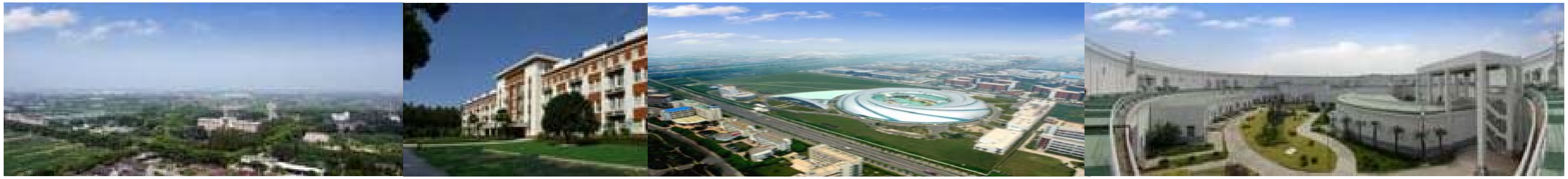

How alpha-Cluster Configuration Affects Giant Dipole Resonance

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Collaborators: Xi-Guang Cao, Wan-Bing He, Xiangzhou Cai, Guoqiang Zhang

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PKU-CUSTIPEN Nuclear Reaction Workshop “Reactions and Spectroscopy of Unstable Nuclei"

Outline:

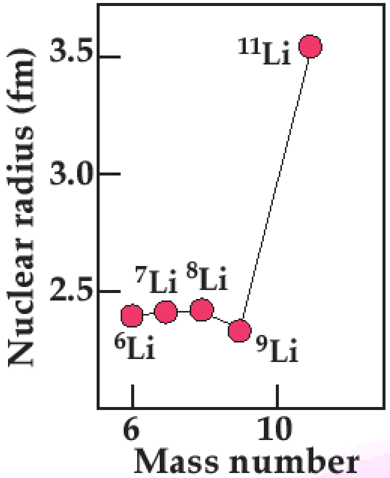
- ☐ Background & method introduction
  - ✓ Nuclear cluster in light nuclei
  - ✓ Nuclear collective motion
  - ✓ Microscopic dynamical model
- ☐ GDR algorithm & verification
- ☐ Results and discussion
  - ✓ Density distribution of cluster nuclei and wave packets
  - ✓ GDR of ^{8}Be, ^{12}C & ^{16}O with different α configurations
- ☐ Summary

Background & method introduction

-- cluster in light nuclei

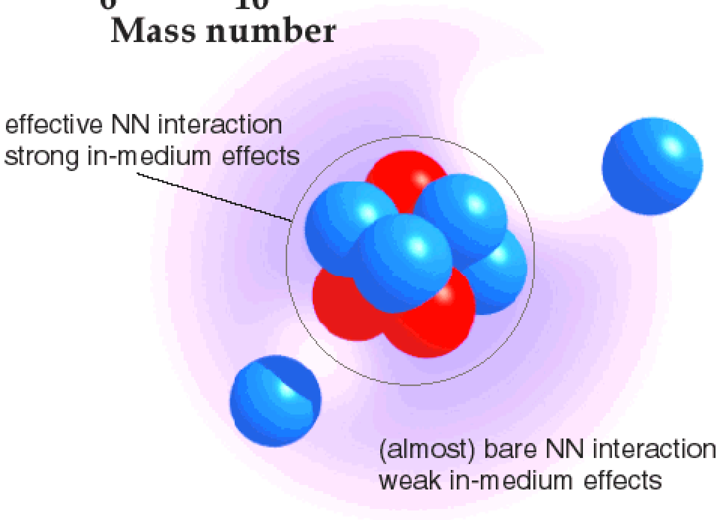
Cluster completes with mean field in the region of light nuclei

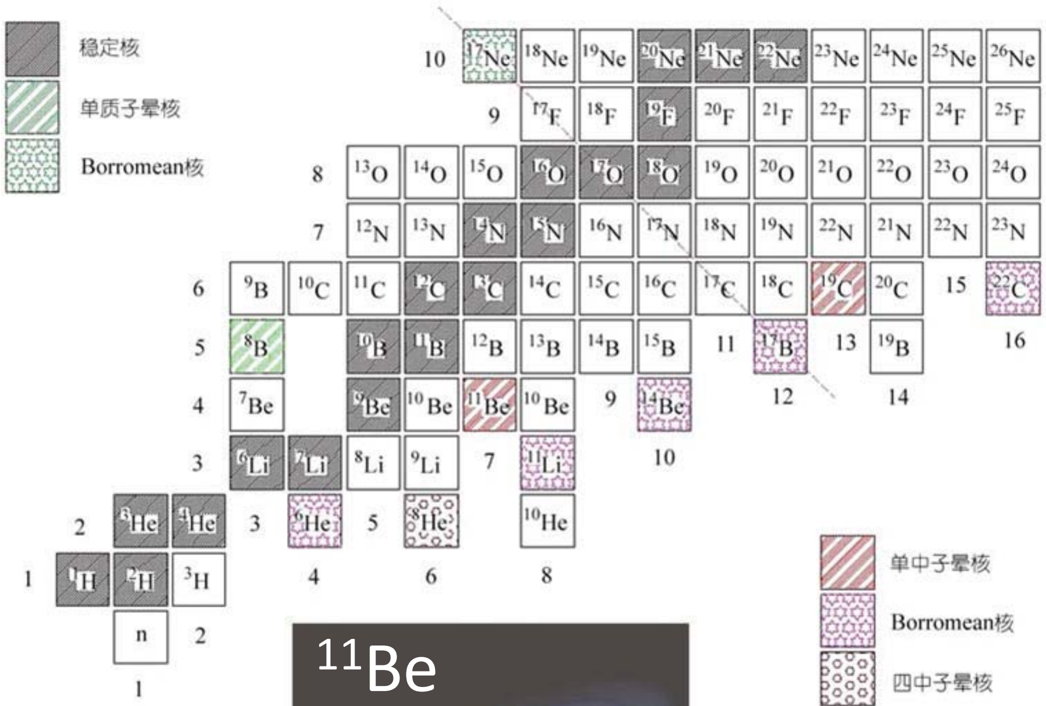
✓ Far from β stability line, the cluster phenomenon appears as halo

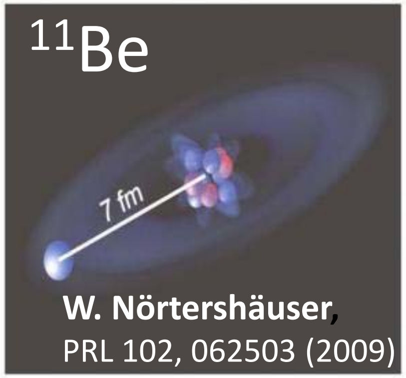


I. Tanihata et al.
Phys. Rev. Lett. 55, 2676 (1985)

Interaction cross section measurements at Bevalac (790 MeV/u)

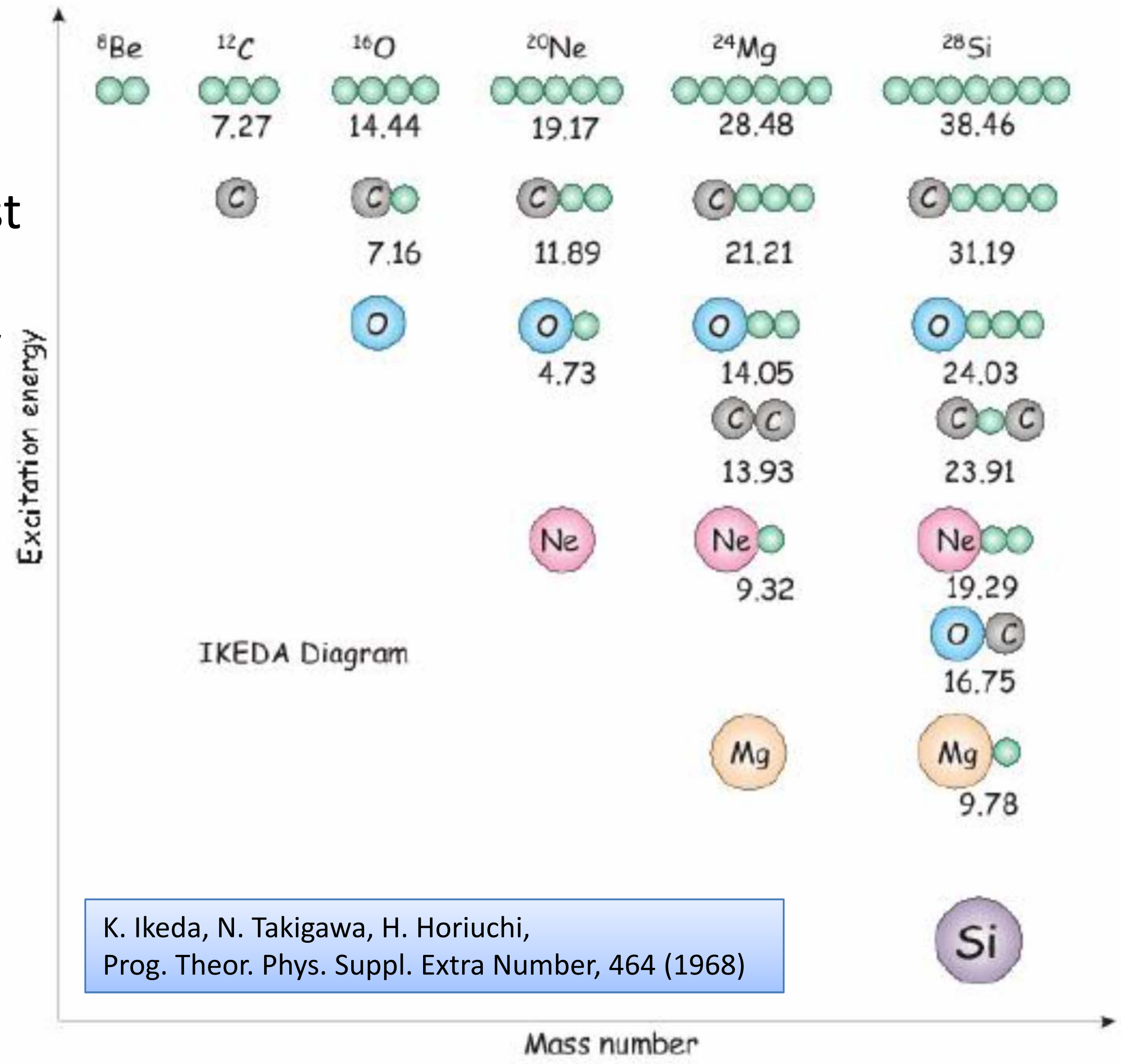






✓ Cluster is predicted to appear near cluster decay threshold in α-conjugate nuclei

The α cluster is the most prominent case since the high binding energy of α and the strong α-α correlation



K. Ikeda, N. Takigawa, H. Horiuchi,
Prog. Theor. Phys. Suppl. Extra Number, 464 (1968)

✓ The α cluster configuration in ^{12}C

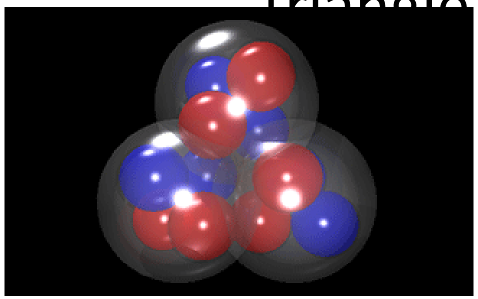
- Non-localized, condensed-like wave function, gas of α cluster in Hoyle state

THSR (Tohsaki-Horiuchi-Schuck-Ropke) wave function:
A. Tohsaki et al., *Phys. Rev. Lett.* 87, 192501 (2001)
T. Suhara et al., *Phys. Rev. Lett.*112,062501 (2014)

- AB initio calculation based on effective field theory obtains that Hoyle state is more like a linear chain of three alpha clusters

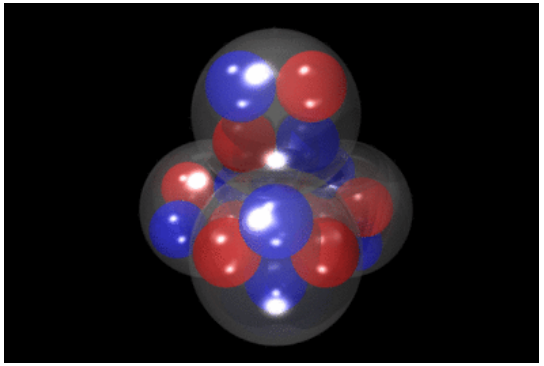
E. Epelbaum et al., *Phys. Rev. Lett.* 106, 192501 (2011)

- However, the recent data supports the triangle α configuration of ^{12}C Hoyle state



D. Marin-Lámbarri, R. Bijker, M. Freer et al. **Evidence for Triangular D3h Symmetry in ^{12}C**. *Phys. Rev. Lett*. 113, 012502 (2014)

✓ The α cluster configuration in ^{16}O



- Many different calculations support the tetrahedral structure in ^{16}O ground state, which challenges the traditional shell model picture.

  Algebraic model: Bijker, Iachello, **Evidence for Tetrahedral Symmetry in 16O**. *Phys. Rev. Lett*. 112, 152501 (2014)
  Effective field theory: E. Epelbaum, H. Krebs, T. A. Lähde, D. Lee, U.-G. Meißner, and G. Rupak, *Phys. Rev. Lett.* 112, 102501 (2014)
  Covariant density functional theory: L. Liu and P. W. Zhao, *Chin. Phys. C* 36, 818 (2012)

- The excited ^{16}O may evolve into square, or linear chain, or non-localized gas configuration

  Effective field theory: E. Epelbaum, H. Krebs, Timo A. Lähde, Dean Lee, Ulf-G. Meißner, and G. Rupak, *Phys. Rev. Lett*. 112, 102501 (2014)
  Covariant density functional theory: L. Liu and P. W. Zhao, *Chin. Phys. C* 36, 818 (2012)
  THSR wave function: T. Suhara et al., *Phys. Rev. Lett.* 112,062501 (2014)

Two important points need to be explored:

- From the experimental point of view, the probe is needed to diagnose the different configurations

- What are the aspects of the collective dynamics of excited α clustering systems and the underlying mechanism?

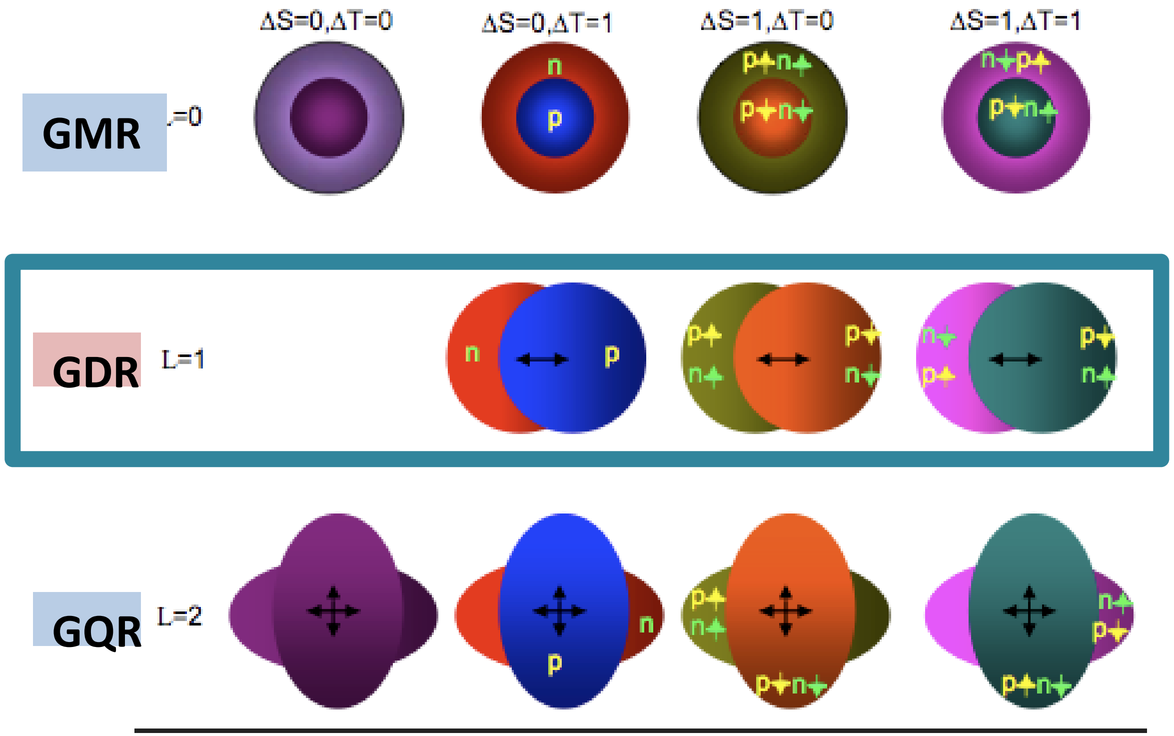
Giant Resonance ⟺ α Cluster Configuration

- Centroid energy of GR can provide direct information about nuclear size and the nuclear equation of state
- Width of GR closely relates with nuclear deformation, temperature, and angular momentum

Background & method introduction

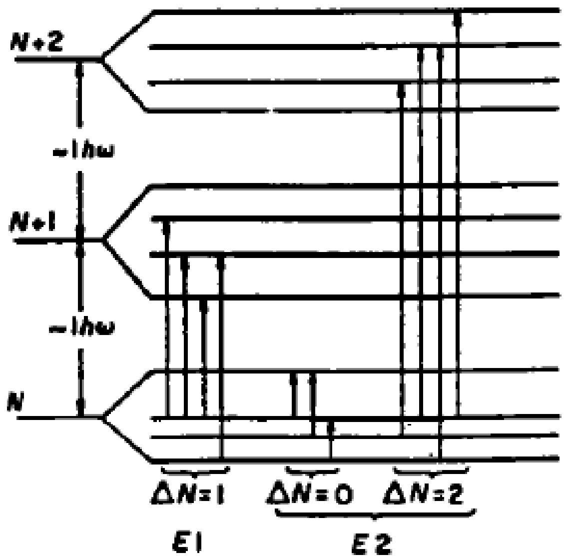
-- Giant Resonance

Giant resonances are typical collective excitations in nuclei



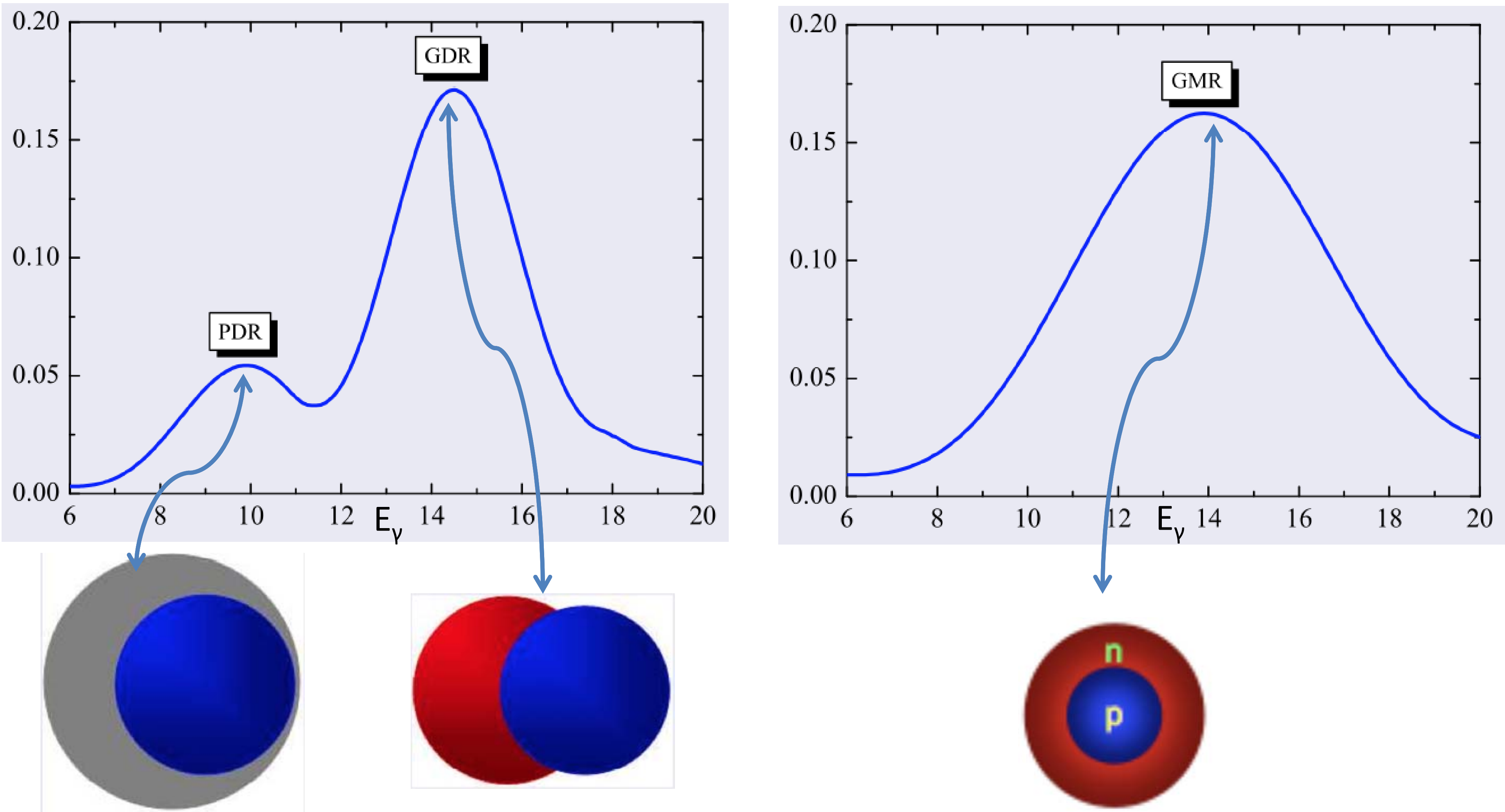
Different collective excitation modes

Macroscopic description



Microscopic description

There are three main excitation modes: GDR, PDR, GMR



PDR
Valence neutron <=> Core

GDR
Proton <=> Neutron

Background & method introduction

-- microscopic dynamical model

The EQMD model

T. Maruyama, et al., Phys Rev C 53, 297(1996)
R. Wada et al., Phys. Lett. B 422, 6 (1998).

Compared with other Molecular Dynamics (MD) models: QMD, IQMD, AMD, CoMD , ImQMD, IDQMD and LQMD has the following features:

1) Dynamical wave packet width in wave function (as in FMD).
   Taking into account the kinetic energy term of the momentum variance of wave packets to the Hamiltonian

$$\Psi = \prod_i \phi_i(\mathrm{r}_i)$$

$$\phi_i(r_i) = \left(\frac{\nu_i + \nu_i^*}{2\pi}\right)^{3/4} \exp\left[-\frac{\nu_i}{2}(\mathrm{r}_i - \mathrm{R}_i)^2 + \frac{i}{\hbar}\mathrm{P}_i \cdot \mathrm{r}_i\right]$$

$$\nu_i \equiv \frac{1}{\lambda_i} + i\delta_i$$

$$H = \left\langle \Psi \left| \sum_i -\frac{\hbar^2}{2m}\nabla_i^2 - \hat{T}_{c.m.} + \hat{H}_{\mathrm{int}} \right| \Psi \right\rangle$$

$$= \sum_i \left[\frac{P_i^2}{2m} + \frac{3\hbar^2(1+\lambda_i^2\delta_i^2)}{4m\lambda_i}\right] - T_{c.m.} + H_{\mathrm{int}}$$

The equation of motion of nucleon

$$\delta \int_{t_1}^{t_2} \zeta \, dt = 0$$

$$\zeta\left(\{R_{i,} P_i, \lambda_i, \delta_i, \dot{R}_i, \dot{P}_i, \dot{\lambda}_i, \dot{\delta}_i\}\right) \equiv \left\langle \Psi \left| i\hbar \frac{d}{dt} - \hat{H} \right| \Psi \right\rangle$$

$$\dot{R}_i = \frac{\partial H}{\partial P_i} + \eta_R \frac{\partial H}{\partial R_i} \qquad \dot{P}_i = -\frac{\partial H}{\partial R_i} + \eta_P \frac{\partial H}{\partial P_i}$$

$$\frac{3\hbar}{4}\dot{\lambda}_i = -\frac{\partial H}{\partial \delta_i} + \eta_\lambda \frac{\partial H}{\partial \lambda_i} \qquad \frac{3\hbar}{4}\dot{\delta}_i = \frac{\partial H}{\partial \lambda_i} + \eta_\delta \frac{\partial H}{\partial \delta_i}$$

The effective potential considered:

$$H_{\text{int}} = H_{Skyrme} + H_{Coulomb} + H_{Symmetry} + H_{Pauli}$$

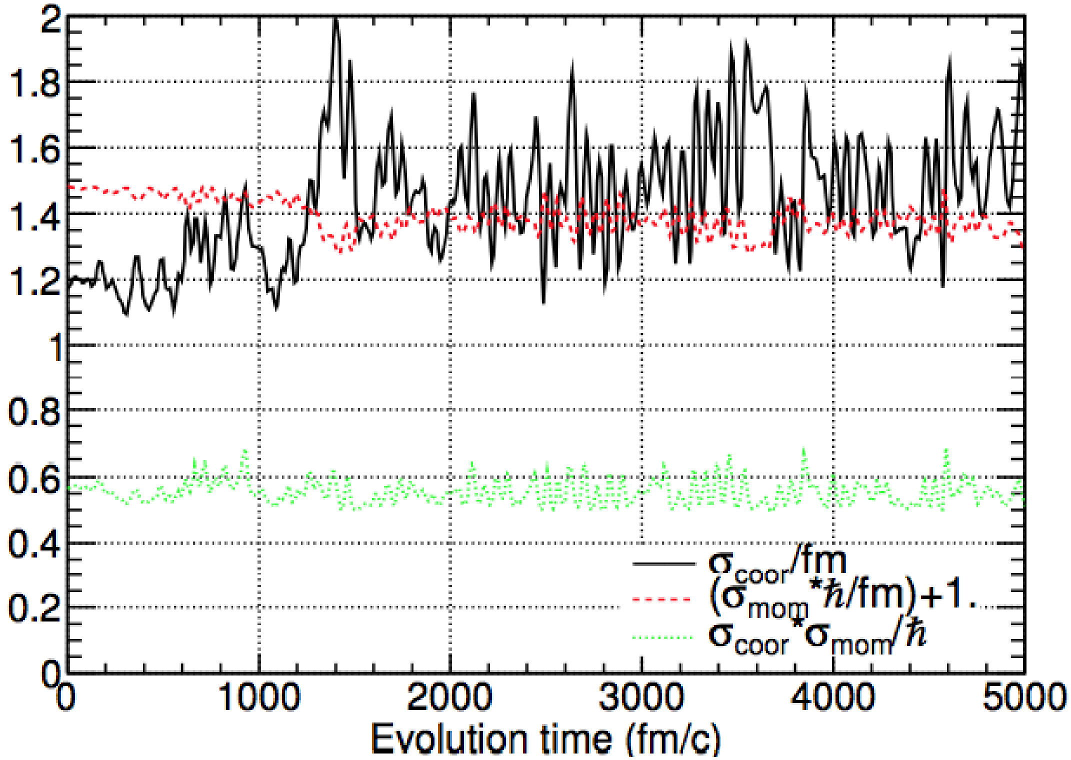
$$H_{Skyrme} = \frac{\alpha}{2\rho_0} \int \rho^2(\mathrm{r})\, d^3r + \frac{\beta}{(\gamma+1)\rho_0^{\gamma}} \int \rho^{\gamma+1}(\mathrm{r})\, d^3r$$

$$H_{Symmetry} = \frac{c_S}{2\rho_0} \sum_{i.\, j\neq 0} \int \left[2\delta(T_{i,}T_j) - 1\right] \rho_i(\mathrm{r})\, \rho_j(\mathrm{r})\, d^3r$$

$$\sigma_x = \sqrt{\frac{1}{2}\lambda_i}$$

$$\sigma_k = \sqrt{\frac{1}{2}\frac{1+\lambda_i^2\delta_i^2}{\lambda_i}}$$

$$\sigma_x^2\sigma_k^2 = \frac{1}{4}\left(1+\lambda_i^2\delta_i^2\right) = \frac{1}{4}\left(1+\frac{a_{I(t)}^2}{a_{R(t)}^2}\right)$$



2) Including Pauli potential into effective interaction to approximate the nature of fermion many-body system: a phenomenological repulsive potential which inhibits nucleons of the same spin S and isospin T to come close to each other in the phase space.

$$H_{Pauli} = \frac{c_P}{2}\sum_i \left(f_i - f_0\right)^{\mu}\theta\left(f_i - f_0\right) \qquad f_i \equiv \sum_j \delta\left(S_i, S_j\right)\delta\left(T_i, T_j\right)\left|\langle\phi_i\|\phi_j\rangle\right|^2$$

3) The initialization of ground nuclei: fraction cooling

Advantages:

- ✓ QMD based many-body model, mature and powerful
- ✓ Full microscopic, without assuming cluster in advance
- ✓ Without assuming reaction mechanism in advance
- ✓ Dynamical evolution -> links with observables directly
- ✓ Compared with TDHF cal., this method can be used at higher energy, many-body correlations, more realistic linkage with observables

Disadvantages:

- ✓ Semi-classical
- ✓ No anti-symmetrized

Unique Advantages of EQMD compared with other version QMD:

- ✓ Energy conservation more better duration evolution thanks to strict threefold loop computation for three body interaction
- ✓ Stable enough ground state to study low energy region reaction process, without spurious particle emission
- ✓ Dynamical wave packet evolution, reasonable fluctuation and dissipation

GDR algorithm & verification

-- How to extract giant resonance from QMD

Fourier transformation

V. Baran et al, Nucl. Phys.A 679,373(2001)

- ✓ $\mathrm{DR}(t) = \frac{NZ}{A}(R_p - R_n)$

  $R_p(R_n)$ is center of mass for protons (neutrons)

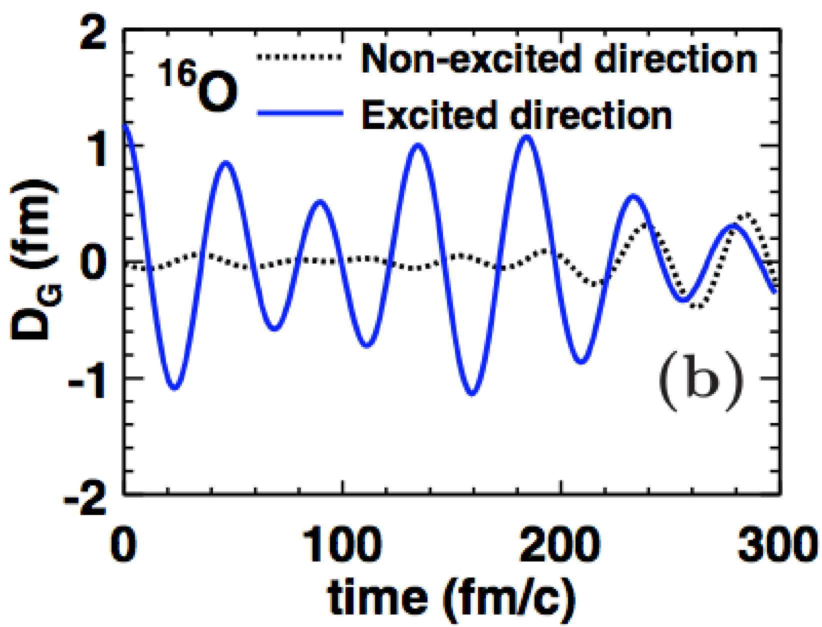
- ✓ $\bar{V} \equiv \overline{\frac{dDR(t)}{dt}}$,

- ✓ $\frac{dV}{dt}(E) = \int_0^{\infty} \frac{d^2DR(t)}{dt^2} e^{i\left(\frac{Et}{\hbar c}\right)} dt$

- ✓ $\frac{dP}{dE} = \frac{2}{3\pi}\frac{e^2}{E\hbar c}\left|\overline{\frac{dV}{dt}}(E)\right|^2$

dP/dE is GDR strength

Dipole moment vs time



This approach has been successfully applied in GDR, PDR, GMR calculations by IQMD & BUU model based on the fact that the quasiperiodic motion of nucleons in GR represents a known classical limit of quantum mechanics, which has be confirmed by TDHF calculations long before [A. S. Umar Phys. Rev. C 32, 172 (1985)].

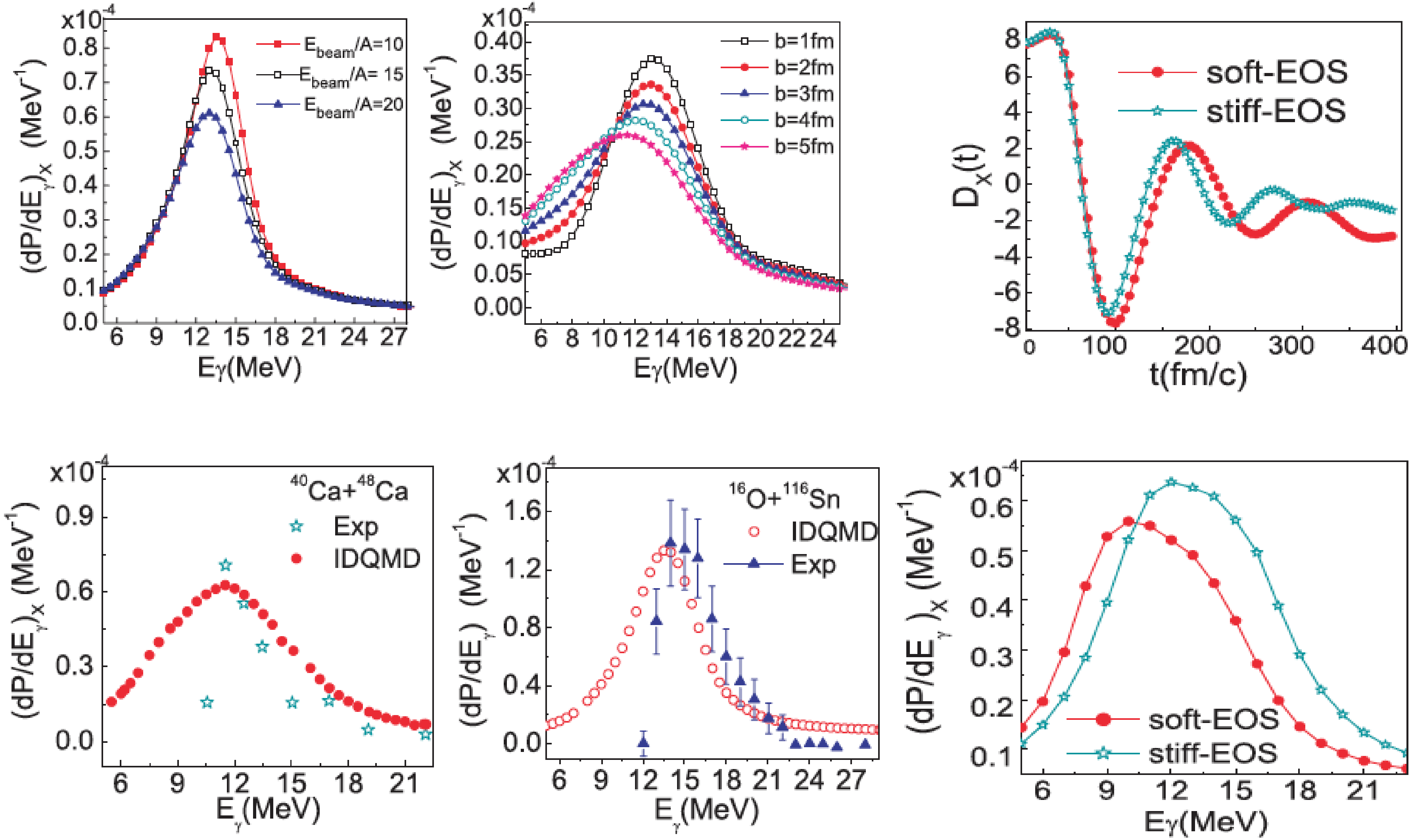
Our recent works:

- H. L. Wu, W. D. Tian and YGM et al., "Dynamical dipole \gamma radiation in heavy ion collisions on the basis of a quantum molecular dynamics model ", Phys. Rev. C **81**, 047602 (2010)
- C. Tao and YGM et al., "Pygmy and giant dipole resonances by Coulomb excitation using a quantum molecular dynamics model", Phys. Rev. C **87**, 014621 (2013)
- C. Tao and YGM et al., "Isoscalar giant monopole resonance in Sn isotopes using a quantum molecular dynamics model ",Phys. Rev. C **88**, 064615 (2013)
- S. Q. Ye, X. Z. Cai and YGM et al., "Symmetry-energy dependence of the dynamical dipole mode in the Boltzmann-Uehling- Uhlenbeck model", Phys. Rev. C **88**, 047602 (2013)

H. L. Wu, W. D. Tian and YGM et al.

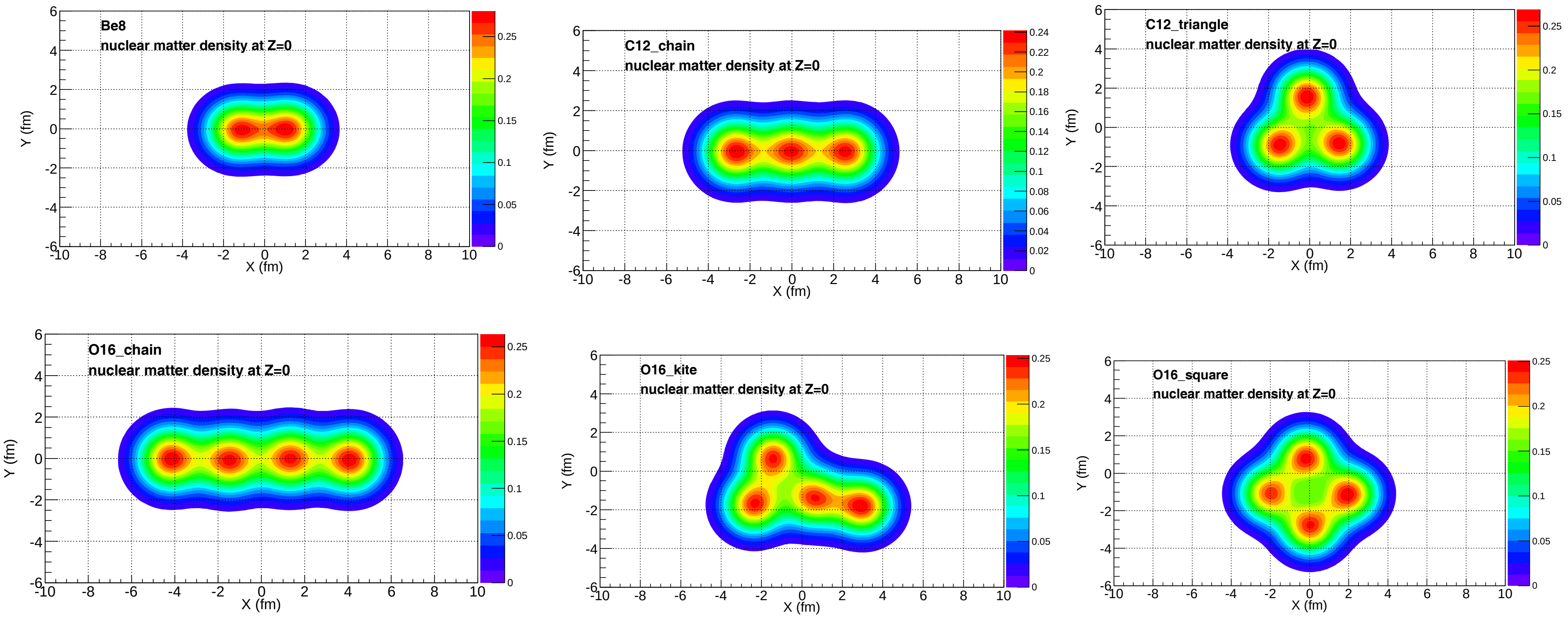
PHYSICAL REVIEW C **81**, 047602 (2010)

Dynamical dipole γ radiation in heavy-ion collisions on the basis of a quantum molecular dynamics model



Results & discussion

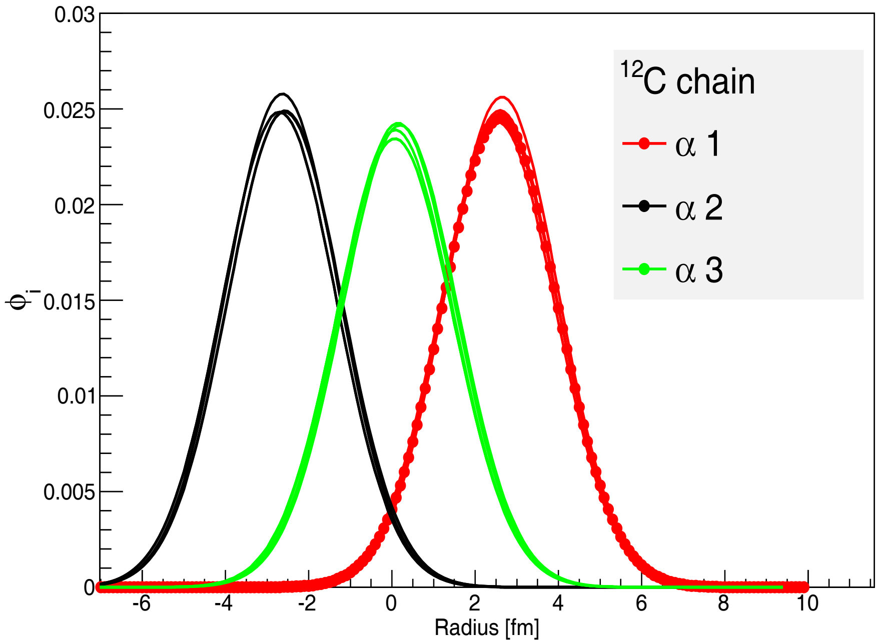
-- Density distribution of clustering nuclei and wave packets

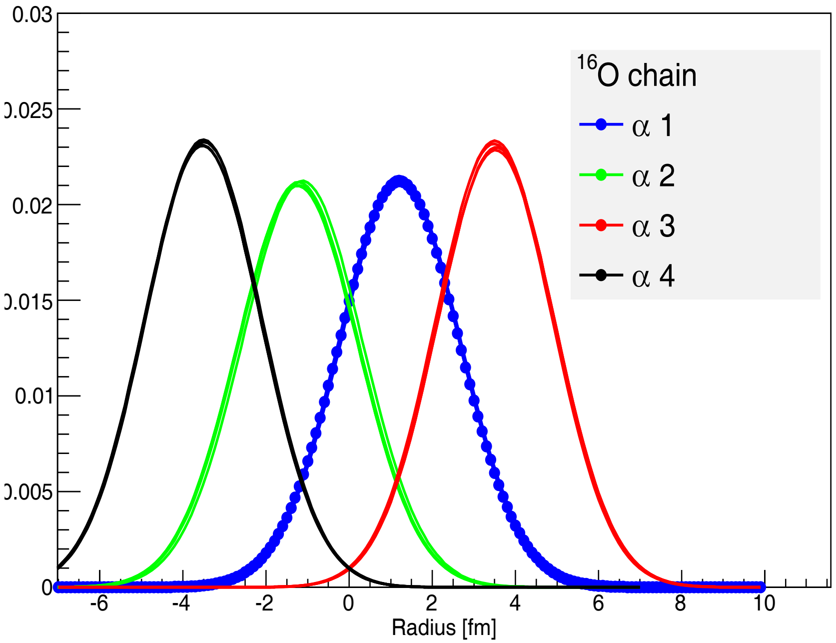


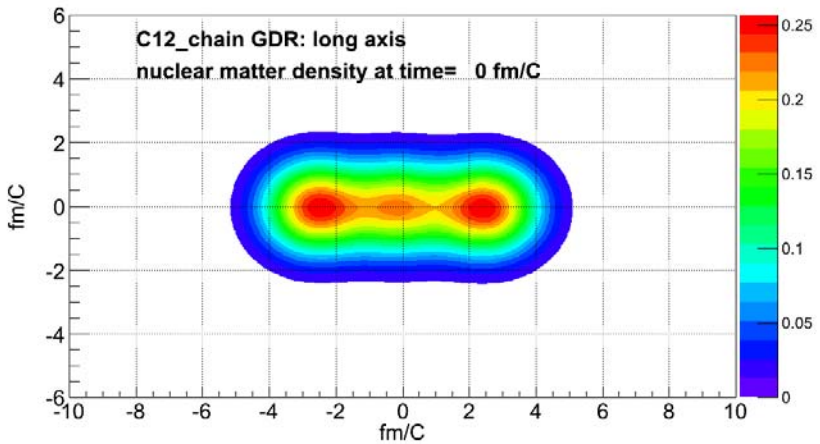
Binding energy of nuclei with cluster configuration

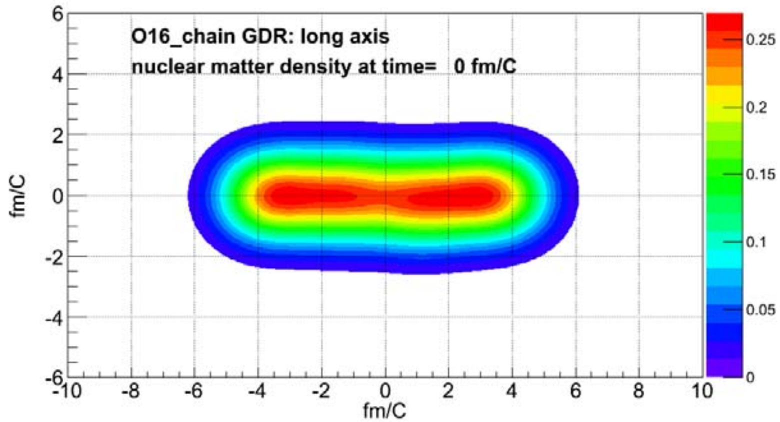
Nuclei	^{8}Be	^{12}C chain	^{12}C triangle	^{16}O chain	^{16}O kite	^{16}O square
Binding energy (AMeV)	7.19	7.21	7.26	7.22	7.18	7.26

Density of each nucleon in nuclei with alpha cluster configuration

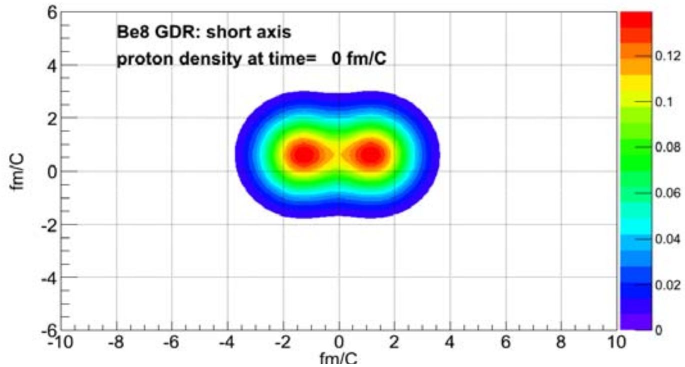


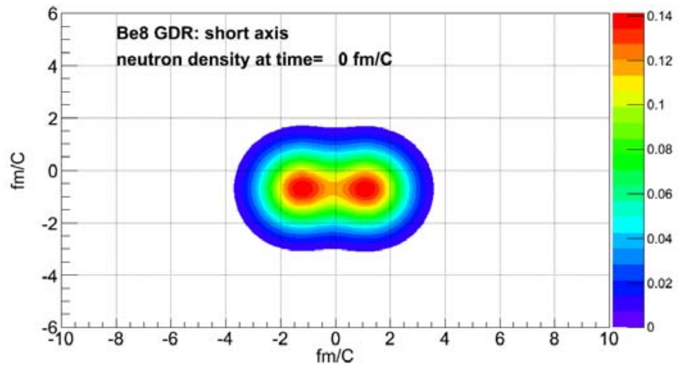


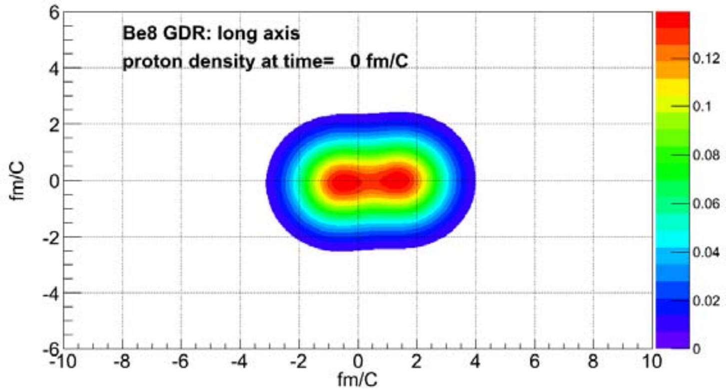


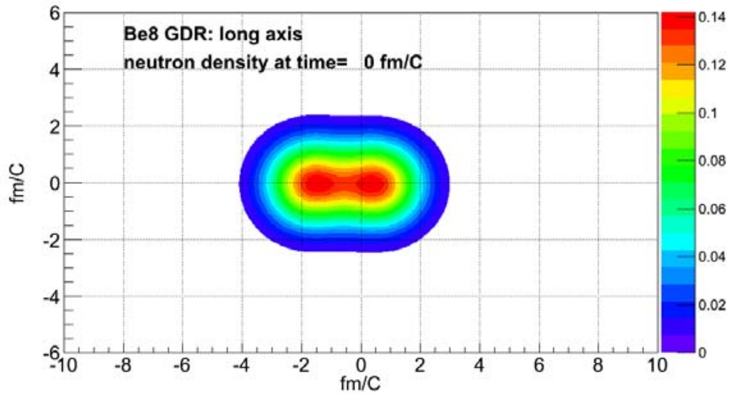


◆ Dynamical evolution of density current

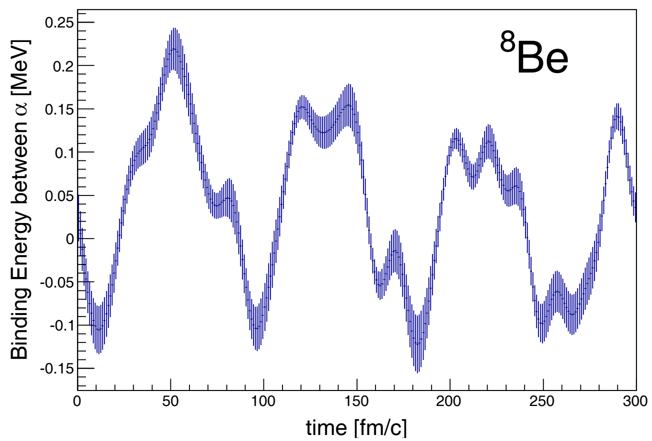




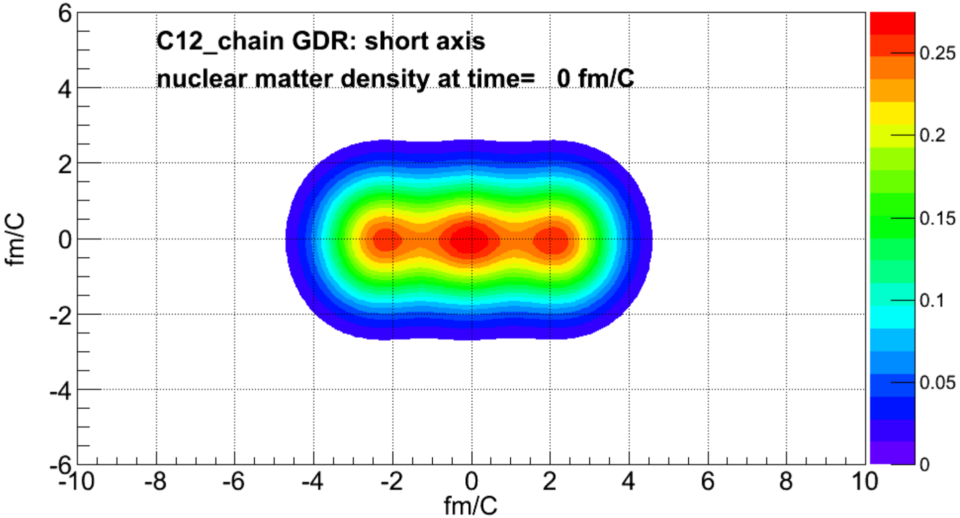


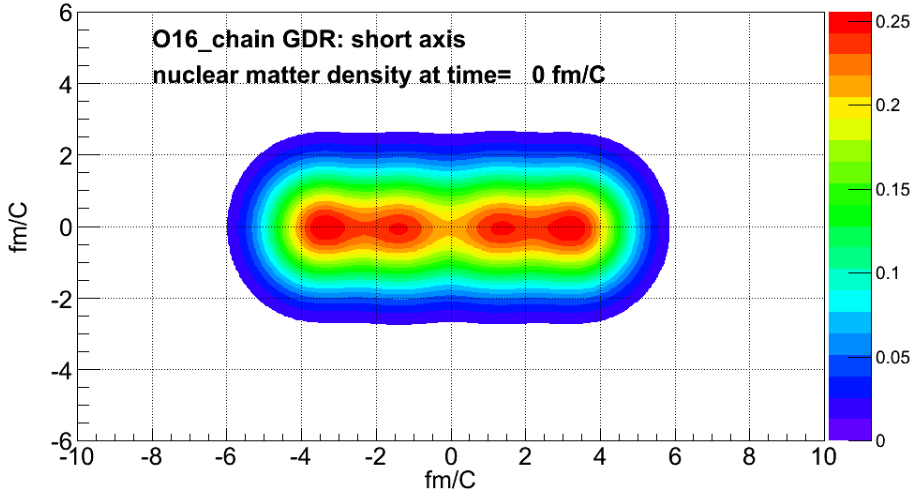


The α cluster is very different from free α particle



Binding energy evolution between two alphas in 8Be


C12_chain GDR: short axis
nuclear matter density at time= 0 fm/C
fm/C
fm/C
0.25
0.2
0.15
0.1
0.05
0


O16_chain GDR: short axis
nuclear matter density at time= 0 fm/C
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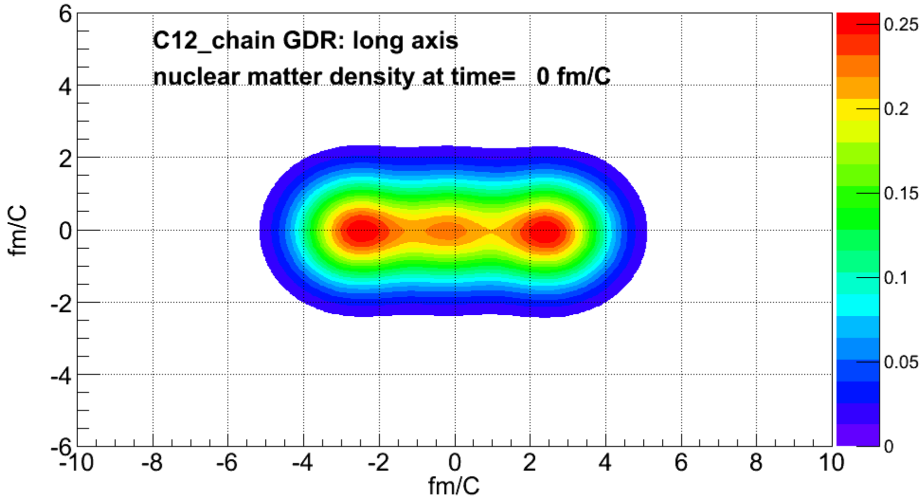
C12_chain GDR: long axis
nuclear matter density at time= 0 fm/C
fm/C
fm/C
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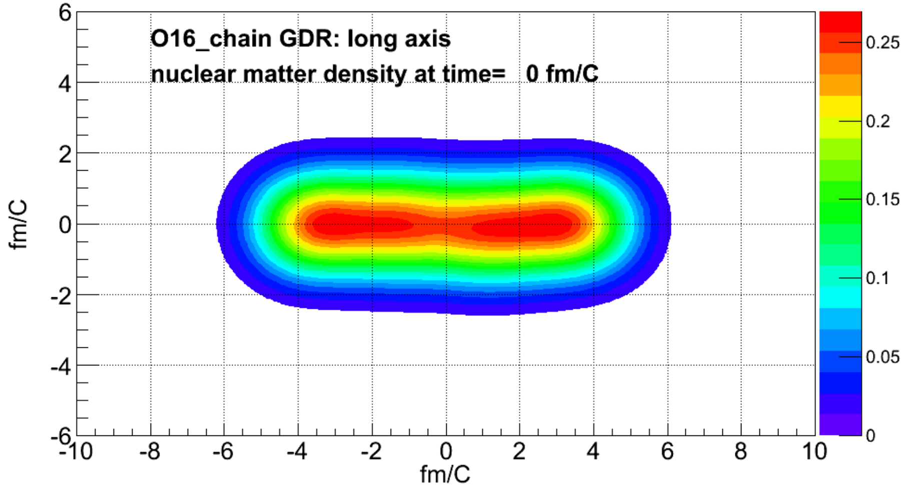
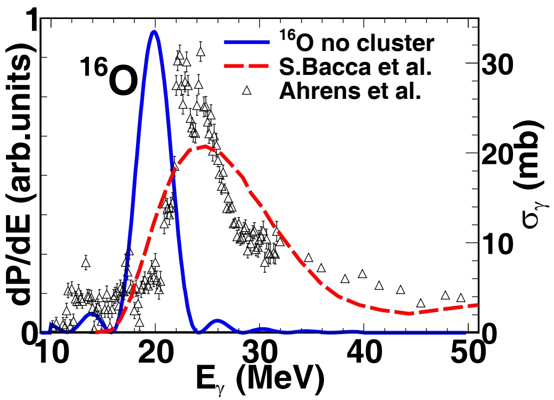

O16_chain GDR: long axis
nuclear matter density at time= 0 fm/C
fm/C
fm/C
0.25
0.2
0.15
0.1
0.05
0

Results & discussion

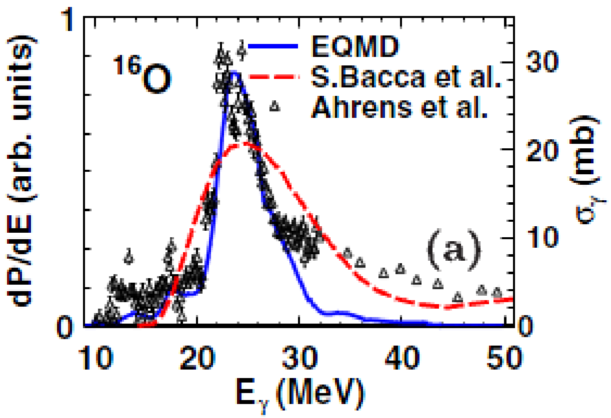
-- GDR of ^{8}Be, ^{12}C & ^{16}O with different α configurations

W. He, YGM, X. Cao, X. Cai, G. Zhang, *Phys. Rev. Lett. 113*, 032506 (2014)

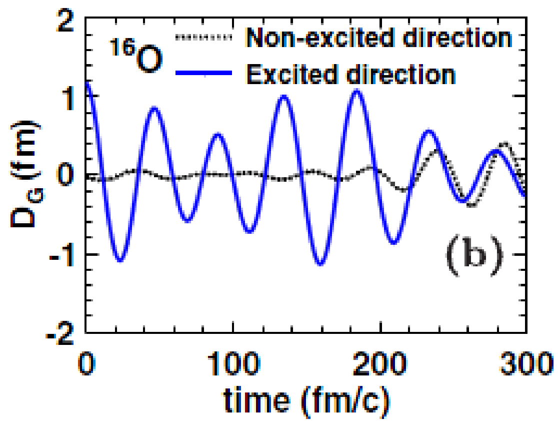
- EQMD calculation supports ^{16}O ground state with tetrahedron



^{16}O ground state without cluster



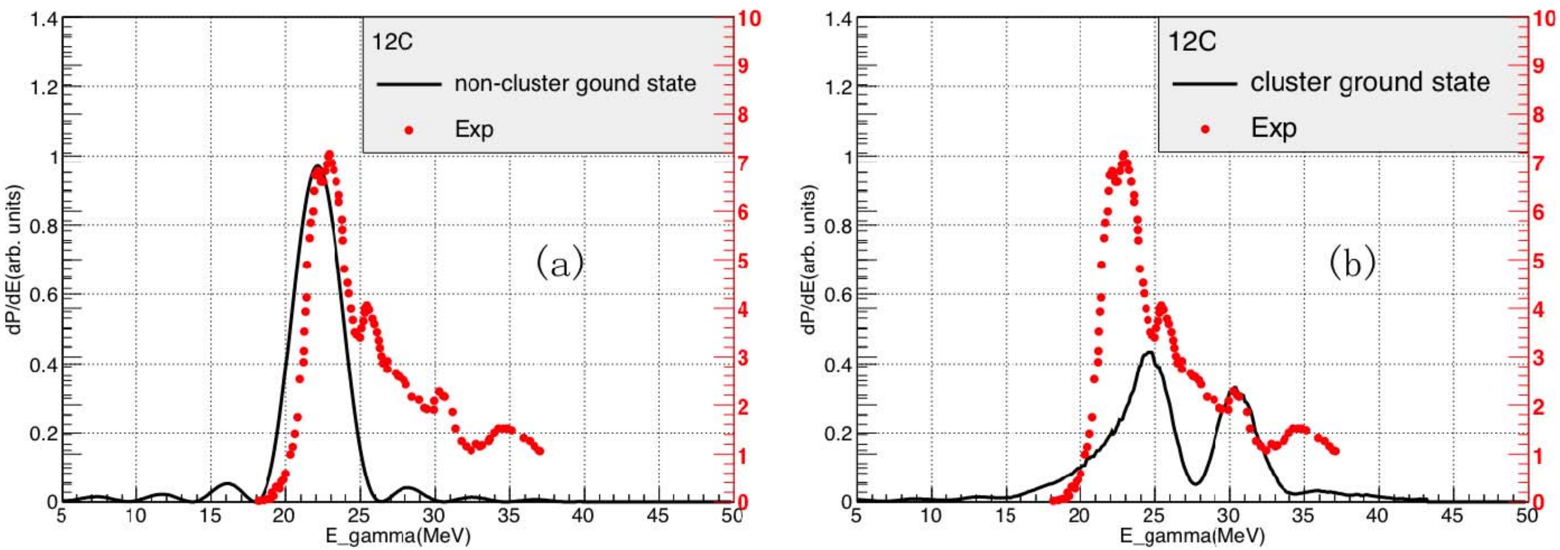
^{16}O ground state with tetrahedron



Dipole evolution of ^{16}O

◆ EQMD calculation indicates the ground of ^{12}C is a multiconfiguration mixing of shell-model-like and cluster-like configurations,

which is consistent with the prediction of AMD [Y. Kanada-En'yo, Phys. Rev. Lett 81, 5291 (1998)] and FMD [M. Chernykh, H. Feldmeier et al., Phys. Rev. Lett. 98, 032501 (2007)]



^{12}C GDR without (left panel) and with (right panel) cluster configuration with data.

Giant Dipole Resonance as a Fingerprint of α Clustering Configurations in ^{12}C and ^{16}O

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[3]Shanghai Tech University, Shanghai 200031, China
(Received 6 May 2014; published 17 July 2014)

Correspondence between GDR and α cluster configurations

- ✓ GDR spectrum is highly fragmented into several apparent peaks due to the α structure
- ✓ The different α cluster configurations in ^{12}C and ^{16}O have corresponding characteristic spectra of GDR
- ✓ The number and centroid energies of peaks in the GDR spectra can be reasonably explained by the geometrical and dynamical symmetries of α clustering configurations

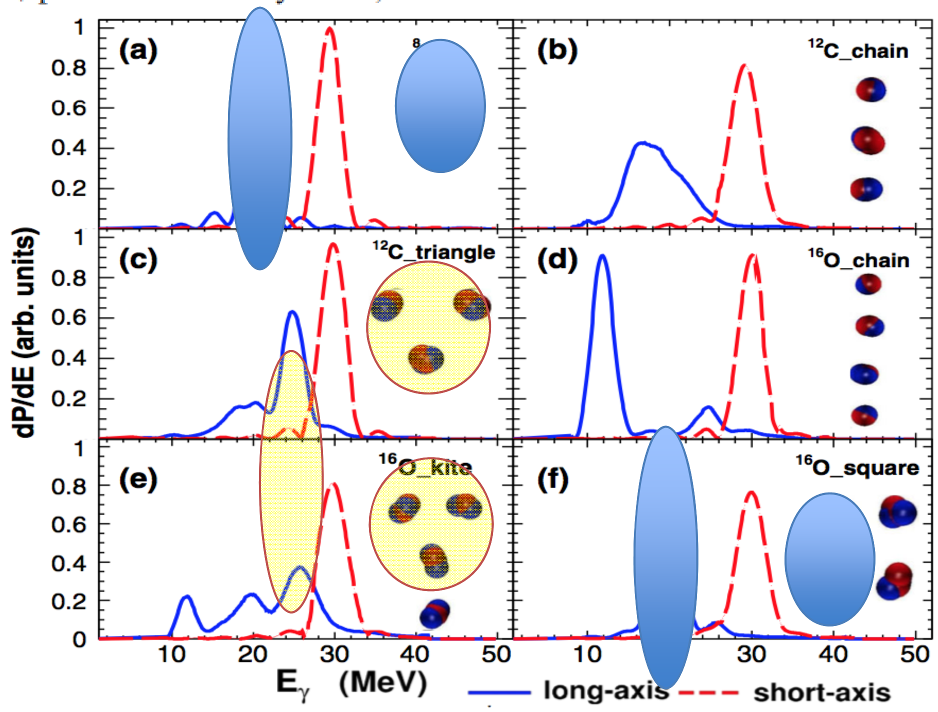

FIG. 2 (color online). ^{8}Be, ^{12}C, and ^{16}O GDR spectra with different cluster configurations. The corresponding α cluster configuration in the present EQMD model calculation is drawn in each panel, in which blue and red balls indicate protons and neutrons, respectively. The dynamical dipole evolution of ^{8}Be, ^{12}C, and ^{16}O with linear-chain configurations are shown in [51].

◆ Hints from an experimental point of view
--- sensitive probe

- ✓ The measurement of the GDR peak located around 30 MeV is a feasible way to confirm the existence of an α clustering state

- ✓ Analysis of other low- lying peaks can be used to diagnose the different configurations formed by α clusters

- ✓ The similar GDRs of ^{8}Be and triangle ^{12}C appear as substructures in the GDRs of square ^{16}O and kite ^{16}O, respectively, which will help to recognize the α configuration in ^{16}O

◘ Summary & outlook

- ✓The semi-classical QMD-like model is suitable to study GR
- ✓The GDR of excited state with α cluster is studied by EQMD
  - ✧ GDR as an effective probe of α configuration
    - Peak near 30 MeV
    - Substructure in ^{12}C and ^{16}O
  - ✧ The density evolution shows the complicated underlying dynamics of α cluster in nuclei
- ✓ Possible experimental chance on HIγS (Triangle Univ.) and SLEGS (SINAP)

Thanks for discussions with P. Schuck, T. Maruyama, J. Natowitz, S. Shlomo, R. Wada

Thanks very much for you attention!

Backup slides

PRL 112, 112501 (2014) PHYSICAL REVIEW LETTERS week ending 21 MARCH 2014

Signatures of α Clustering in Light Nuclei from Relativistic Nuclear Collisions

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(Received 1 December 2013; published 18 March 2014)

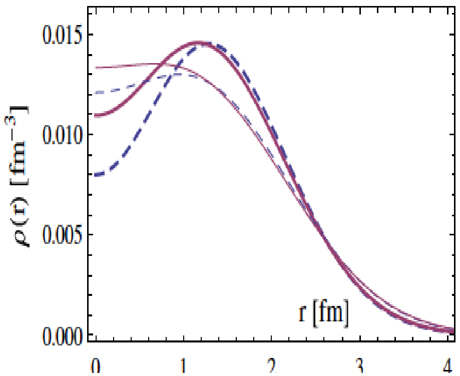
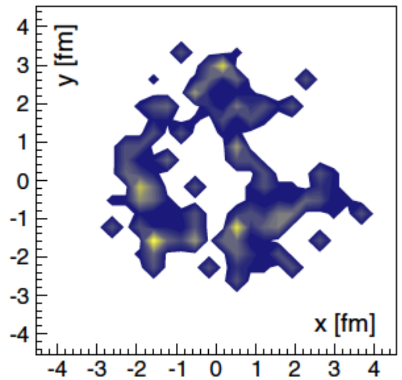
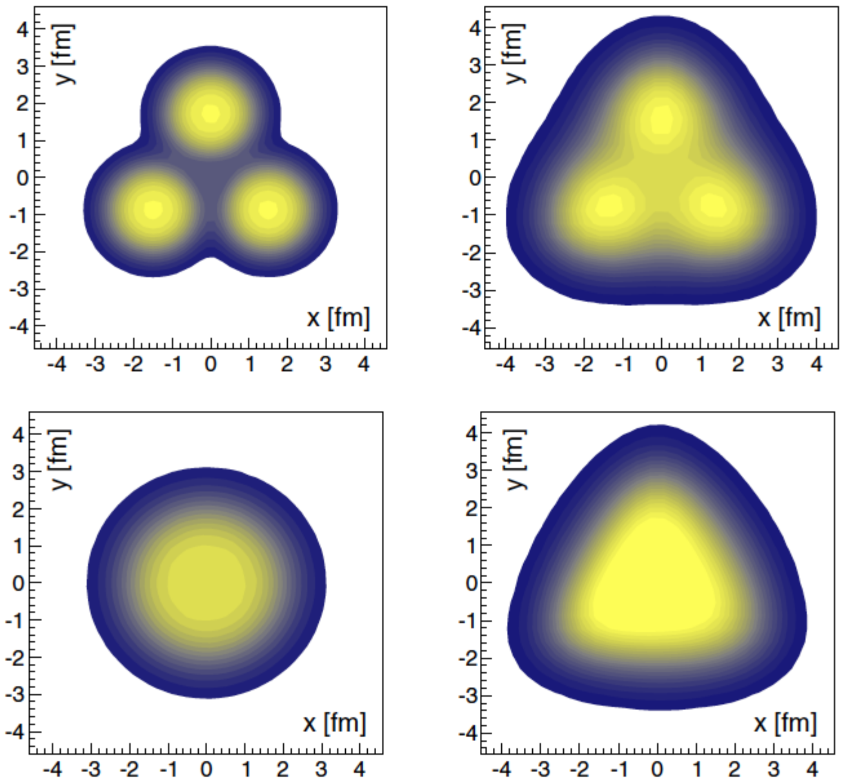
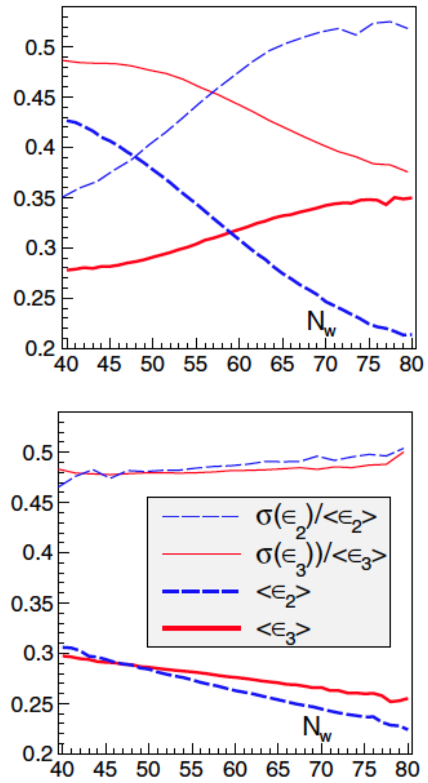


FIG. 1. (Color online) (color online). The electric charge density (thin lines) and the corresponding distribution of the centers of nucleons (thick lines) in ^{12}C for the data and BEC calculations (dashed lines), and for the FMD calculations (solid lines), plotted against the radius.







C. Tao and Y. G. Ma et al.,

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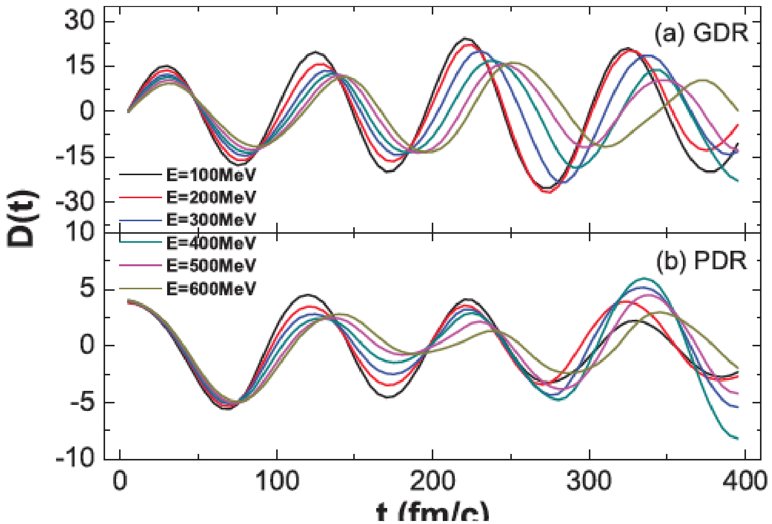
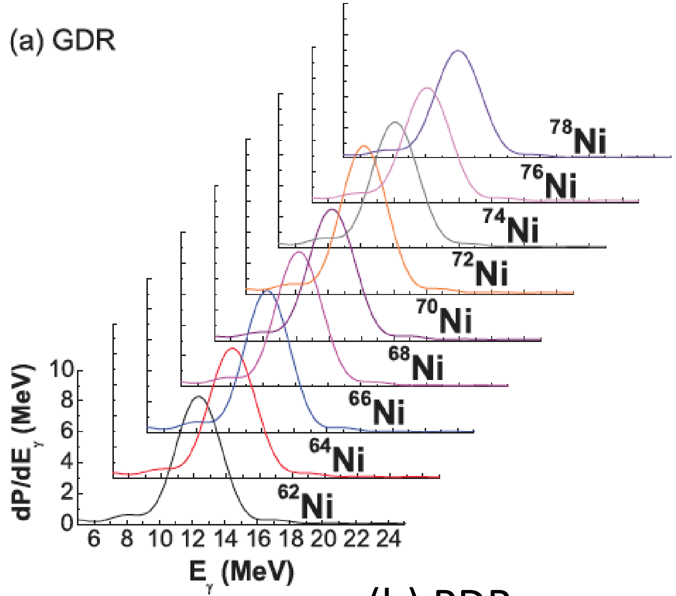
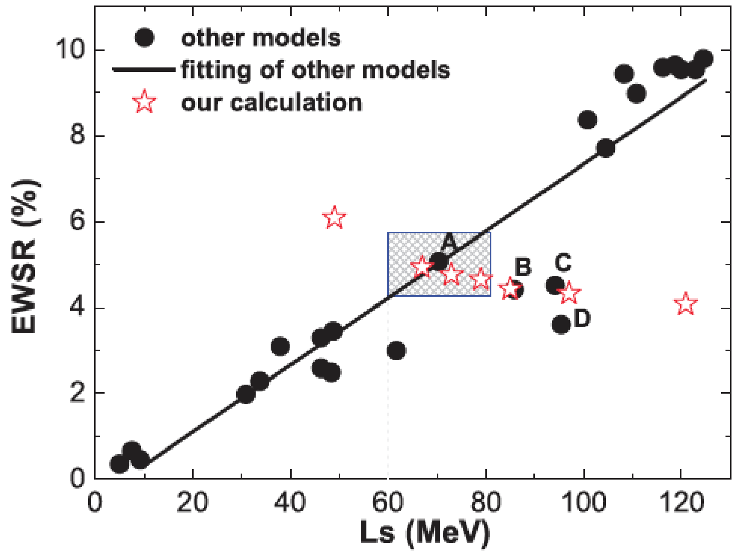
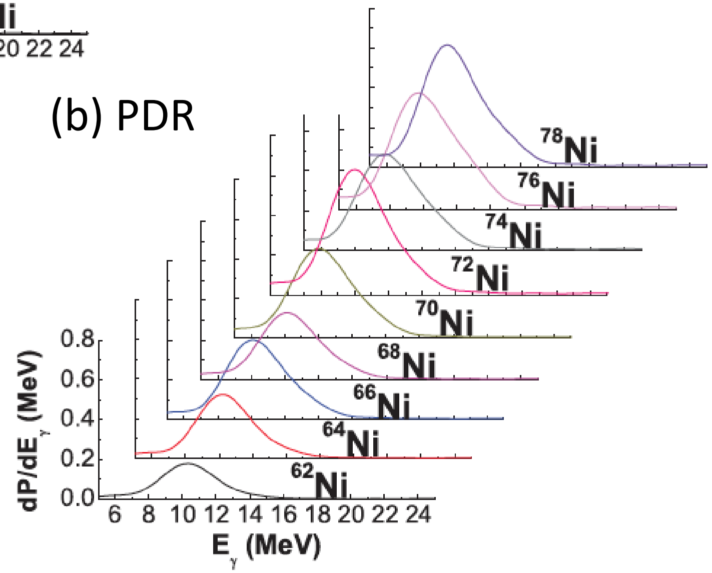
Pygmy and giant dipole resonances by Coulomb excitation using a quantum molecular dynamics model





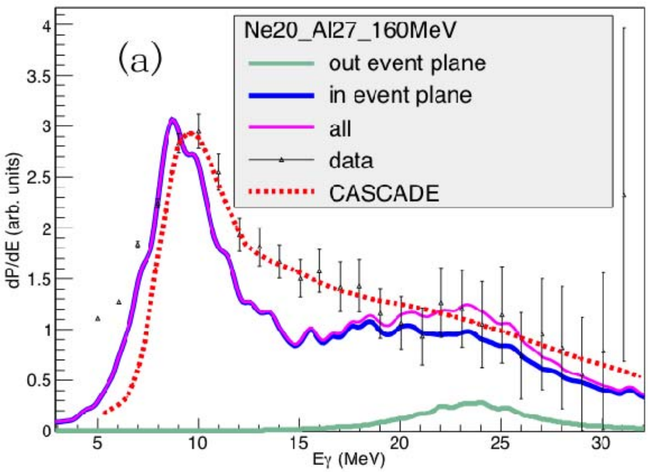




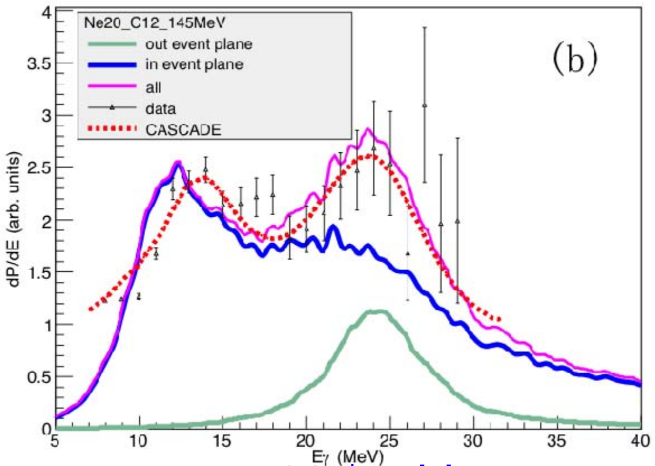
GDR algorithm & verification

-- verification the reliability of EQMD in GDR calculations

GDR in fusion reaction

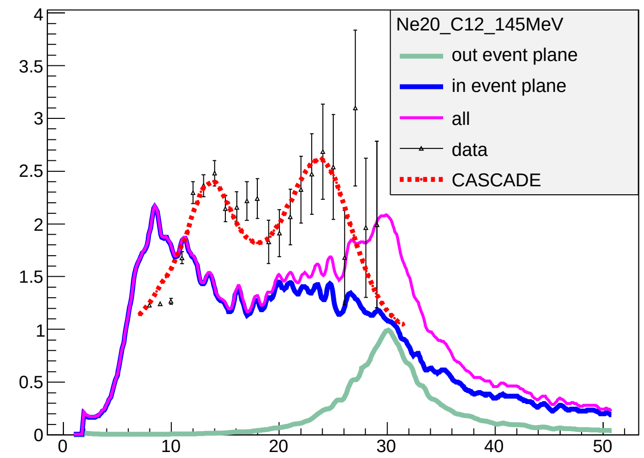


cuts 100±5 hbar

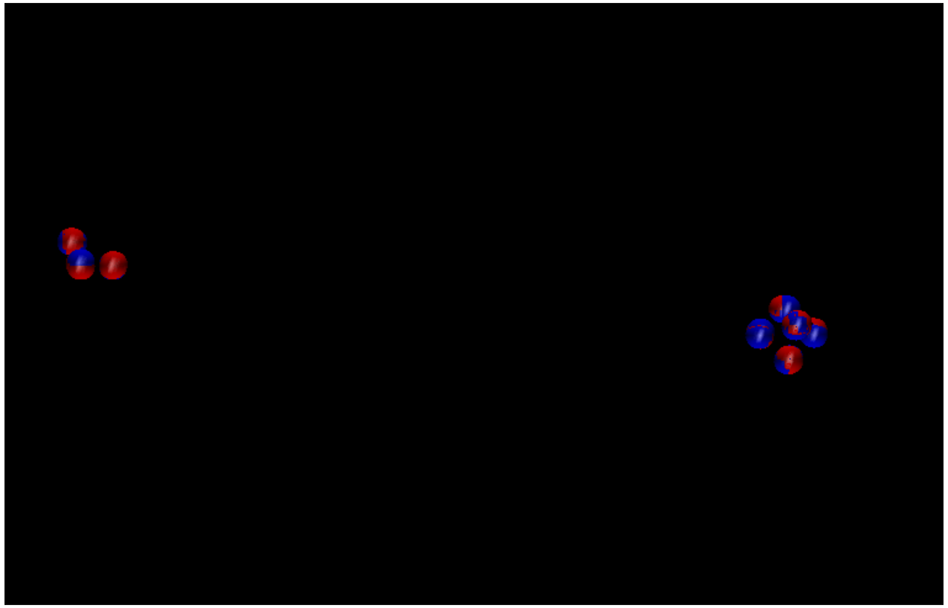


cuts 60±5 hbar

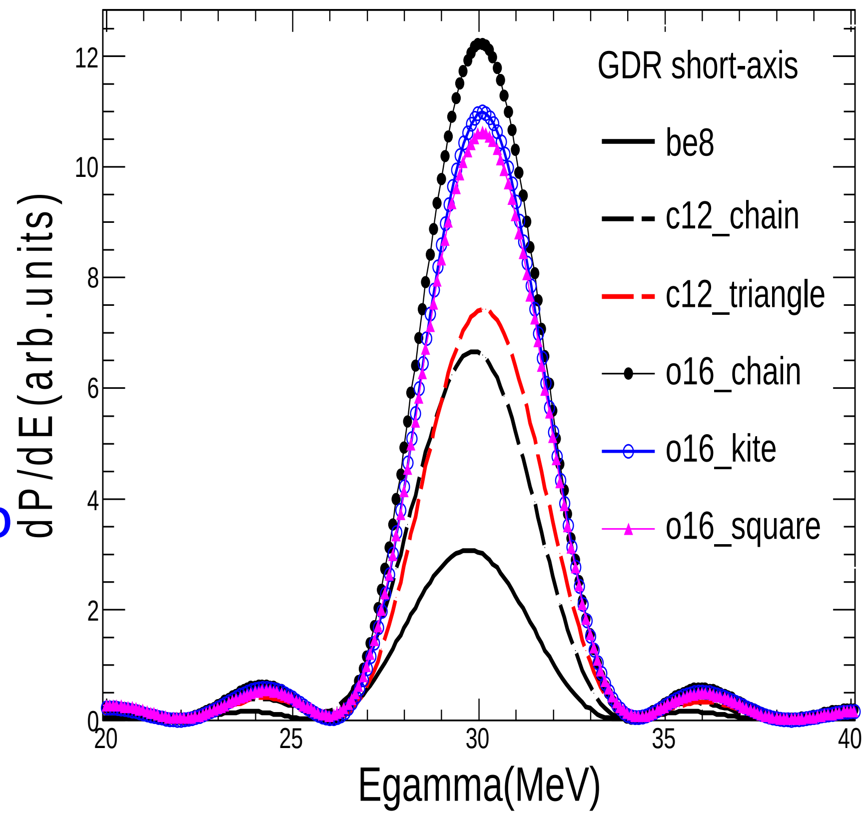
the data is from D. Pandit et al, Phys. Rev. C 81, 061302 (2010)

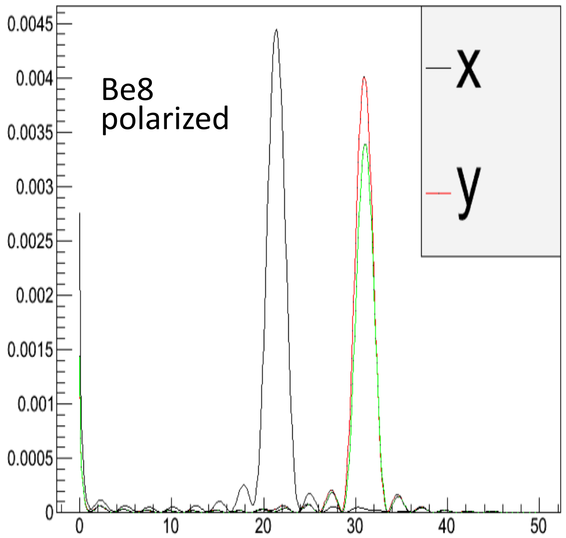


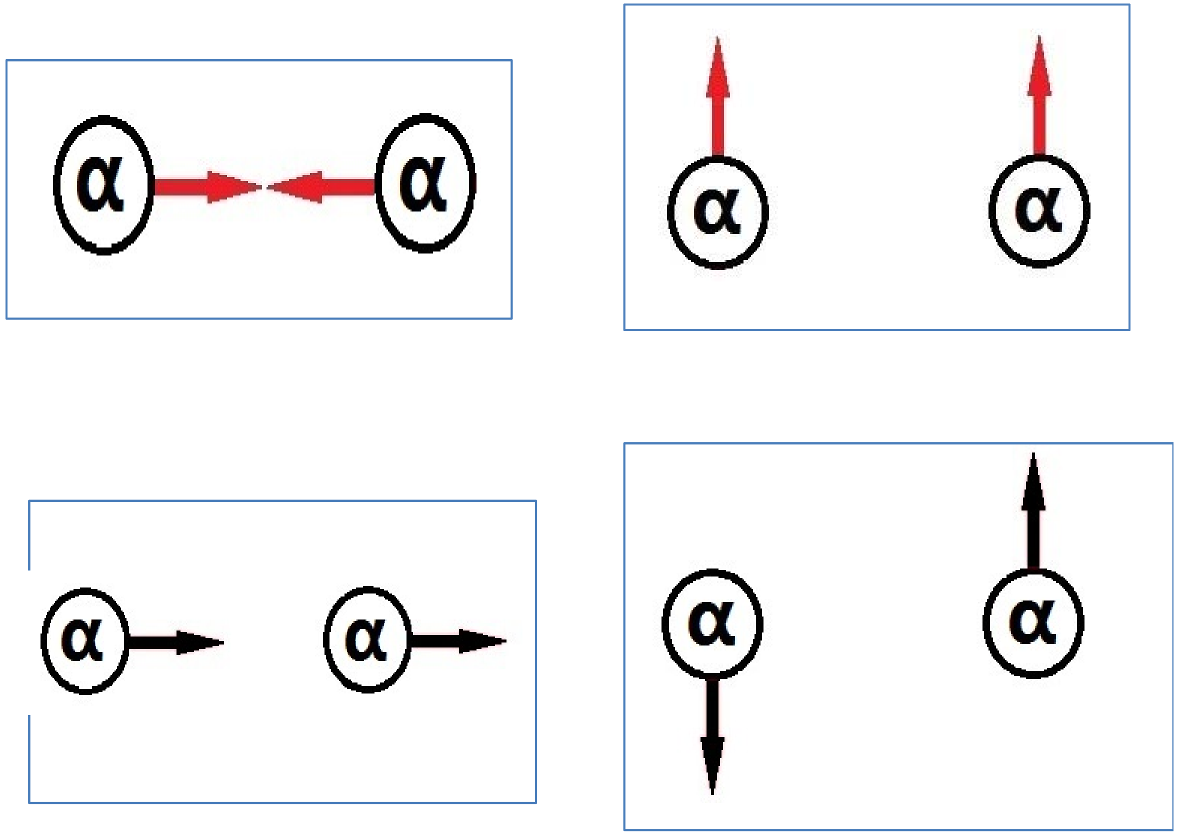
cuts >95 hbar



The strength perpendicular has strong correlation with the number of alphas: more alphas, more big strength. The relationship is not a simple linear relation due to the interaction among alphas, which can be seen clearly in next several slides.





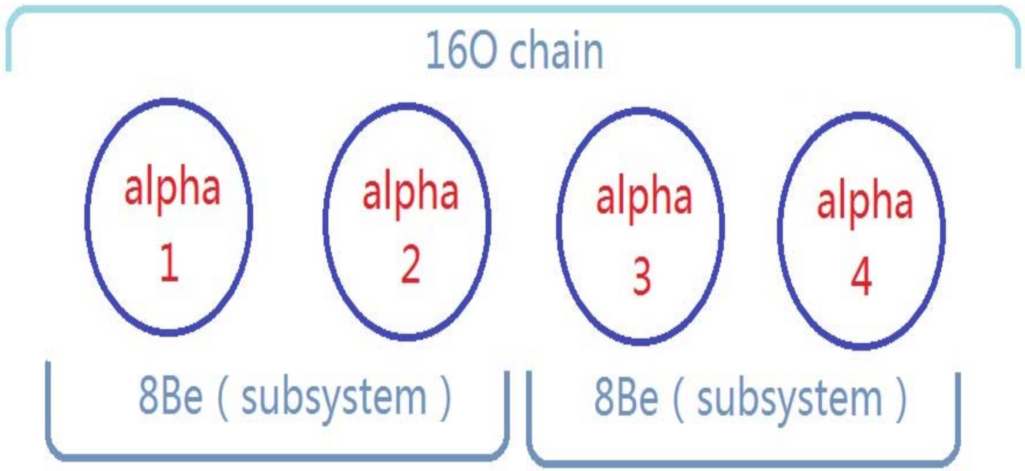


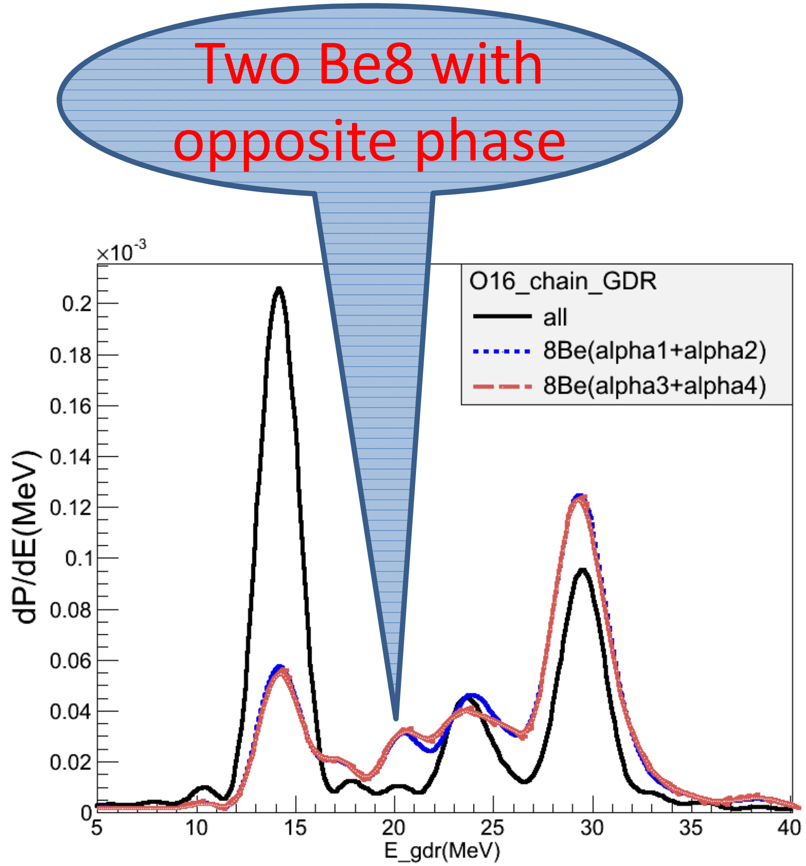
This figure shows dipole moment rather than motion in two direction.

The red arrow shows high frequency component
The black arrow shows low frequency component

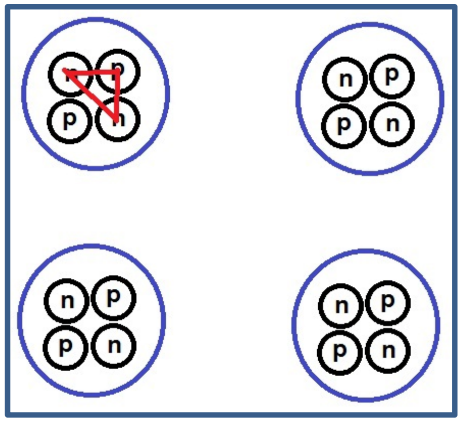
The substructure of Be8 in O16 GDR is shown in the following figures. In right figure, the blue doted and red dashed line represent two substructures.

The peaks near 20MeV in GDR from two Be8 counteract because of the opposite phase.

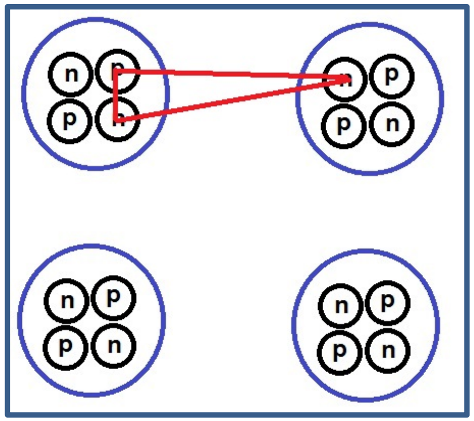




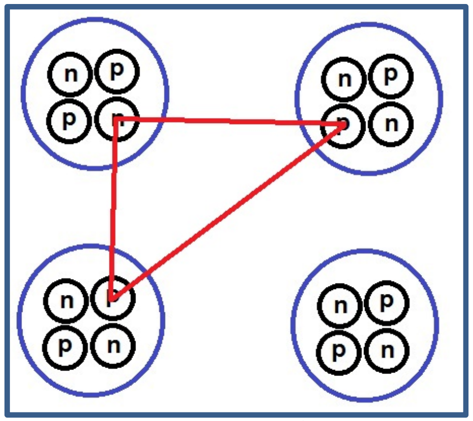
Three body force has three cases in cluster nuclei made of alphas as shown in following three figures. 25 MeV peak in GDR is affected by the third case. The third case manifests as effective three alpha force among alphas. This effective three alpha force favors triangle configuration.



Case 1

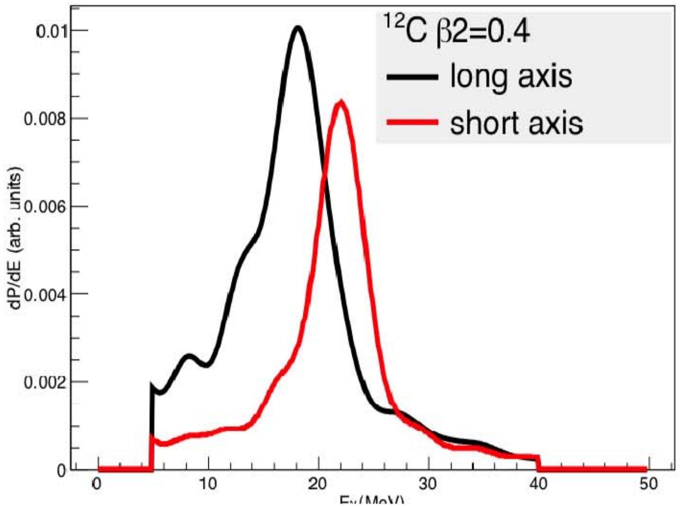


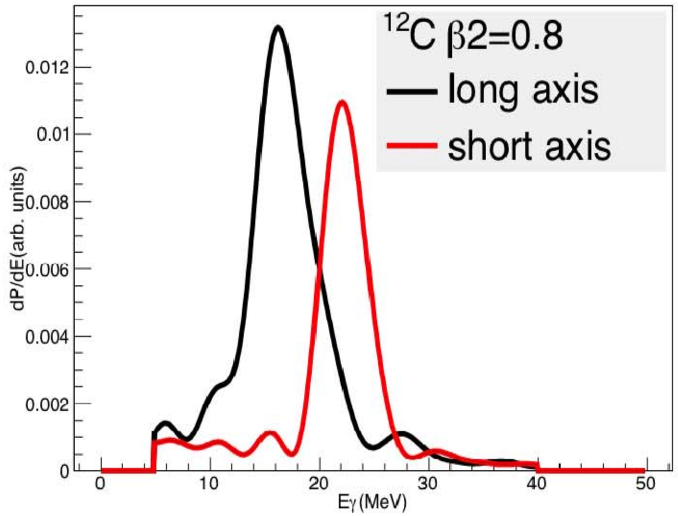
Case 2

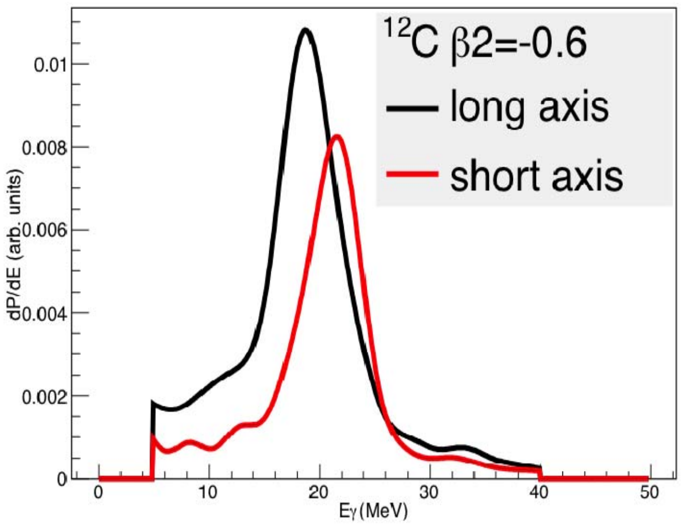


Case 3

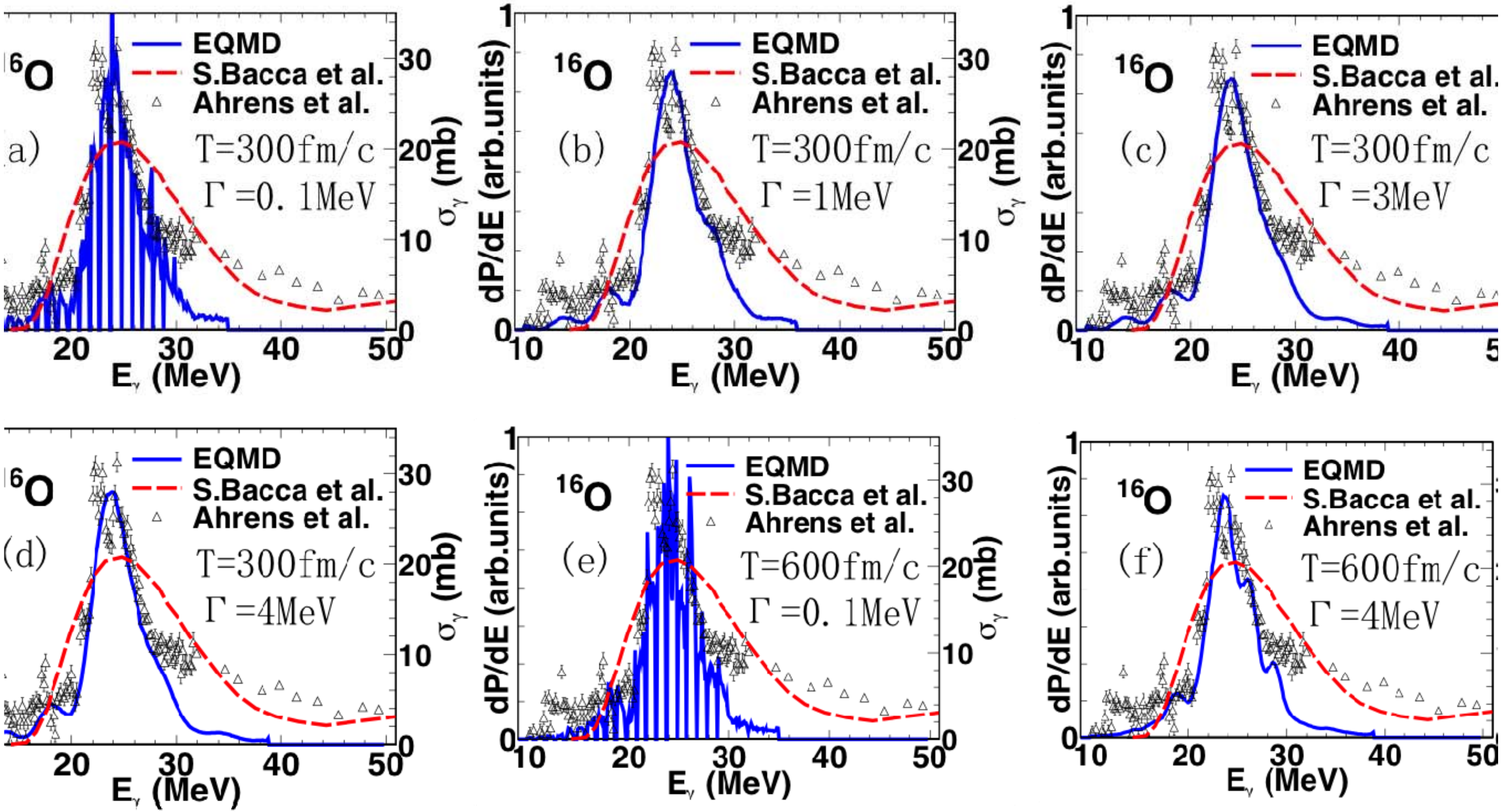
The GDR of ^{12}C with prolate and oblate deformations.







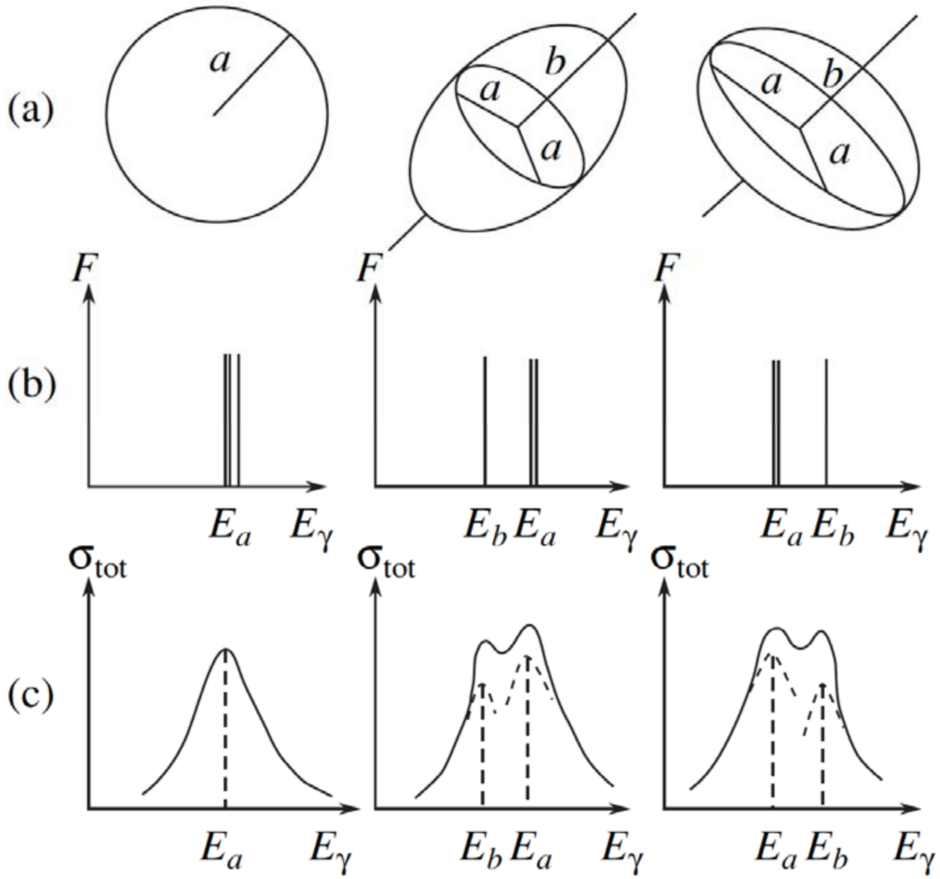
The dependence ^{16}O GDR width on smoothing factor Γ and integration time

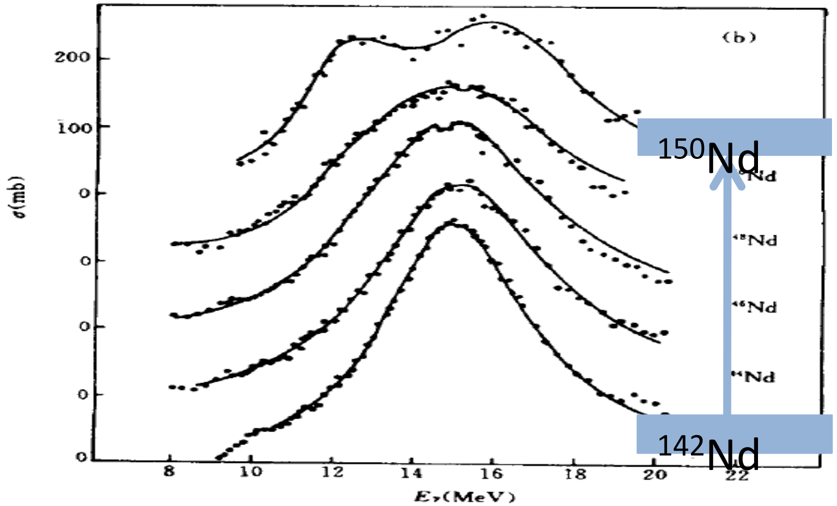


Background

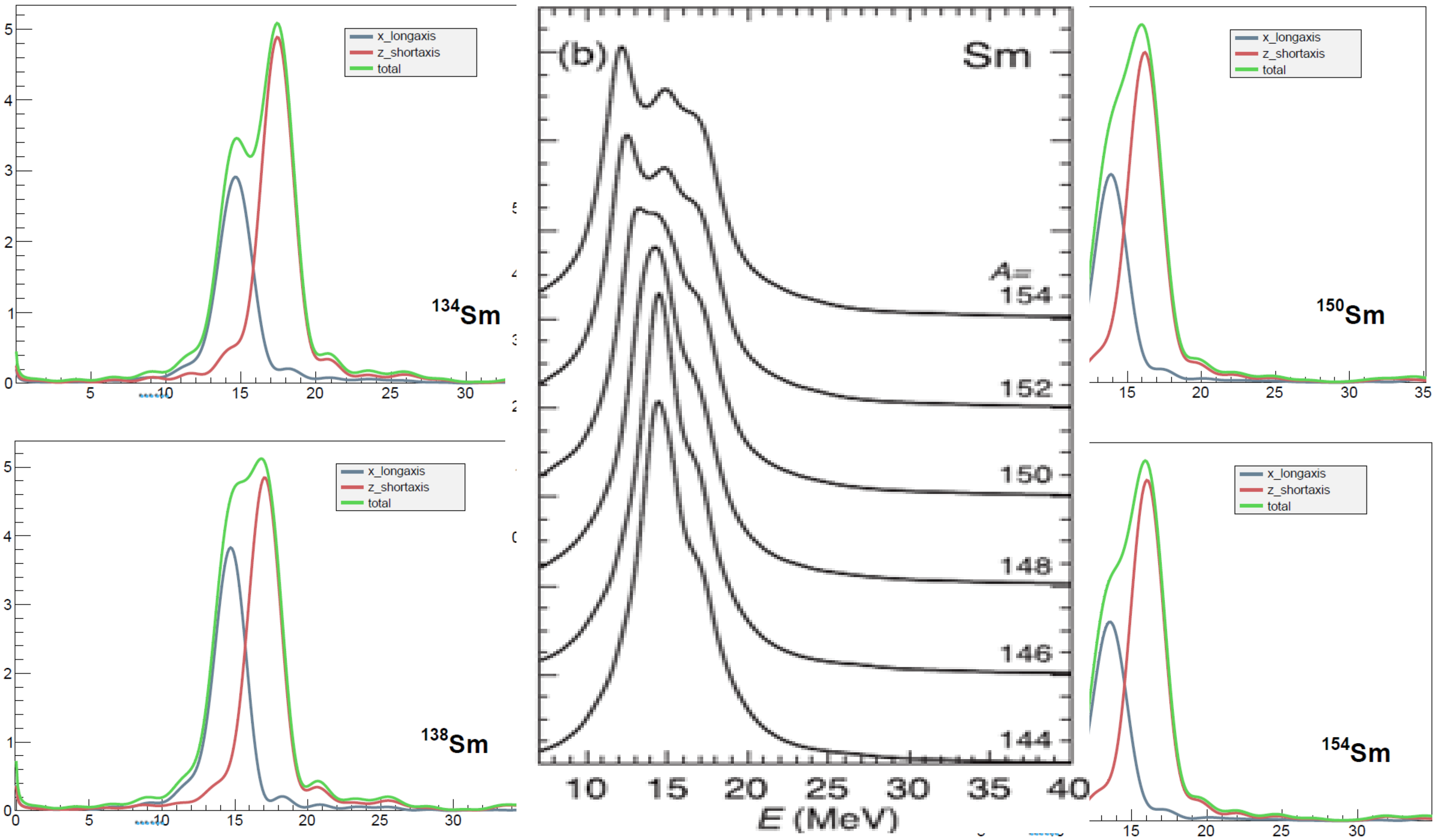
◆ 球形核沿三个轴的振动频率是相同的，因此共振为单峰。而旋转椭球形核沿长轴与短轴的振动频率会有差异，前者频率低于后者，因此共振呈双峰结构；而且对于长椭球变形核的低频振动强度应为高频成分的二分之一，反之则为扁椭球变形核。因此共振峰能反映核的形状。

◆ 形变核有两个共振峰，被解释为原子核吸收E1辐射后引起中子流与质子流相对于共有的质心的振动，为电偶极振动，其恢复力是对称能。

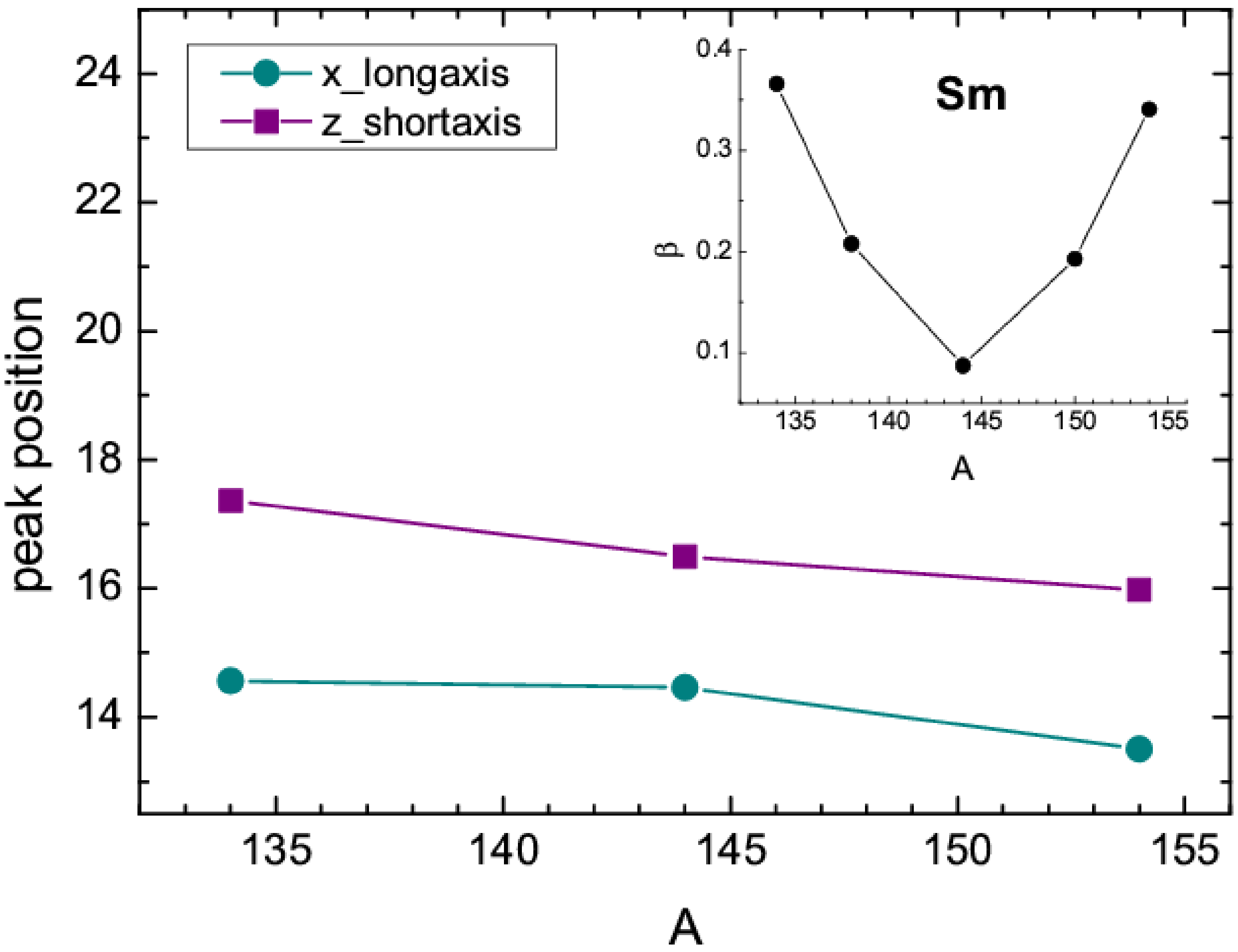


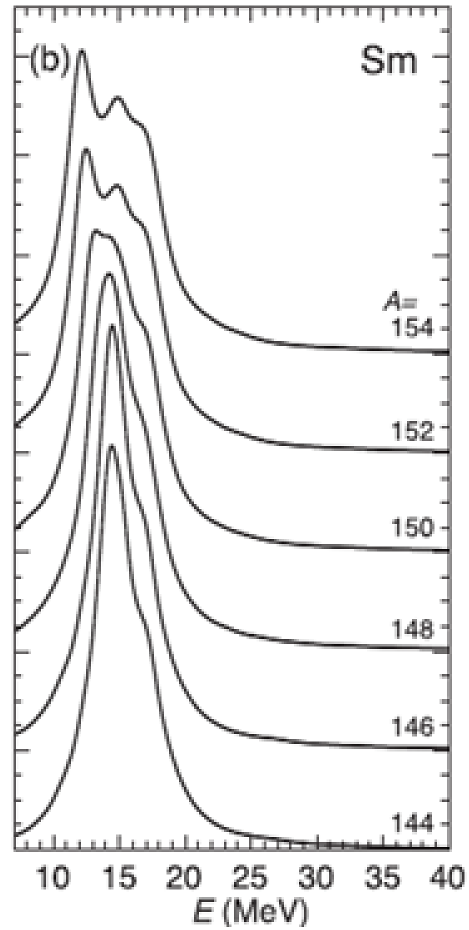


GDR in deformation nuclei



GDR in deformation nuclei





Background

■QMD、AMD、FMD

- ➢QMD不适用于研究低能核反应（例融合、裂变、深度非弹性碰撞）
- ➢AMD和FMD计算重系统时，要花费大量的CPU时间

■EQMD模型的改进之处

- ➢有效相互作用中引入Pauli势，体现核子的费米属性
- ➢把波包变化动能项考虑到系统的Hamiltonian中
- ➢核子波函数中引入复数变量的波包宽度，波包宽度的演化用变分原理处理

Background

系统总的波函数 $\Psi = \prod_i \phi_i(\mathbf{r}_i)$

其中， $$\phi_i(\mathbf{r}_i) = \left(\frac{\nu_i + \nu_i^*}{2\pi}\right)^{3/4} \exp\left[-\frac{\nu_i}{2}(\mathbf{r}_i - \mathbf{R}_i)^2 + \frac{i}{\hbar}\mathbf{P}_i \cdot \mathbf{r}_i\right]$$

$$\nu_i \equiv \frac{1}{\lambda_i} + i\delta_i$$

高斯波包宽度

其中λ_i和δ_i分别代表核子坐标和动量空间宽度，$\mathbf{R}_i$、$\mathbf{P}_i$、λ_i和δ_i 随时间的演化由时间依赖的变分原理得到。

四种相互作用 $$H_{\text{int}} = H_{\text{Skyrme}} + H_{\text{Coulomb}} + H_{\text{symmetry}} + H_{\text{Pauli}}$$

T.Maruyama etal. Phys. Rev. C 53, 297 (1996)