

1p1h





Effective nuclear interactions

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

Central force: MV1 force
two-range Gaussian 2-body + zero-range 3-body forces

ls force: term of G3RS force
two-range Gaussian 2-body (^{3}O)

Coulomb force: 7-range Gaussians

Matter properties of MV1 force (case-1 with m=0.62, b=h=0)
ρ_0=0.192 fm^{-2}, E_0/A=17.9 MeV, K=245 MeV, m*=0.59m

	α	^{12}C	^{16}O	^{2}C+α thres.
Cal. (MeV)	27.8	87.6	123.5	8.2
Exp. (MeV)	28.3	92.2	127.6	7.16

Effective interactions

- Central force : MV1 parameterization

  two-range Gaussian 2-body+zero-range 3-body

  similar to Gogny central force in a sense
- LS force : two-range Gaussian 2-body from G3RS
- Coulomb force is also added.

➢ Matter properties:

ρ_0=0.192 fm^{-2}, E_0/A=17.9 MeV, K=245 MeV, m*=0.59m

➢ B.E. of nuclei:

	α	^{12}C	^{16}O	^{2}C+α thres.
Cal. (MeV)	27.8	87.6	123.5	8.2
Exp. (MeV)	28.3	92.2	127.6	7.16