0.before Introduction

I was a student of Prof. Horiuchi, who was a student in Prof.Arima’s group.

- Great and long-time contributions to nuclear physics,
- Cluster physics in the early stage in 1960-70’s:

emergence of alpha cluster in sd-shell nuclei,

^{20}Ne, ^{19}F, ^{16}O etc., as four-nucleon correlations

  - affecting later cluster physics,
  - leading modern cluster physics in RI beam physics

Horiuchi : master thesis on ^{16}O, PhD thesis on ^{20}Ne

Y. K-E.: master on 20Ne, PhD on neutron-rich nuclei...

2016-18 papers on ^{16}O

Dipole excitations in ^{10}Be

Y. Kanada-En'yo, Y. Shikata (Kyoto),
and H. Morita

Y. K-E, Y. Shikata, H. Morita, arXiv:1709.03045
Cluster and toroidal dople modes in 12C
Y. K-E, Y. Shikata. Phys.Rev. C95 (2017) no.6, 064319
Toroidal, compressive dipole and E1 in ^{10}Be,
Y. K-E, PRC93 (2016) 024322: E1& ISD in Be isotopes
Y. K-E, PRC93 (2016) 054307: ISM & ISD in 12C

1. Introduction

low-energy dipole excitations

Giant resonances: GMR, GDR

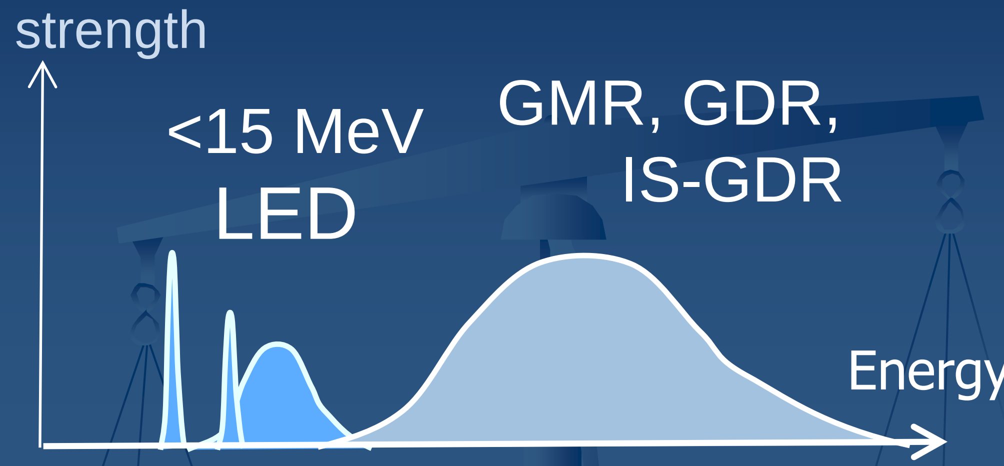
GR: broad bump in HE region

ISM:10-20 MeV

IVGDR:10-30MeV

Collective oscillation of system

coherent 1p-1h excitation

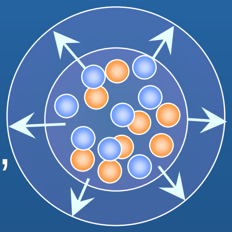


IS monopole (IS0):

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

GMR

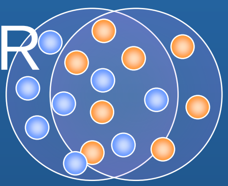
Compressive,
breathing



IV dipole (E1):

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

IVGDR

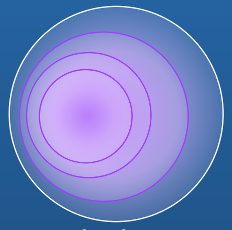


translational ⟺

IS dipole (IS1):

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

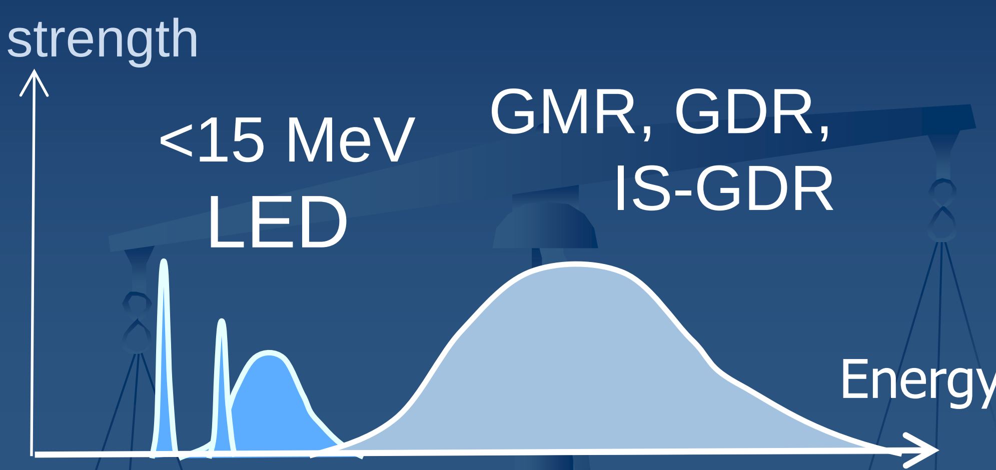
ISGDR



compressive ⟺

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

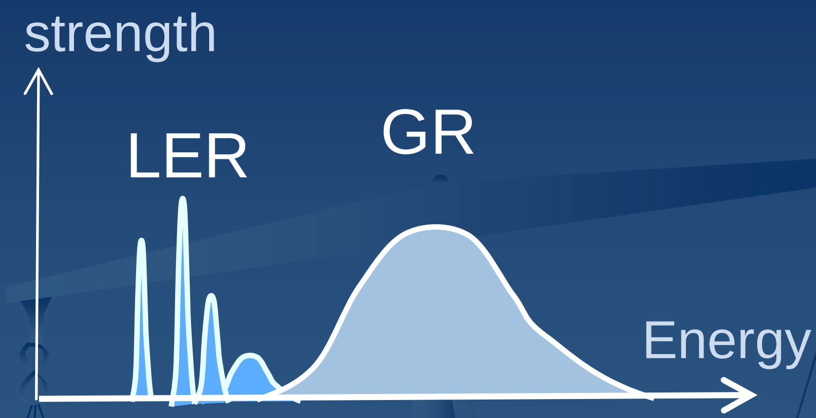
Separation of LE strengths from GRs

⇨ New excitation modes decoupled from GRs.

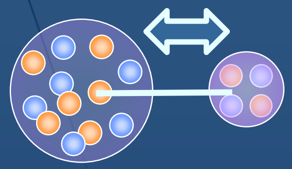
Origins of LE strengths have not clarified yet.
Various origins?

LE-ISM, LE-ISD for cluster states

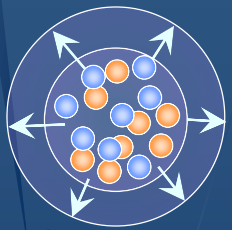
Yamada et al. PRC**85**, 034315 (2012)
Chiba et al. PRC93 (2016) no.3, 034319



LE
Inter-cluster motion



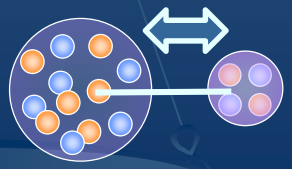
GR
compressive



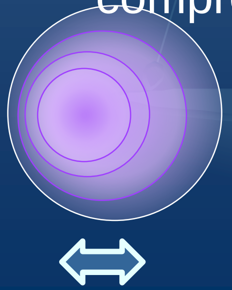
Isoscalar monopole (IS0):

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

Inter-cluster motion



compressive



Isoscalar dipole (ISD=CD):

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

Dipole excitations

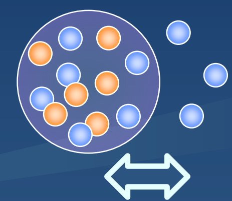
LE?

GR in HE

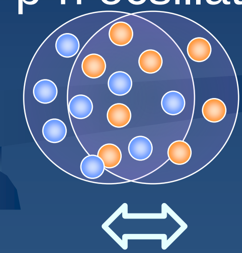
1.Isovector dipole (E1):

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

Neutron skin oscillation:Core-Xn



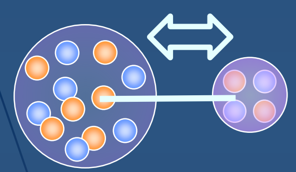
translational p-n ocsillation



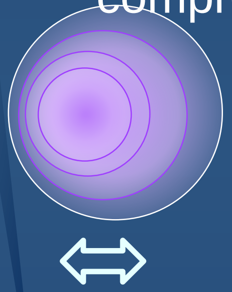
2.Isoscalar dipole (ISD=CD):

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

Inter-cluster motion



compressive



- Compressive

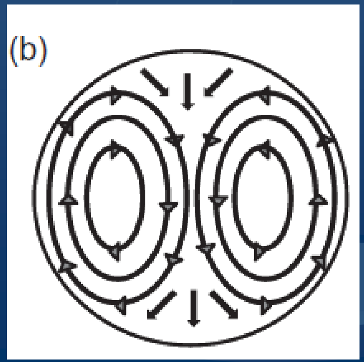
$$(\nabla \cdot \mathbf{j}) r^3 Y_{1\mu}$$

3. IS(IV) Toroidal dipole (TD)

- Toroidal

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

Density conserved
-> LED?



hydrod models , Semenko(1981)
microsciopic MF calc. 2000's~

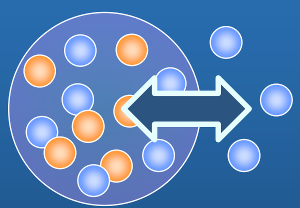
N. Ryezayeva et al., PRL89, 272502 (2002).
P. Papakonstantinou, EPJA 47, 14 (2011).

What are natures of LED?

LED

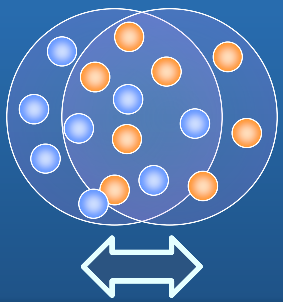
HED

IVD (E1)

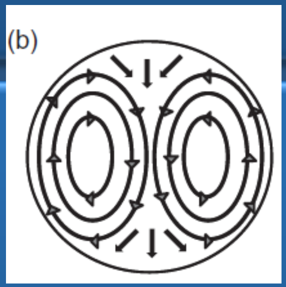


Neutron skin
only N>Z nuclei

IVGDR

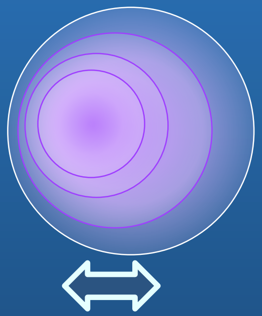


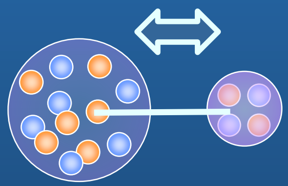
ISD



Toroidal

ISGDR





Cluster

Method: Shifted basis AMD method+cluster-GCM

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

2.Formulatoion of 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

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

Intrinsic spins

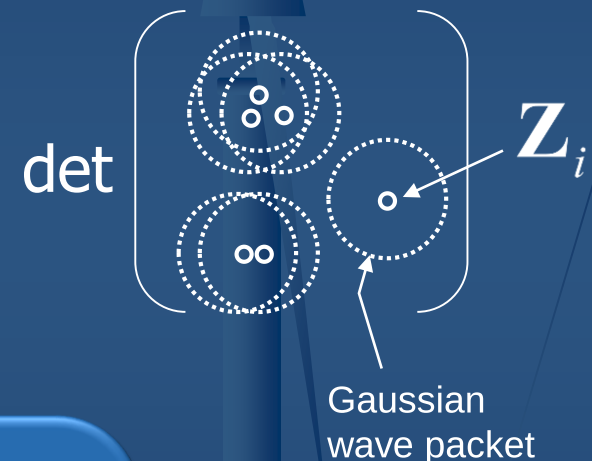
isospin

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

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

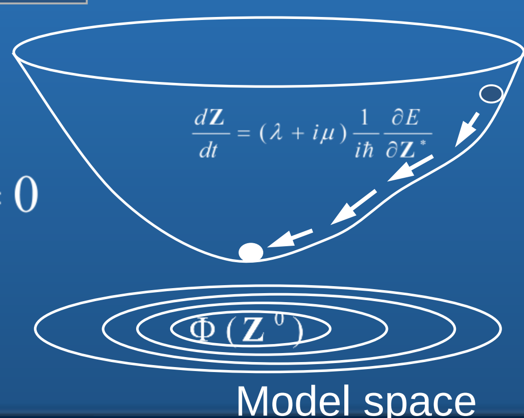
Variational parameters:

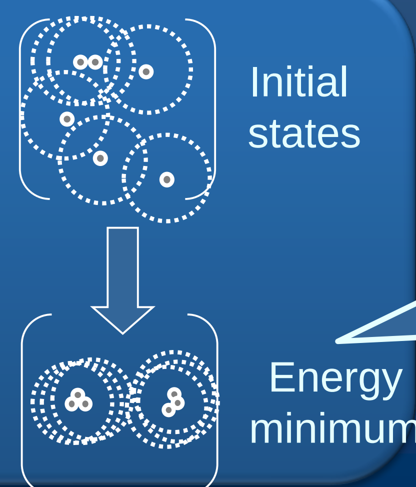
Gauss centers, spin orientations



Energy Variation

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





J^{π}-VAP

to get the ground state wave function.

Shifted basis AMD (sAMD)

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

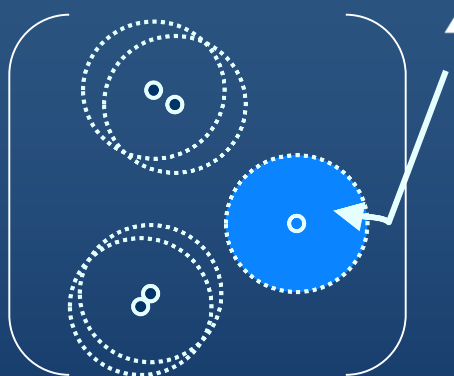
Ground st. wave functions

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

small shift of spatial part

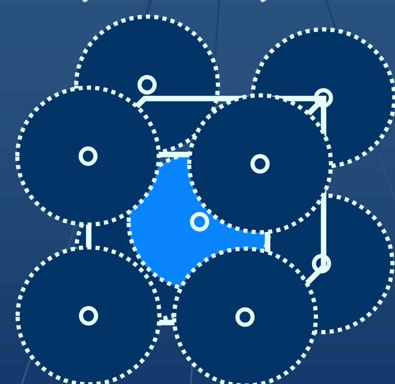
$$\det\left\{\varphi_1, \cdots, \varphi_i + \delta\varphi_i, \cdots, \varphi_A\right\}$$

A shifted basis

det 

$\mathbf{Z}_i$

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



Small shift for 8 orientations

(8A basis)

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

sAMD+GCM

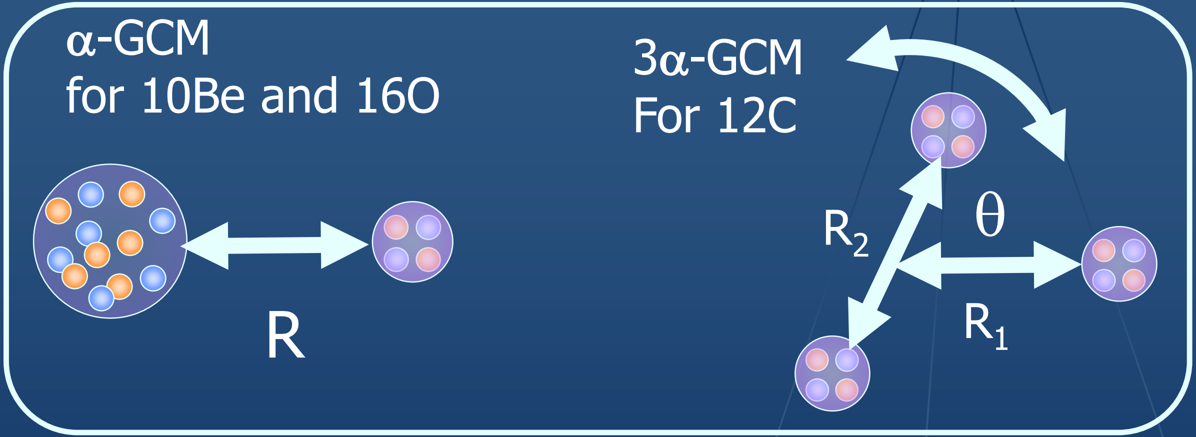
VAP

Ground state wave function → g.s. cluster correlation

sAMD

1p1h excitations on g.s. → GRs

GCM various cluster configurations



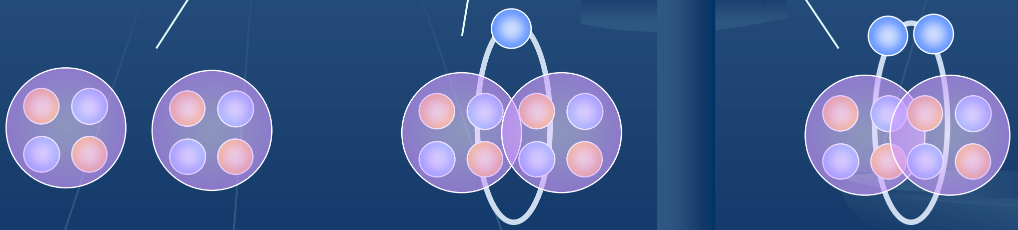
→ Large amp. cluster motion in LE

sAMD+GCM: all bases are superposed.

Jπ-projection, cm motion are treated microscopically

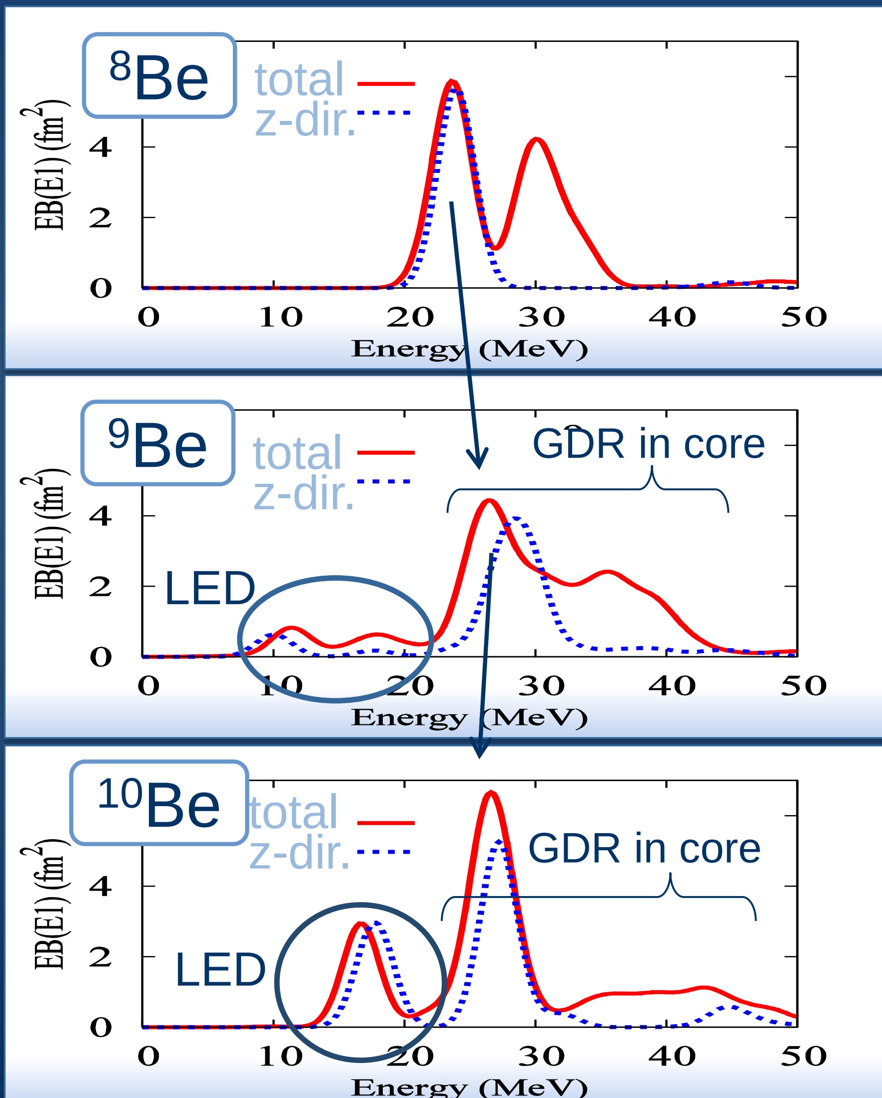
3.Results

E1 and ISD in ^{8}Be, ^{9}Be, ^{10}Be



2α+Xn

E1 excitations in 8Be,9Be,10Be



smearing factor 2MeV

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

two peaks in prolate state

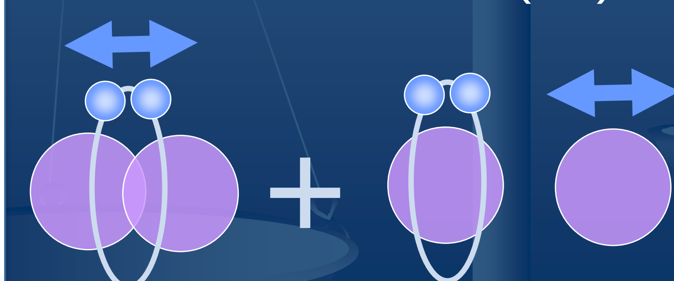
Lower peak
not affected

higher peak
broadened

- **LEDR:**

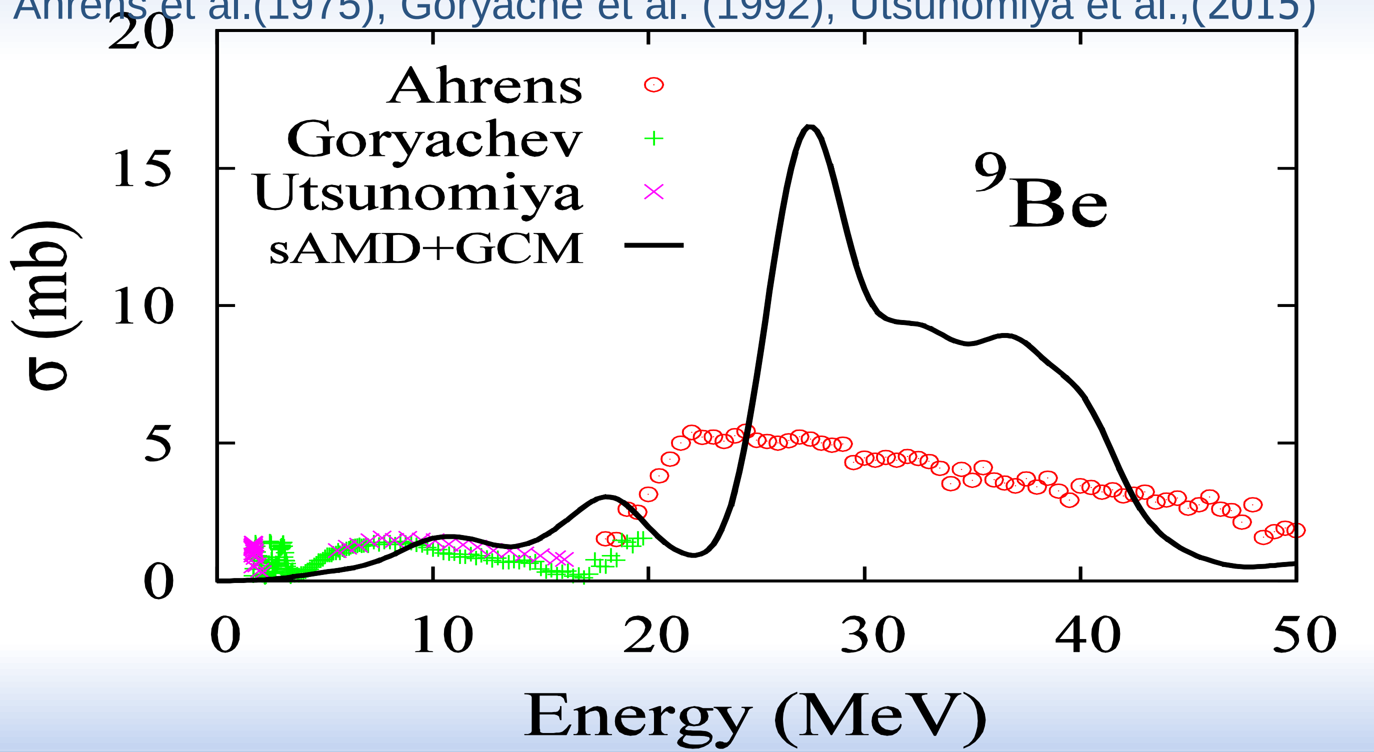
Coherent two-neutron motion
coupling with 6He+α

B(E1), B(ISD)

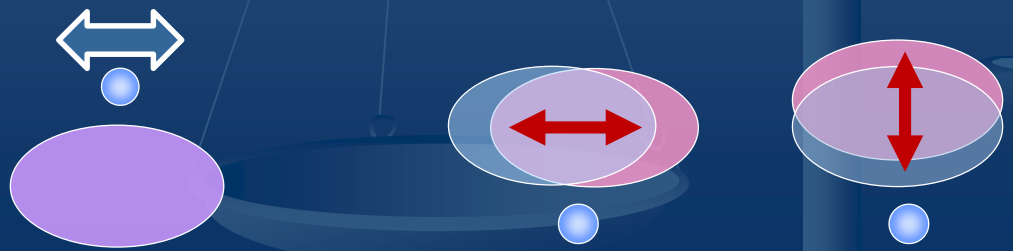


B(E1) in ^{9}Be compared with experimental photo nuclear σ

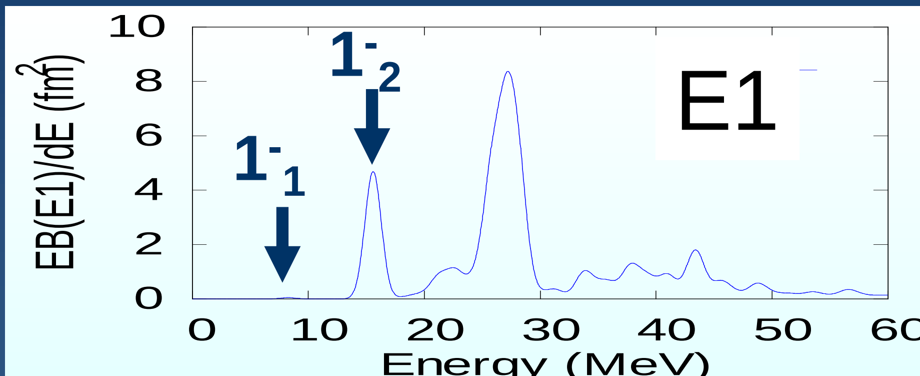
Ahrens et al.(1975), Goryache et al. (1992), Utsunomiya et al.,(2015)

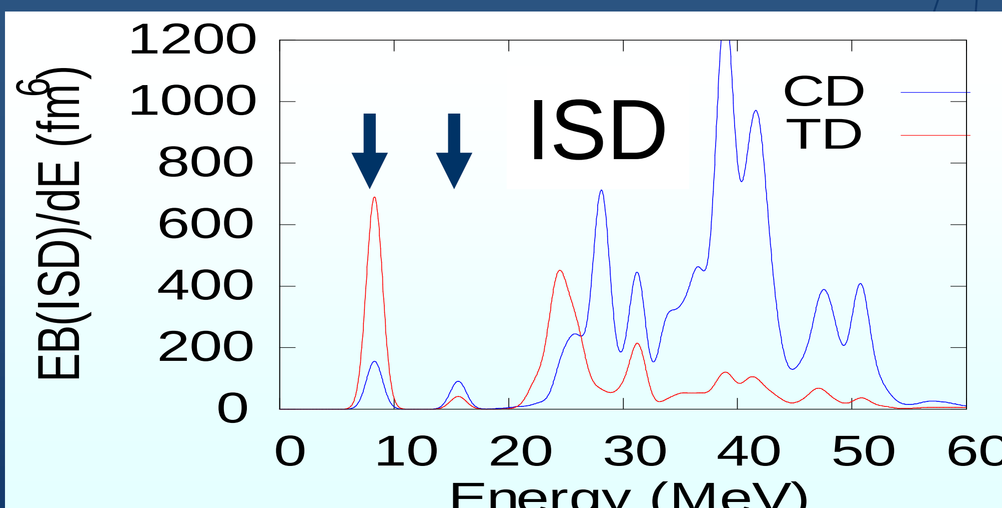


Decoupling of
LE & HE modes



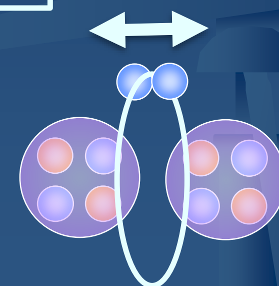
Two LED modes in ^{10}Be





1^-_2 E~15 MeV

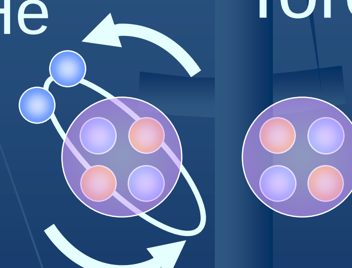
E1 mode



1^-_1 E~8 MeV

Toroidal mode

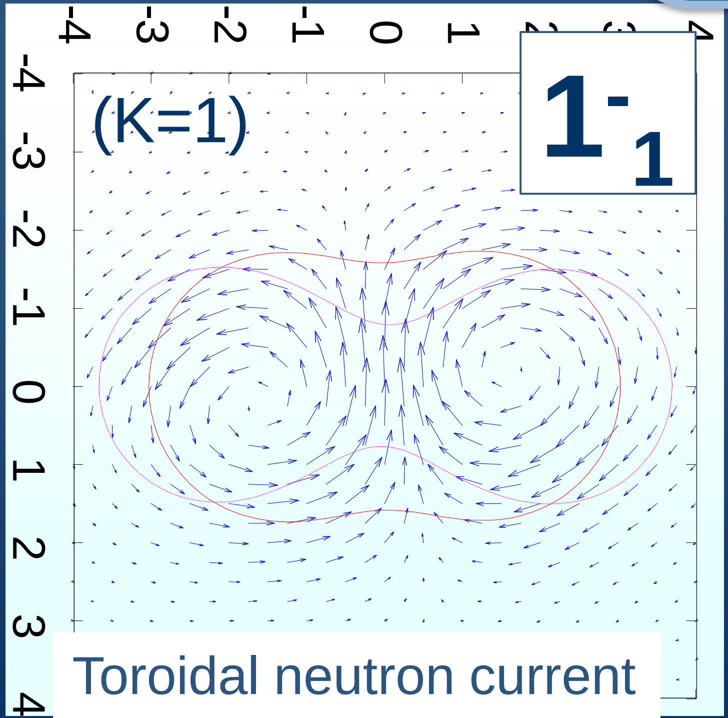
^{6}He



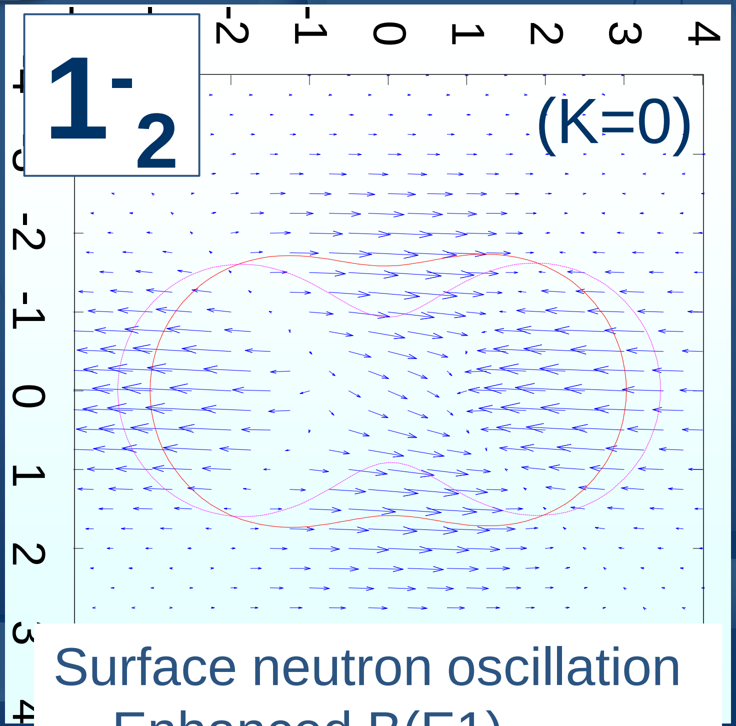
Compressive $(\nabla \cdot \mathbf{j}) r^3 Y_{1\mu}$

Toroidal $(\nabla \times \mathbf{j}) \cdot r^3 \mathbf{Y}_{11\mu}$

Two LED modes in ^{10}Be



Toroidal neutron current
Enhanced B(TD)



Surface neutron oscillation
Enhanced B(E1)

Summary

- sAMD+GCM was applied to investigate ISD & E1 in ^{10}Be, ^{12}C, ^{16}O
- ^{10}Be: TD dominant 1^-_1 & E1 dominant 1^-_2 states.
- TD nature of LEDs: rotation of deformed cluster

Massage

- Coexistence of two natures, cluster and mean-field aspects, brings rich phenomena in nuclear systems

ex) cluster modes & 1p-1h modes in excitations

Massages

- Prof. Arima guided many students(children), gand-children, collaborators(friends) in Japan, China, and the world, who are now promoting frontier researches in our field, exciting nuclear physics.
- *Thanks to Prof. Arima for his continuous supporting, encouraging, loving next generations*

Happy birthday,

best wish with his long and good health

Many thanks to his friends in China