Alpha-clustering effects of ^{12}C & ^{16}O for reaction from low to relativistic energies

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"Phases of Quantum Chromodynamics (QCD) and Beam Energy Scan Program with Heavy Ion Collisions"

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Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Outline

- Introduction
- Alpha-cluster effect on collective oscillation (GDR)
- Alpha-cluster effect in quasi-deuteron region
- Alpha-cluster effect on flows for $^{16}O+^{16}O$ & $^{12}C+^{12}C$
- Alpha-cluster effect on flows for $^{12}C+Au$
- Summary

Motivation

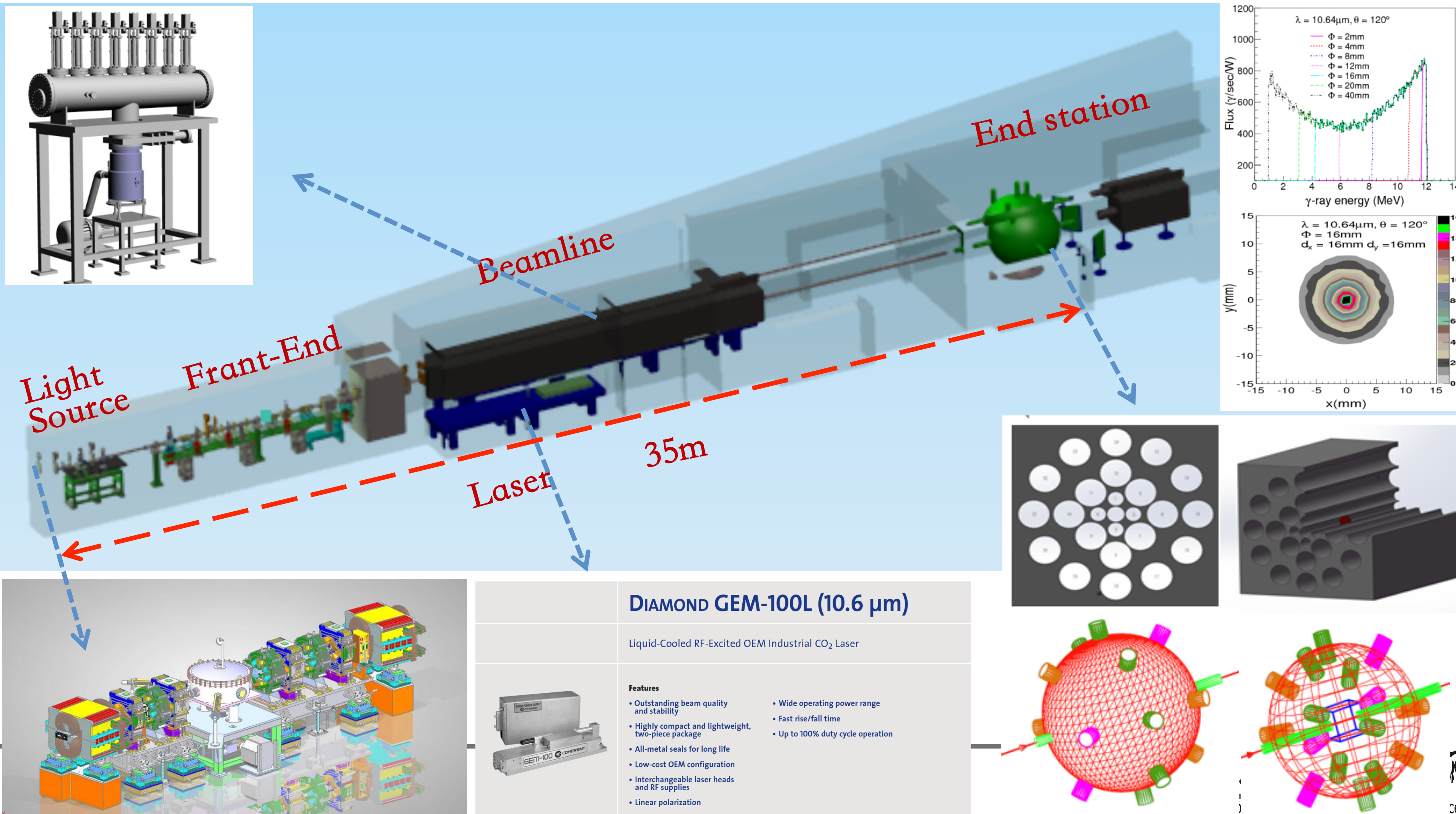

SXFEL(soft X-ray FEL) 840MeV
A new γ source @ SXFEL
SSRF 3.5GeV
SLEGS
Shanghai Laser Electron Gamma Source
Zhangjiang Campus, SSRF (Shanghai Synchrotron radiation Facility,
Shanghai Inst. Of Applied Physics, CAS)
The planned "Shanghai Laser Gamma Source @ SSRF"

Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Shanghai Laser Electron Gamma Source @ SSRF

(Start to construct in 2017 and will be in operation in 2020)

Energy range： 0.4-20.MeV; Energy resolution ： ~5%; Divergence angle： 0.5mrad; Flux： 10^5 -10^7 phs/s

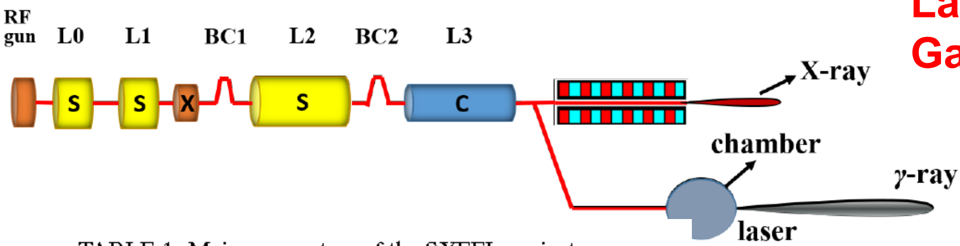


MeV LCS gamma beams at SINAP

1.3 A new proposal for LCS Gamma Source similar to ELI-NP @ SXFEL

Electron Energy： 0.85GeV， Update to 1.3GeV
Laser： 800 nm Ti: Sapphire
Gamma Energy： 3.7MeV ~ 38.9MeV

Schematic layout of the gamma source at SXFEL



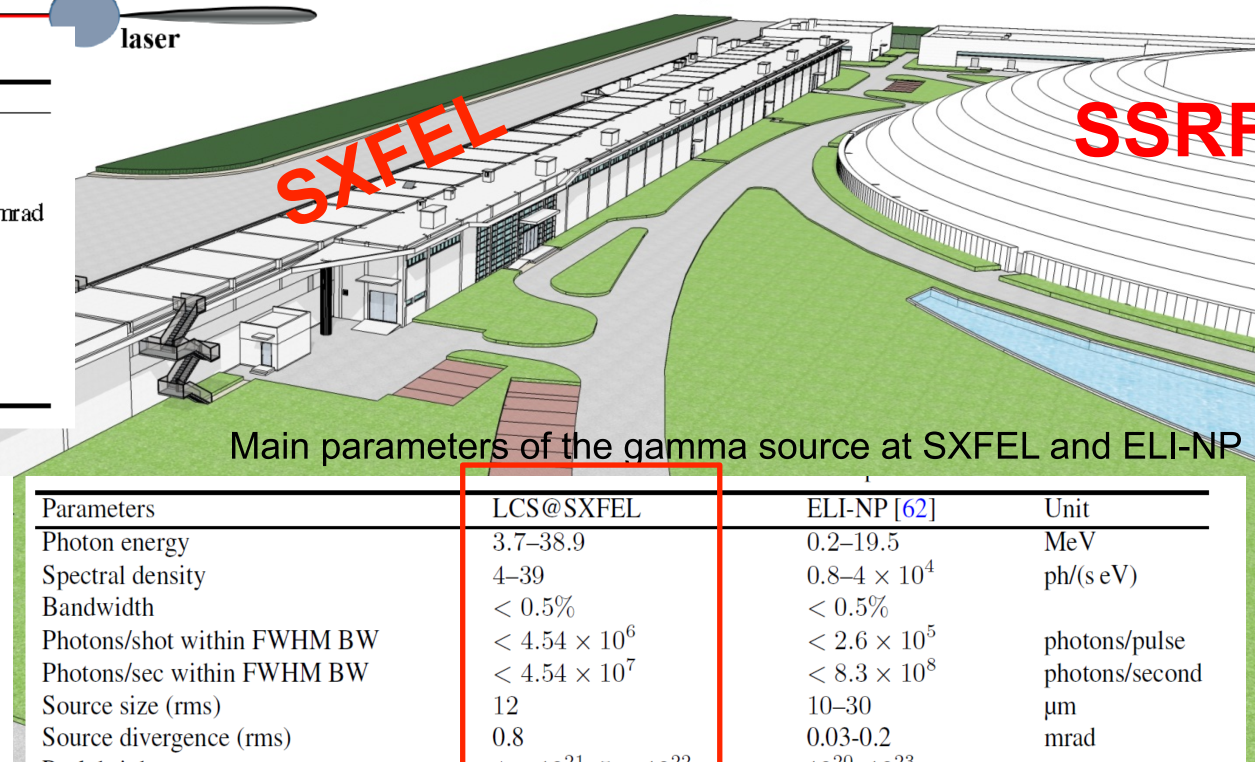
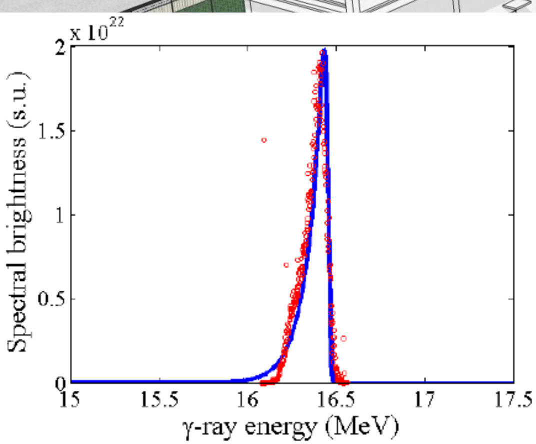


TABLE 1. Main parameters of the SXFEL project.

Parameters	Baseline	Upgrade	Unit
e- beam energy	0.84	1.3	GeV
e- energy spread	<0.15%	<0.15%	
e- bunch charge	0.5	0.5	nC
e- normalized emittance	<1.5	<1.5	mm mrad
e- pulse length (FWHM)	<1	< 1	ps
e- beam current	500	500	A
e- repetition rate	10	10	Hz
FEL wavelength	8.8	3	nm
FEL power	>100	>100	MW
FEL pulse length	<150	<150	fs



Main parameters of the gamma source at SXFEL and ELI-NP

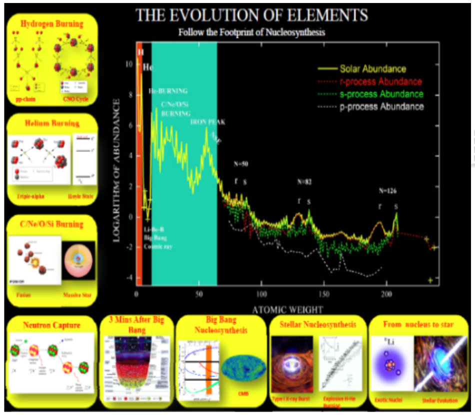
Parameters	LCS@SXFEL	ELI-NP [62]	Unit
Photon energy	3.7–38.9	0.2–19.5	MeV
Spectral density	4–39	$0.8–4 \times 10^4$	ph/(s eV)
Bandwidth	< 0.5%	< 0.5%	
Photons/shot within FWHM BW	$< 4.54 \times 10^6$	$< 2.6 \times 10^5$	photons/pulse
Photons/sec within FWHM BW	$< 4.54 \times 10^7$	$< 8.3 \times 10^8$	photons/second
Source size (rms)	12	10–30	μm
Source divergence (rms)	0.8	0.03-0.2	mrad
Peak brightness	$4 \times 10^{21}–5 \times 10^{22}$	$10^{20}–10^{23}$	s.u.
Pulse length (rms)	0.86	0.7–1.5	ps
Repetition rate	10	100	Hz

[1]Nuclear Science and Techniques, Vol.26(2015)050103

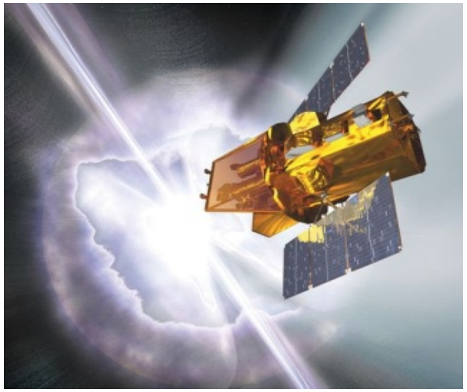
SLEGS for nuclear physics & application

- Photo−nuclear physics:
  - ➢ Nuclear Astrophysics： nuclear reactions which have a critical impact on stellar evolution and nucleosynthesis of elements
  - ➢ Nuclear structure GDR and NRF, etc.
- Research on the anti-γ radiation properties of aerospace device and calibration for the X/γ detector equiped on aerospace device
- Nuclear waste transmutation research and nuclear safety,
- Gamma-ray imaging techniques (in particular: isotope imaging technology), etc.

Nuclear Astrophysics

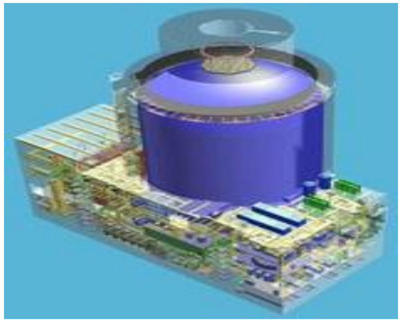


Space (radiation hardened)



Nuclear technology and data

nuclear explosion



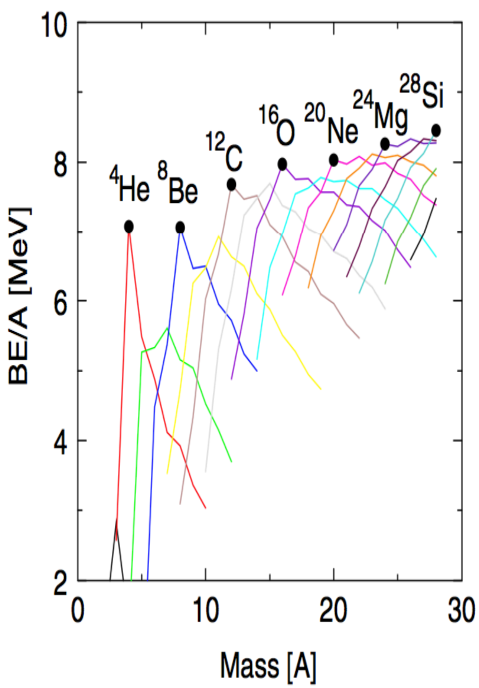
Nuclear reactor

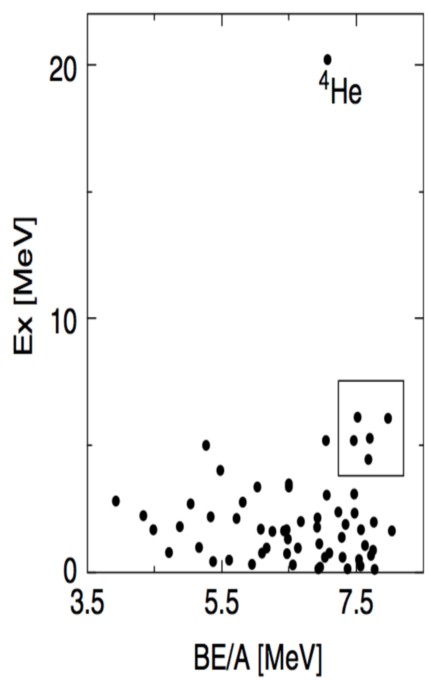
Isotope Detection

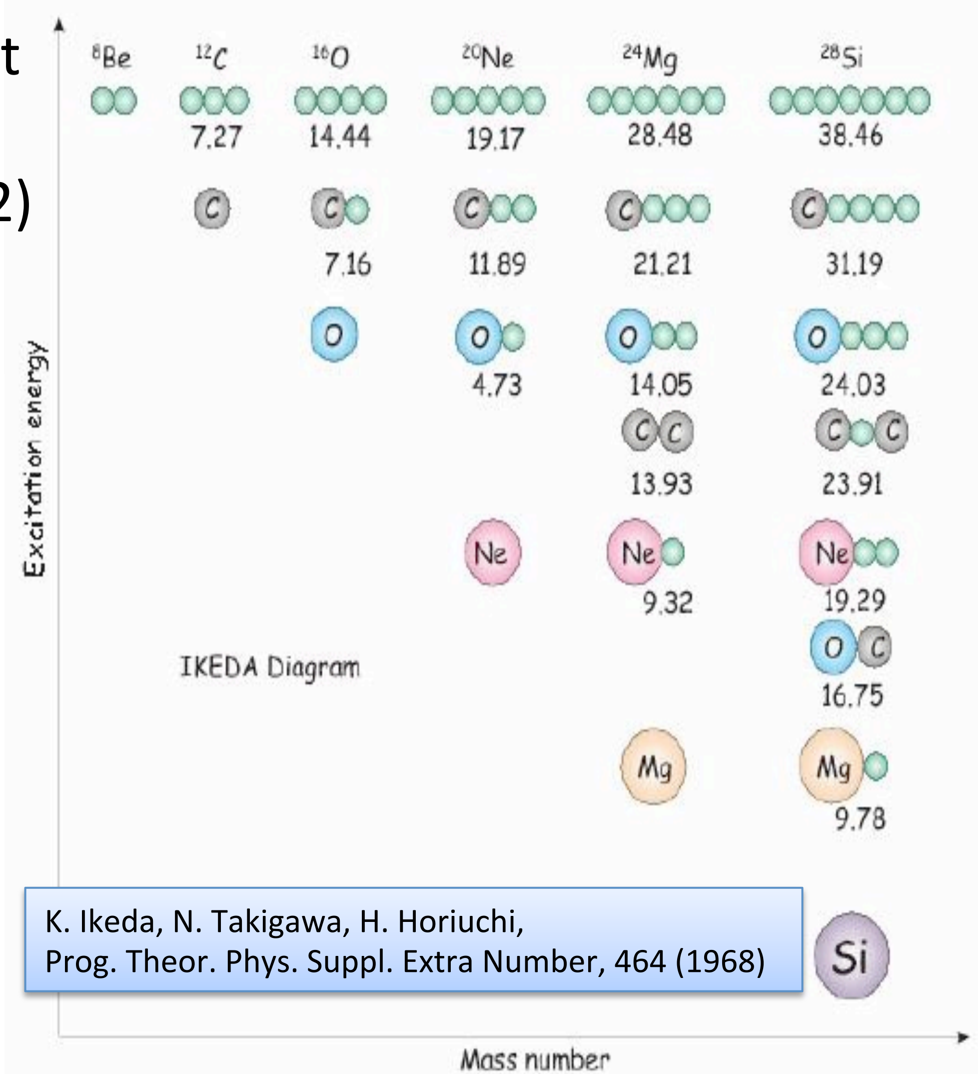
◆Alpha-cluster configuration in light nuclei

✓ Cluster is predicted to appear near cluster decay threshold in α conjugate nuclei about 50 years ago

The α cluster is the most prominent case since (1) the high binding energy of α-conjugate nuclei and (2) high energy of it's first excitation state







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

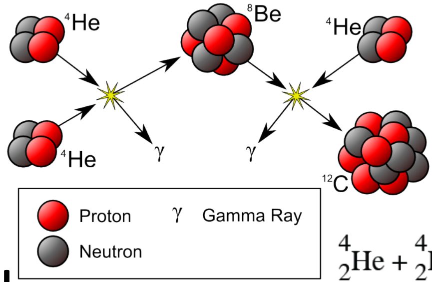
✓ The α cluster configuration in ^{12}C

- 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)

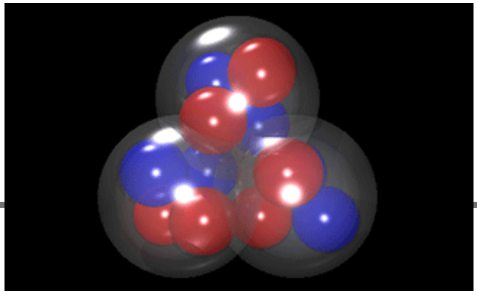
- AB initio calculation based on effective field theory obtains that Hoyle state is more like a linear chain of three alpha clusters

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



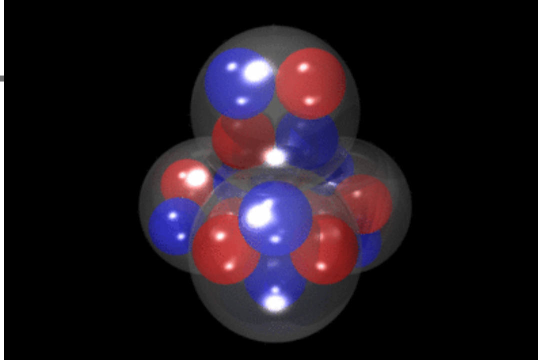
$${}^4_2\text{He} + {}^4_2\text{He} \rightarrow {}^8_4\text{Be} \quad (-93.7\ \text{keV})$$
$${}^8_4\text{Be} + {}^4_2\text{He} \rightarrow {}^{12}_6\text{C} \quad (+7.367\ \text{MeV})$$

- 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)

Extended Quntumn Molecular model

-- microscopic dynamical model

The EQMD model

T. Maruyama, et al., Phys. Rev. C53, 297 (1996).
R. Wada et al., Phys. Lett. B 422, 6 471 (1998).

Compared with other QMD models, EQMD model 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

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

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

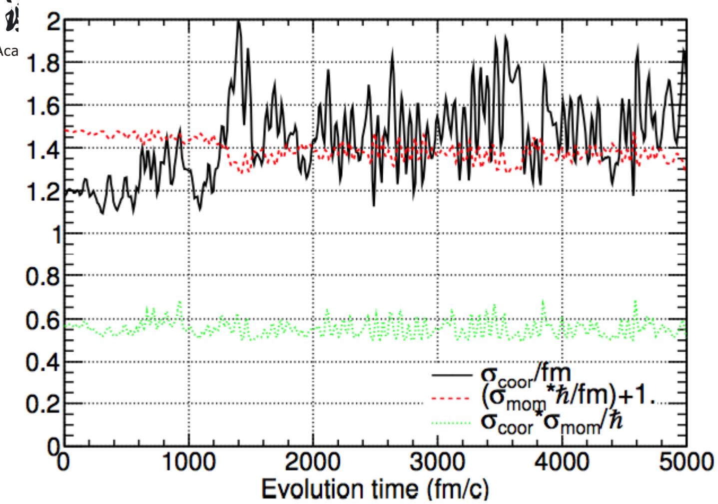
$$\nu_i \equiv \frac{1}{\lambda_i} + i\delta_i$$

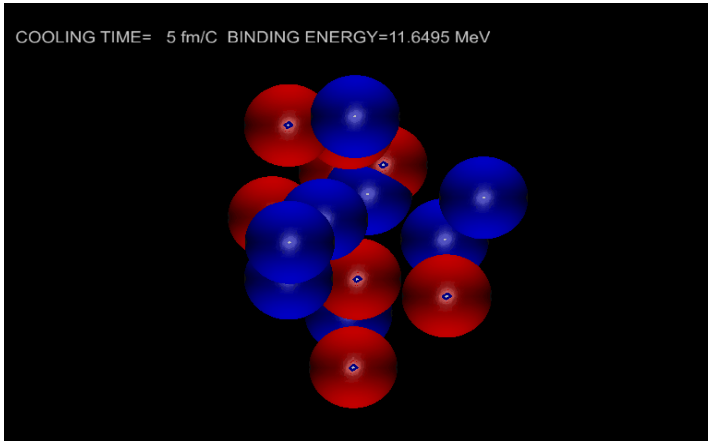
$$H = \left\langle \Psi \left| \sum_i -\frac{\hbar^2}{2m}\nabla_i^2 - \hat{T}_{c.m.} + \hat{H}_{\mathrm{int}} \right| \Psi \right\rangle$$

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

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

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





full Pauli potential cooling to alpha cluster state

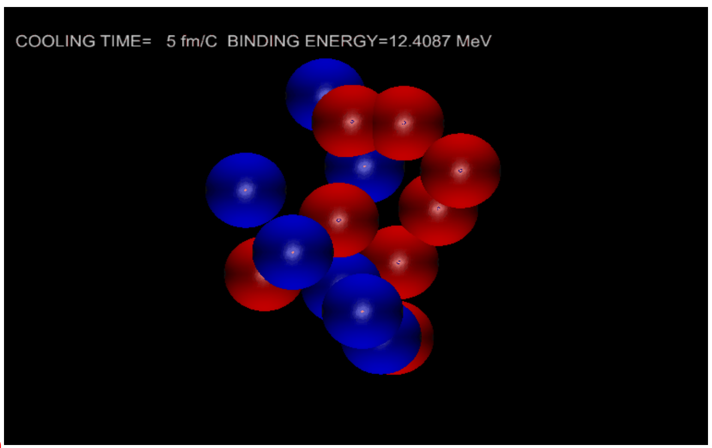
$$\sigma_x^2\sigma_k^2 = \frac{1}{4}\left(1+\lambda_i^2\delta_i^2\right) = \frac{1}{4}\left(1+\frac{a_{I(t)}^2}{a_{R(t)}^2}\right)$$

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

$$H_{Pauli} = \frac{c_P}{2}\sum_i \left(f_i - f_0\right)^{\mu}\theta\left(f_i - f_0\right)$$

$$f_i \equiv \sum_j \delta\left(S_i, S_j\right)\delta\left(T_i, T_j\right)\left|\left\langle \phi_i \middle\| \phi_j \right\rangle\right|^2$$

the overlap of a nucleon i with the same kind of Nucleons ,（including itself）



reduced Pauli potential cooling to non-cluster state

3) The initialization of ground nuclei: friction cooling

$$\dot{\mathbf{R}}_i = \frac{\partial H}{\partial \mathbf{P}_i}, \quad \dot{\mathbf{P}}_i = -\frac{\partial H}{\partial \mathbf{R}_i},$$

$$\frac{3\hbar}{4}\dot{\lambda}_i = -\frac{\partial H}{\partial \delta_i}, \quad \frac{3\hbar}{4}\dot{\delta}_i = \frac{\partial H}{\partial \lambda_i}.$$

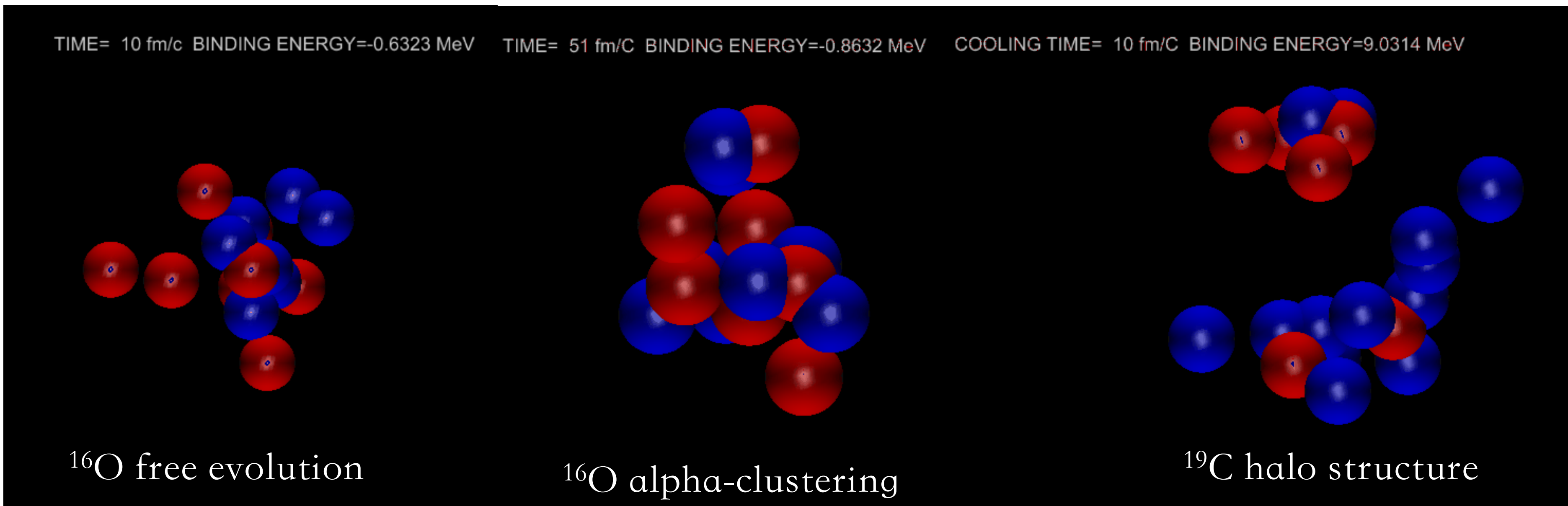
Evolution equ.

Introducing damping eoff.

$$\dot{\mathbf{R}}_i = \frac{\partial H}{\partial \mathbf{P}_i} + \mu_{\mathrm{R}} \frac{\partial H}{\partial \mathbf{R}_i}, \quad \dot{\mathbf{P}}_i = -\frac{\partial H}{\partial \mathbf{R}_i} + \mu_{\mathrm{P}} \frac{\partial H}{\partial \mathbf{P}_i},$$

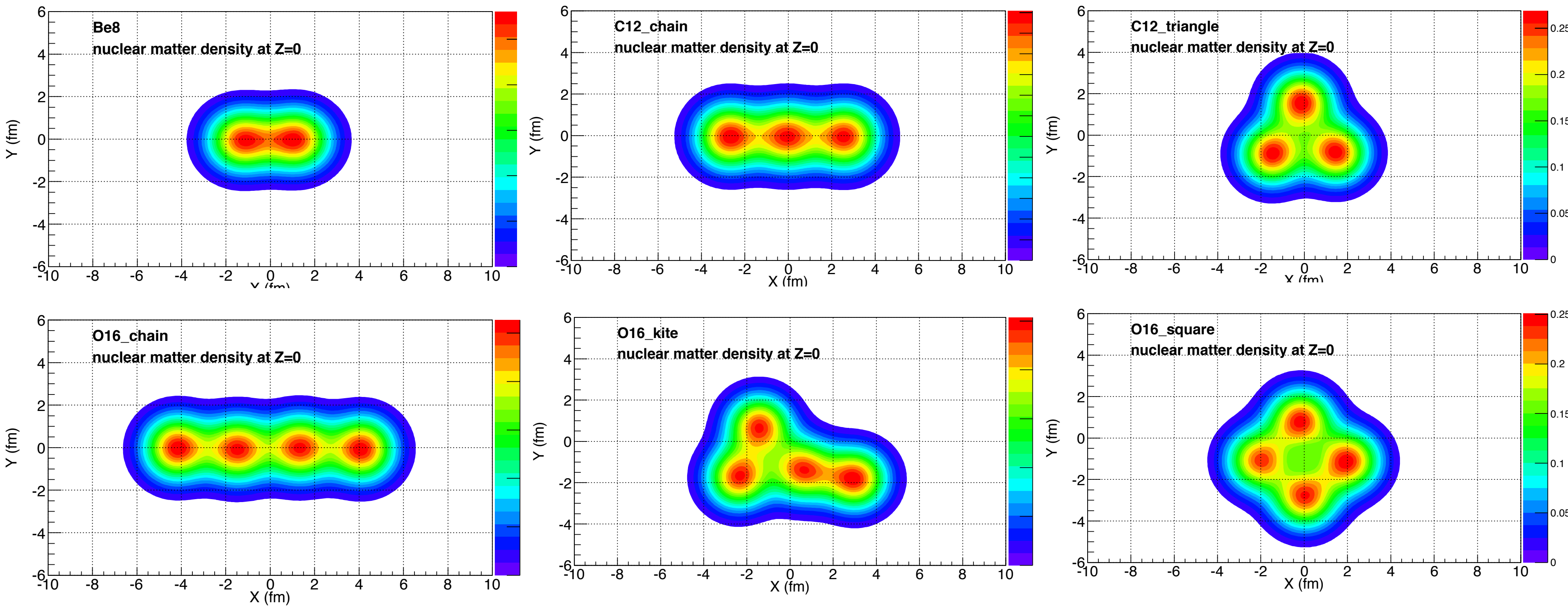
$$\frac{3\hbar}{4}\dot{\lambda}_i = -\frac{\partial H}{\partial \delta_i} + \mu_{\lambda} \frac{\partial H}{\partial \lambda_i}, \quad \frac{3\hbar}{4}\dot{\delta}_i = \frac{\partial H}{\partial \lambda_i} + \mu_{\delta} \frac{\partial H}{\partial \delta_i}.$$

Friction cooling method



EQMD Results on alpha-clustering light nuclei

-- 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

AME2012:Chin. Phys. C 36, 1603 (2014)

^{8}Be: 7.062 MeV, ^{12}C: 7.680 MeV, ^{16}O: 7.976 MeV

◆Alpha-cluster effect on GDR

W. B. He, Y. G. Ma, X. G. Cao, X. Z. Cai and G. Q. Zhang,

Phys. Rev. Lett. 113, 032506 (2014)

W. B. He, Y. G. Ma, X. G. Cao, X. Z. Cai and G. Q. Zhang,

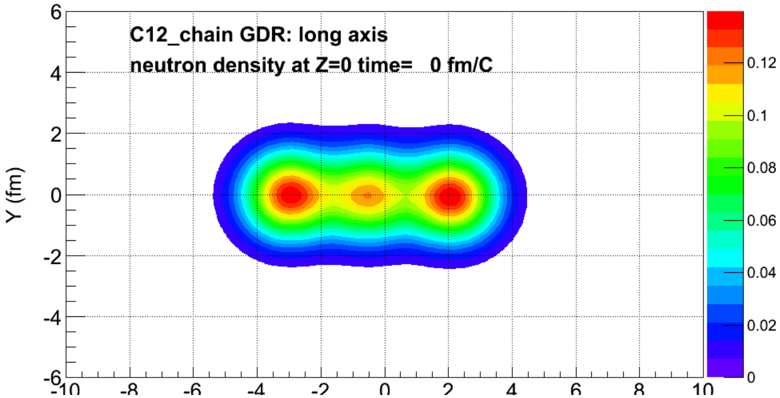
PHYSICAL REVIEW C 94, 014301 (2016)

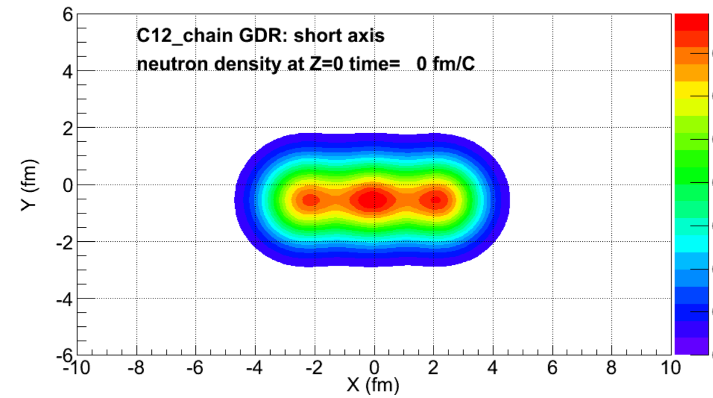
Long axis

Short axis

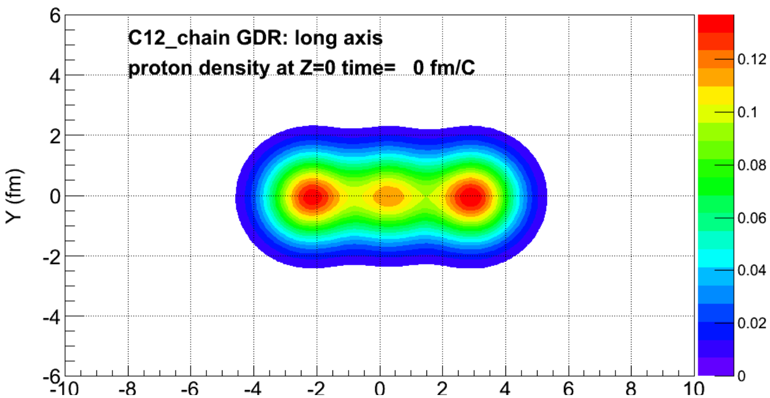
^{12}C

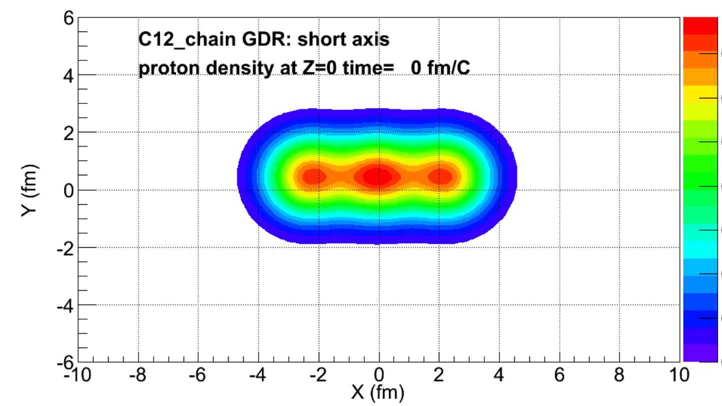
neutrons





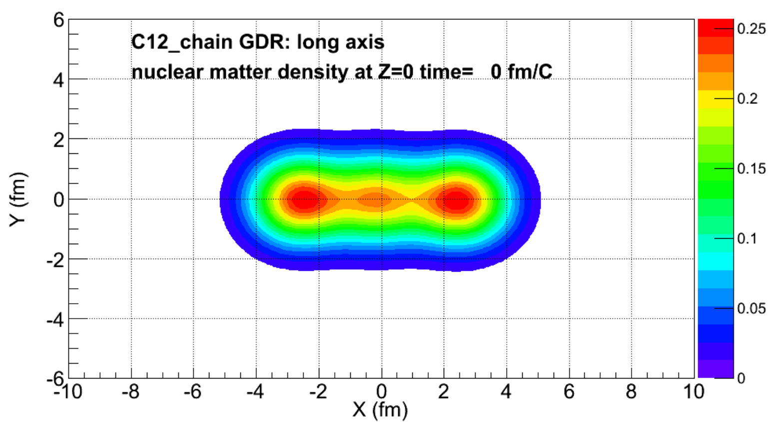
protons

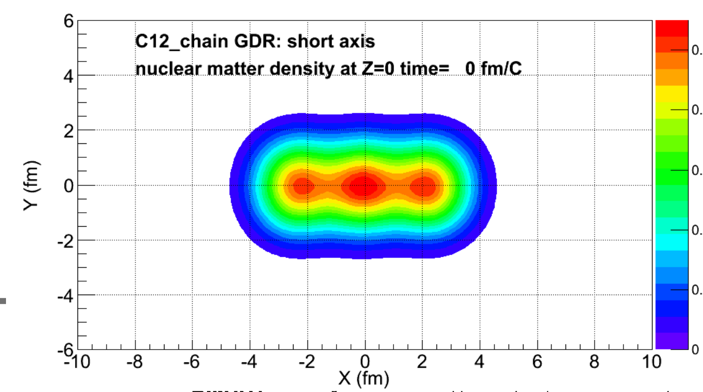




total

CM keeps zero



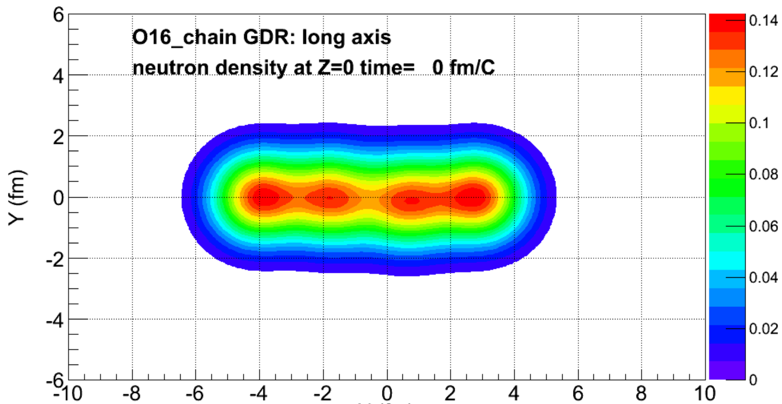


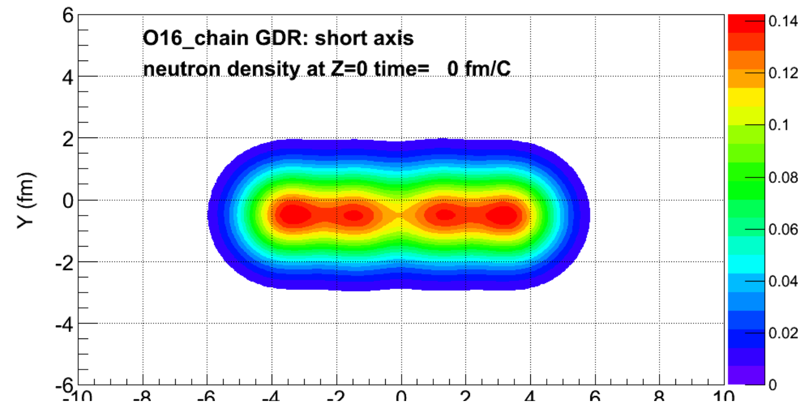
Long axis

Short axis

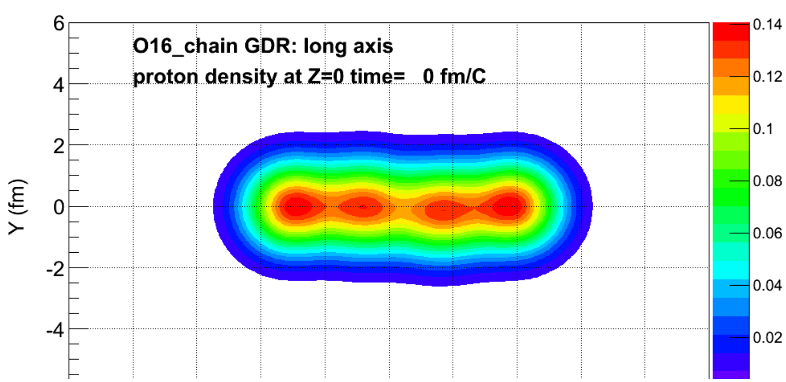
^{16}O

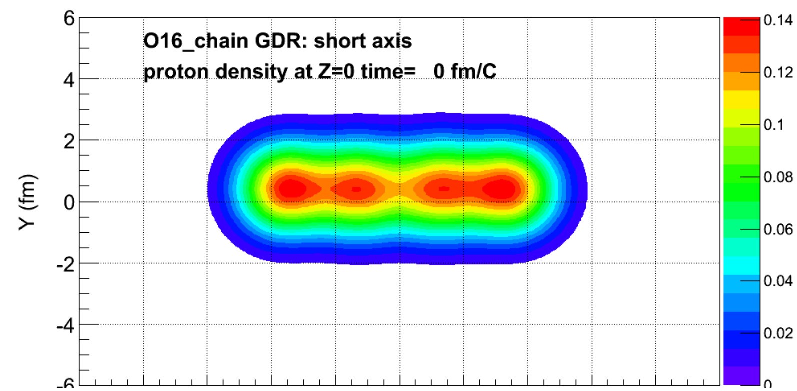
neutrons





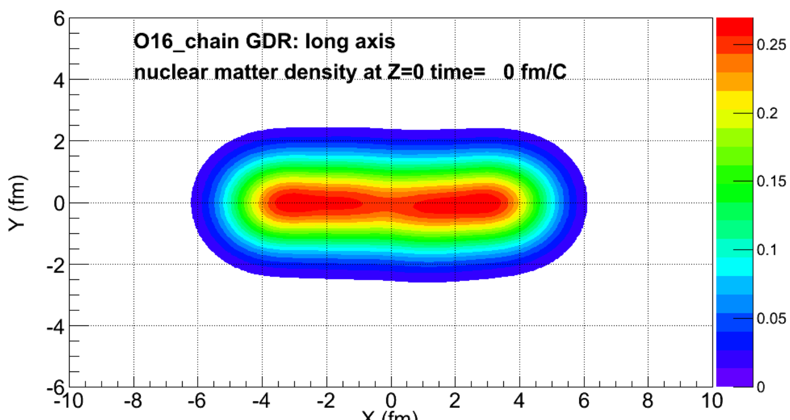
protons

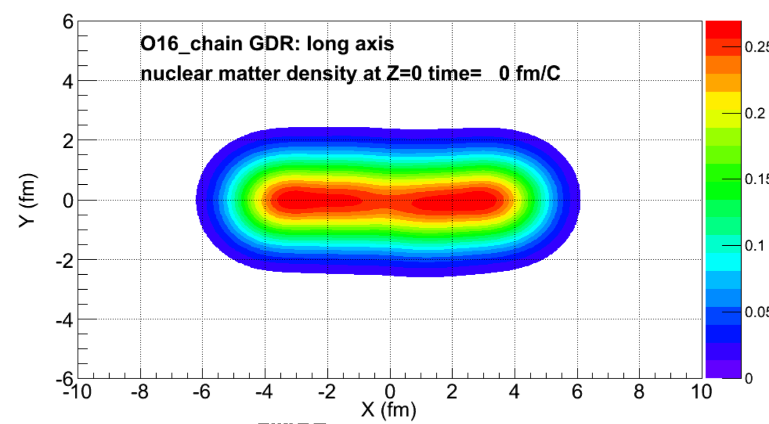




total

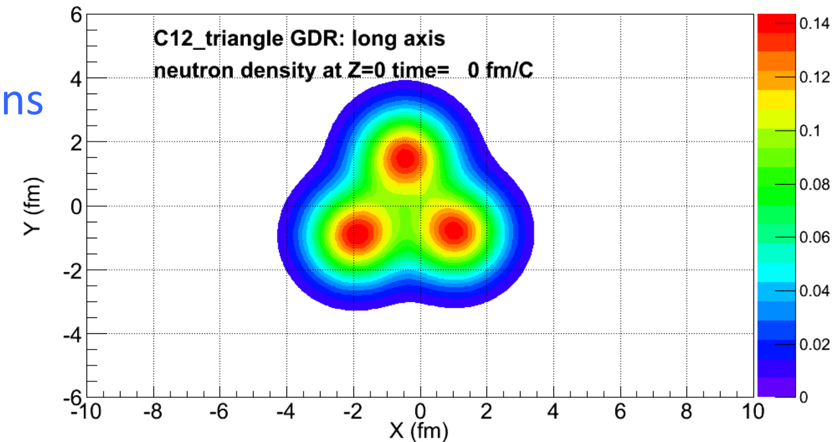
CM keeps zero

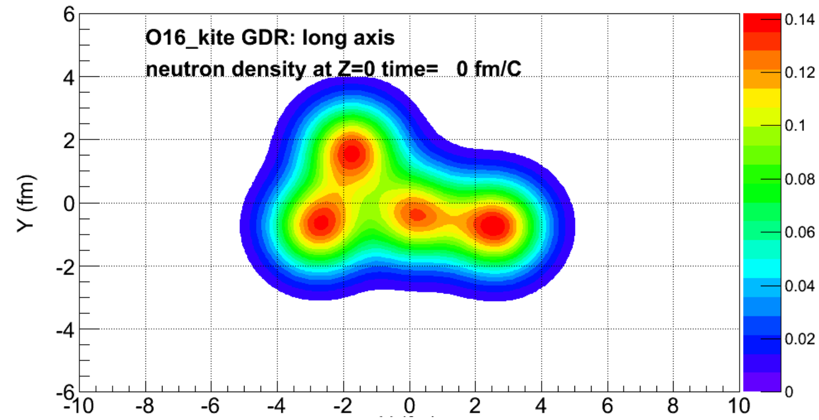




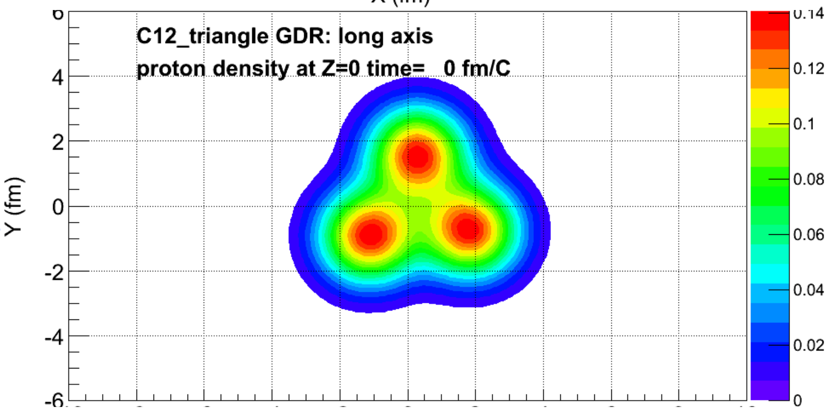
C12-triangle & 16O kite

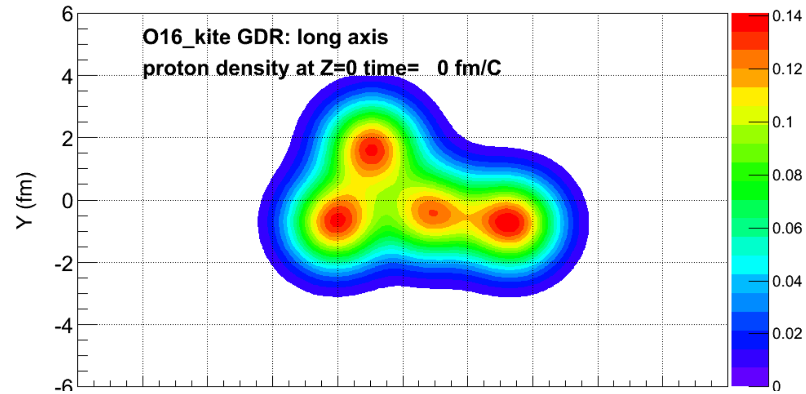
neutrons



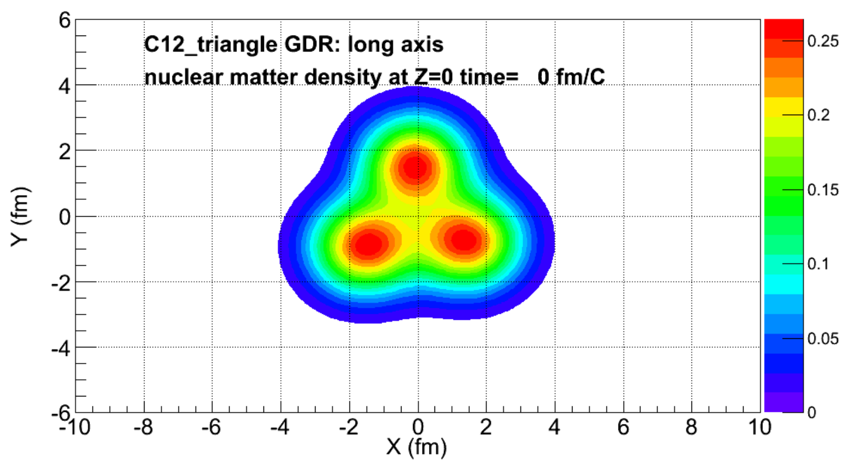


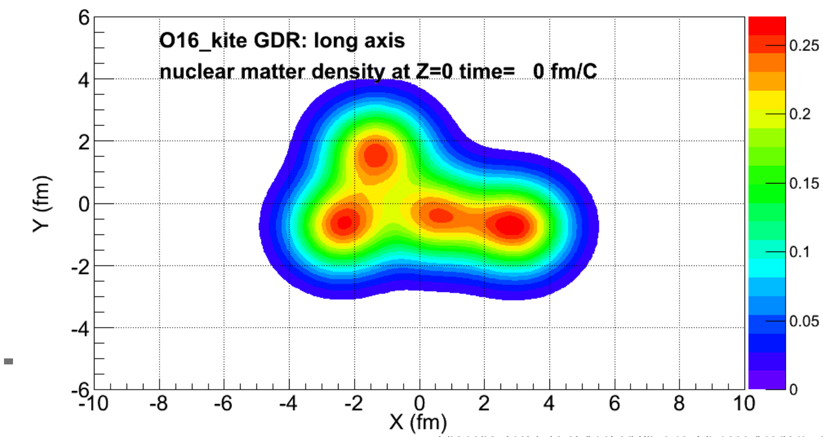
protons





total



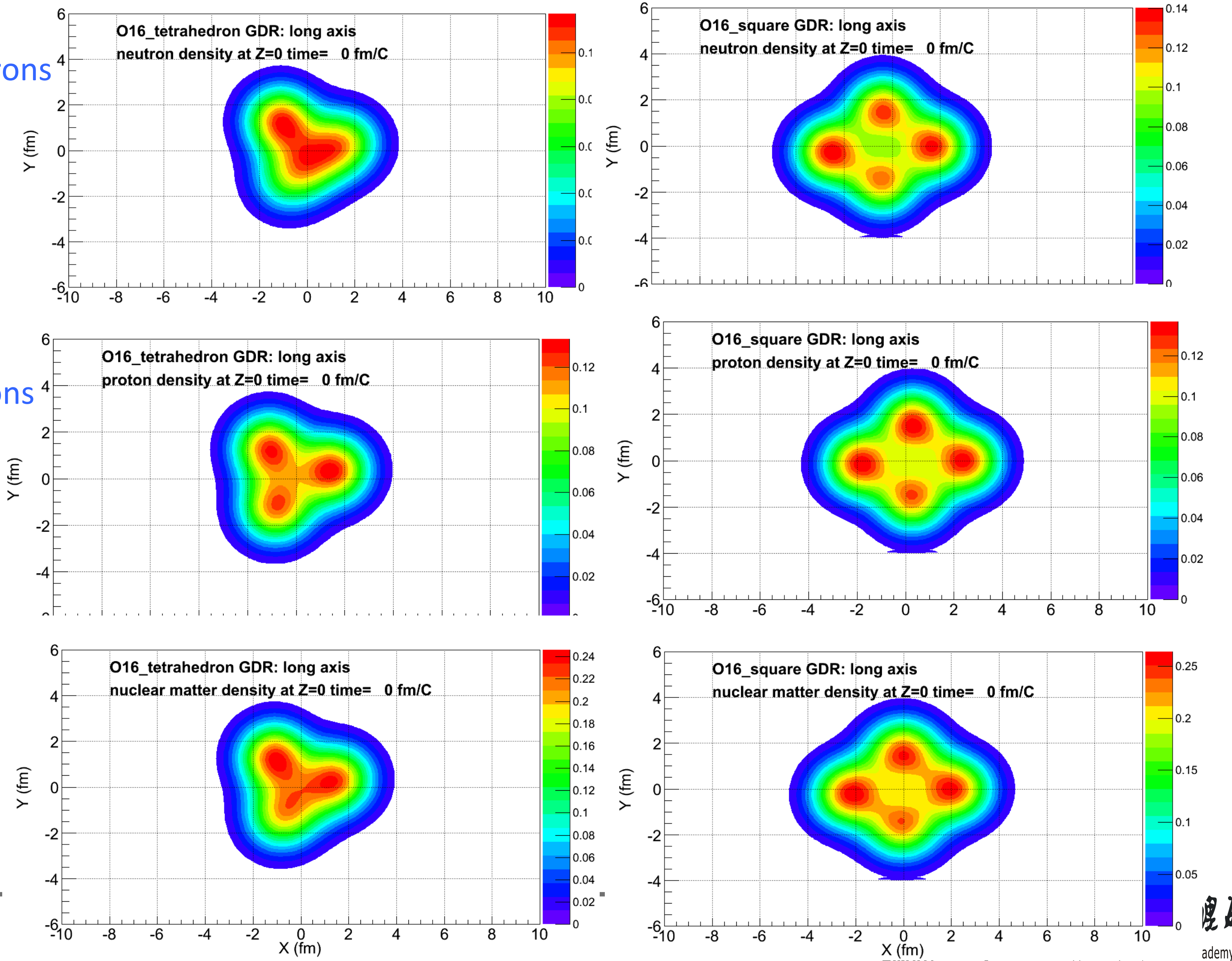


O16-tetrahedron & 16O square

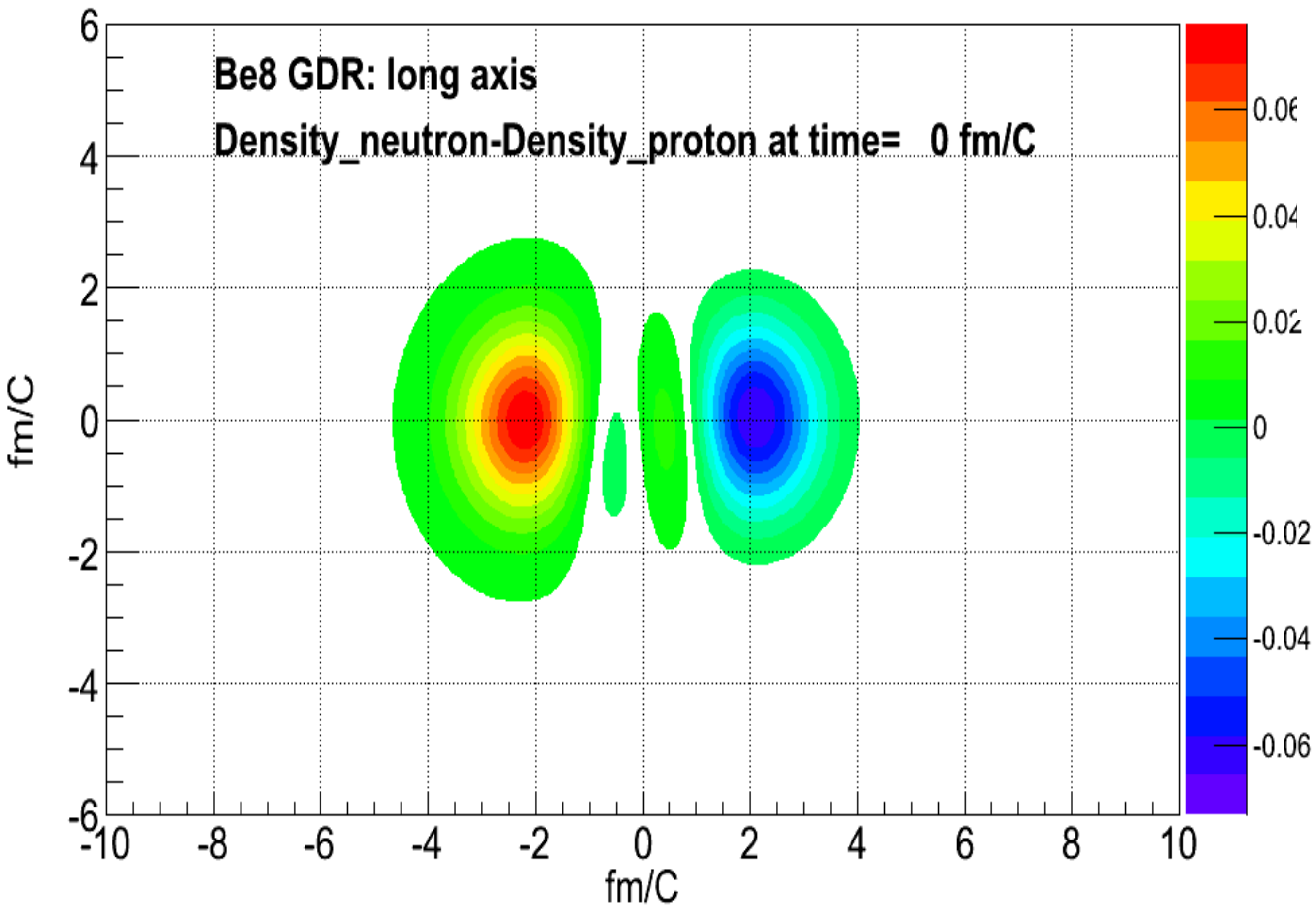
neutrons

protons

total



Density difference between neutrons and protons



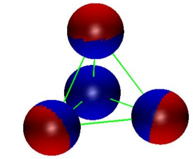
$$D_G(t) = \frac{NZ}{A}[R_Z(t) - R_N(t)],$$

$$K_G(t) = \frac{NZ}{A\hbar}\left[\frac{P_Z(t)}{Z} - \frac{P_N(t)}{N}\right],$$

$$D''(\omega) = \int_{t_0}^{t_{\max}} D''_G(t)e^{i\omega t}dt,$$

$$\frac{dP}{dE} = \frac{2e^2}{3\pi\hbar c^3 E}|D''(\omega)|^2$$

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

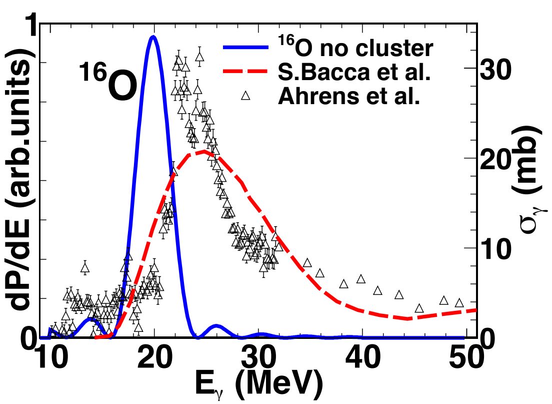


PRL 113, 032506 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

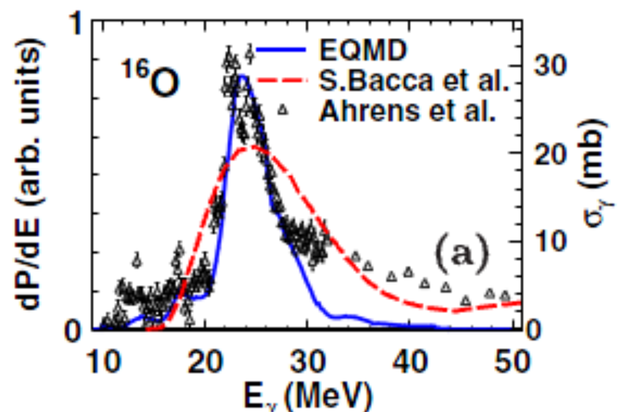
Giant Dipole Resonance as a Fingerprint of α Clustering Configurations in ^{12}C and ^{16}O

W. B. He (何万兵),[1,2] Y. G. Ma (马余刚),[1,3,*] X. G. Cao (曹喜光),[1,†] X. Z. Cai (蔡翔舟),[1] and G. Q. Zhang (张国强)[1]

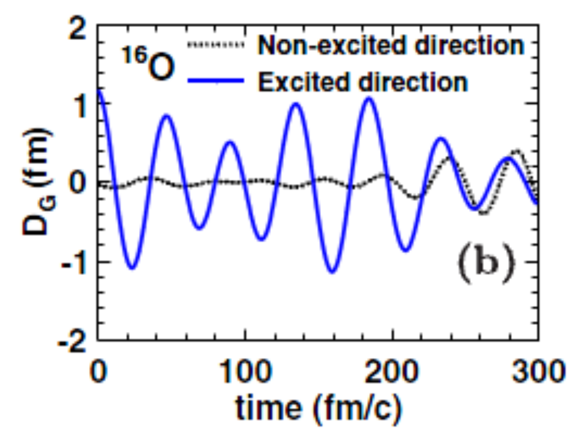
EQMD calculation supports ^{16}O ground state with tetrahedron



^{16}O ground state without alpha cluster



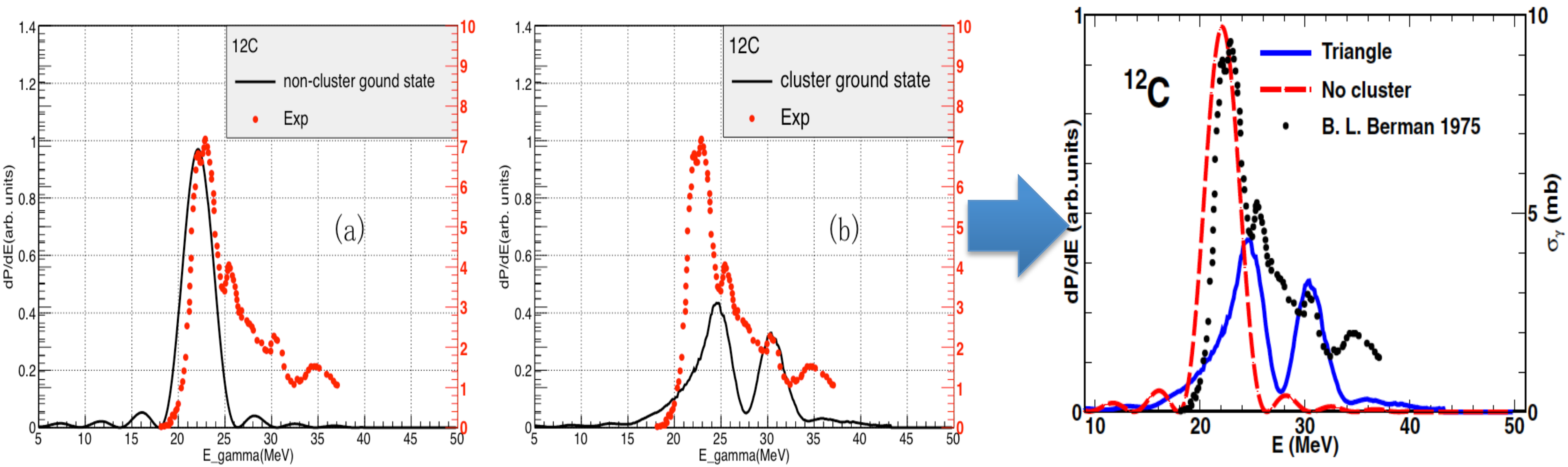
^{16}O ground state with tetrahedron structure



Dipole evolution of ^{16}O

The data is from J. Ahrens, H. Borchert, K. H. Czock et al., Nucl. Phys. A251, 479 (1975).
The first principle calculation is from S. Bacca et al., Phys. Rev. Lett. 111, 122502 (2013).

- 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 et al., Phys. Rev. Lett. 98, 032501 (2007)]



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

The data is from J. Ahrens, H. Borchert, K. H. Czock et al., Nucl. Phys. A251, 479 (1975).

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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

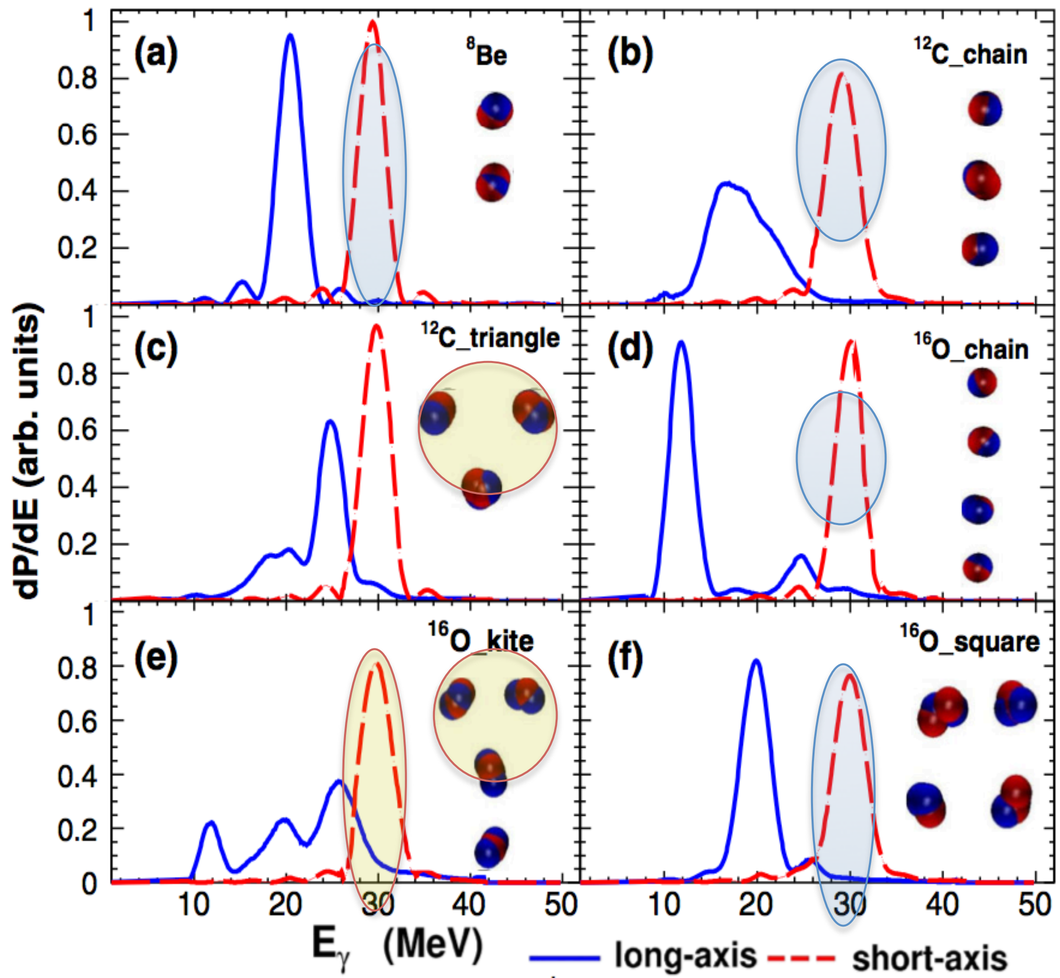


FIG. 2 (color online). ^{8}Be, ^{12}C, and ^{16}O GDR spectra with different cluster configurations. The corresponding α cluster configuration in the present EQMD model calculation is drawn in each panel, in which blue and red balls indicate protons and neutrons, respectively. The dynamical dipole evolution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

◆Alpha-cluster effect in quasi-deuteron region

B. S. Huang, Y. G. Ma, W. B. He,

PHYSICAL REVIEW C 95, 034606 (2017)

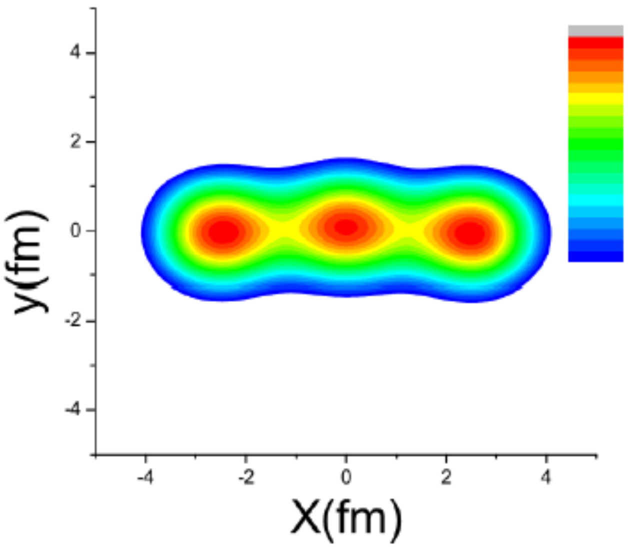
B. S. Huang, Y. G. Ma, W.B. He,

Eur. Phys. J A 53 , 119 (2017)

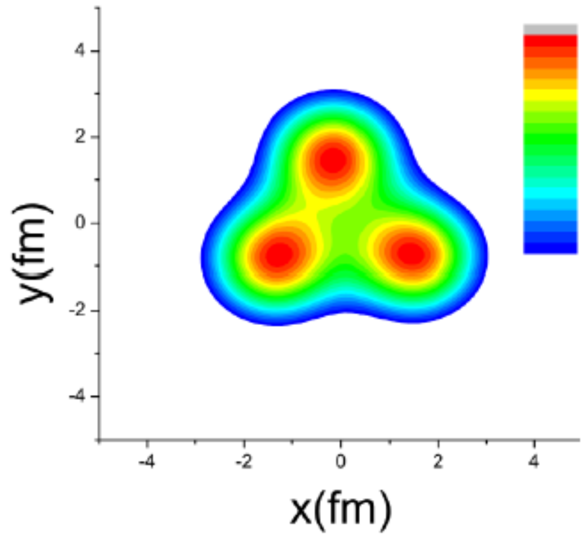
If photons hit alpha cluster inside nucleus, what happens?

We consider: $^{12}C(\gamma,np)^{10}B$ @ Quasi-deuteron: ~70-140MeV

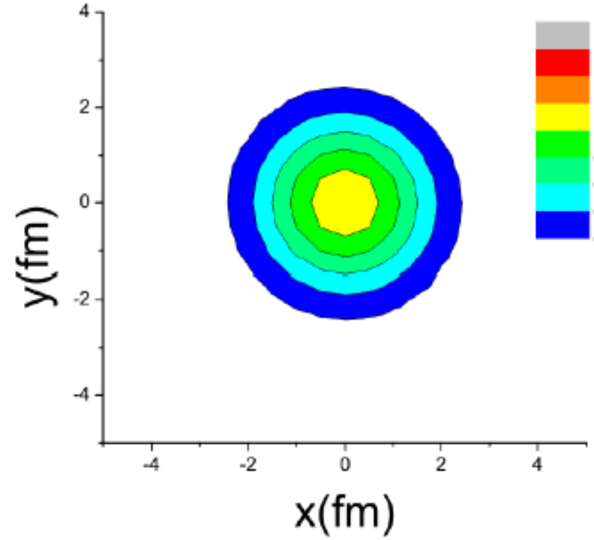
(a) chain



(b) triangle



(c) spherical



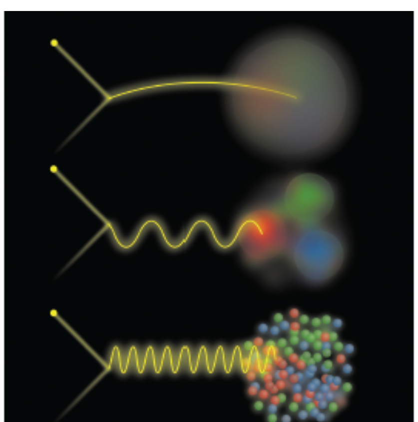
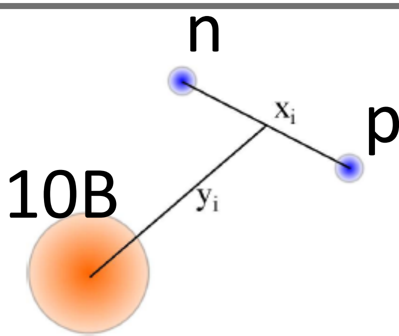


TABLE I: RMS radius and binding energy of different configurations of 12C and the ground state data.

Configuration	r_{RMS} (fm)	E_{bind} (MeV/nucleon)
Chain	2.71	7.17
Triangle	2.35	7.12
Sphere	2.23	7.60
Exp. Data	2.47	7.68

Three-body decay



$^{12}C(\gamma,np)^{10}B$

Jacobi coordinate (x_i, y_i)

We consider the emitted proton, neutron and the residual nucleus as the three-body, its i-th set of Jacobi coordinate:

$$x_i = \mu_{jk}(\mathbf{p_j} - \mathbf{p_k}),$$

$$y_i = \mu_{i,jk}(\mathbf{p_i} - \frac{m_j\mathbf{p_j} + m_k\mathbf{p_k}}{m_j + m_k})$$

where

$$\mu_{jk} = \sqrt{\frac{m_j m_k}{m(m_j + m_k)}},$$

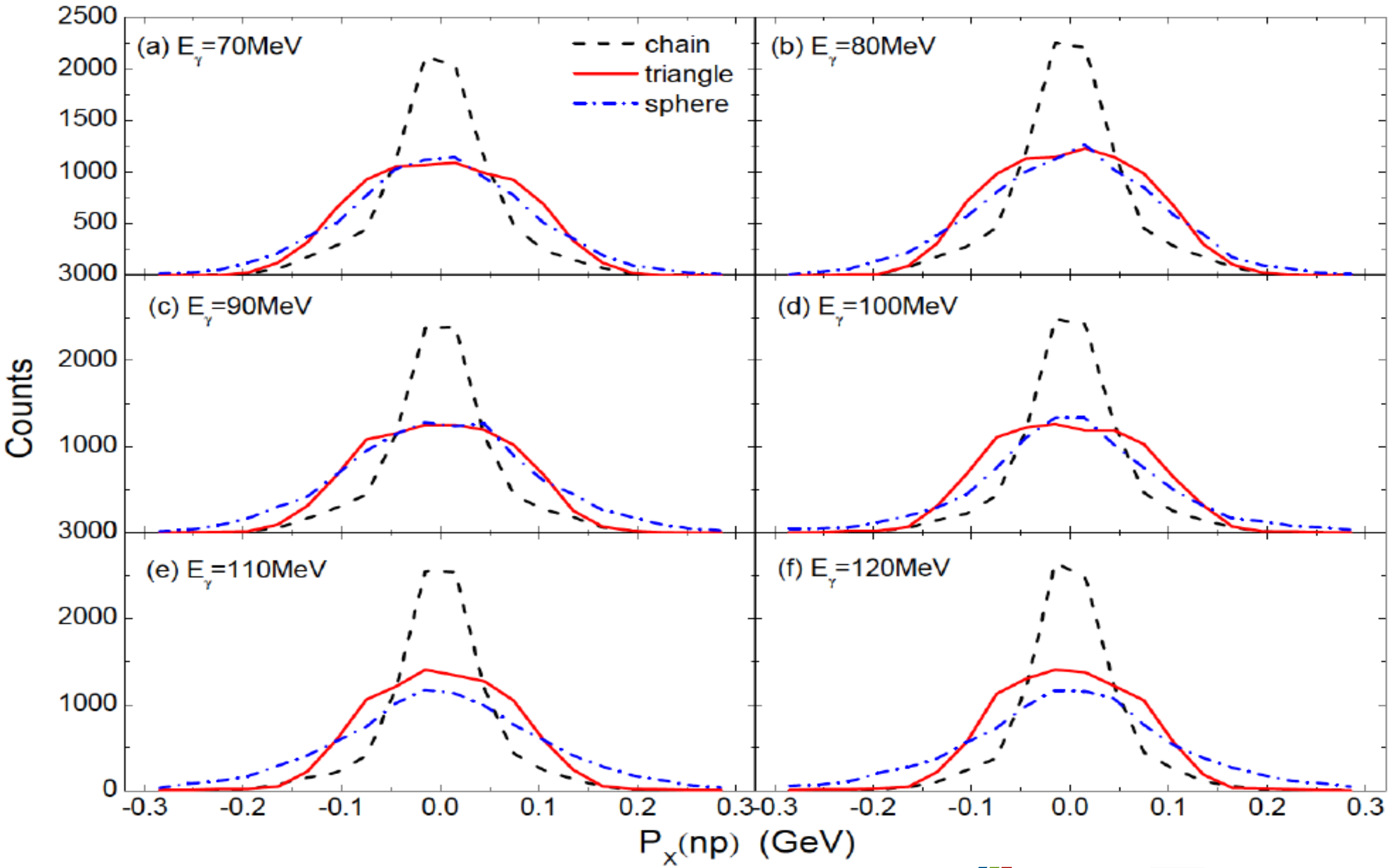
$$\mu_{i,jk} = \sqrt{\frac{m_i(m_j + m_k)}{m(m_i + m_j + m_k)}},$$

With p_j and p_k represent the momentum of emitted proton and neutron, m_i, m_j and m_k represent for the mass number of the residue nucleus, proton and neutron, respectively, and m is the total mass number of the mother nucleus, i.e. 12C.

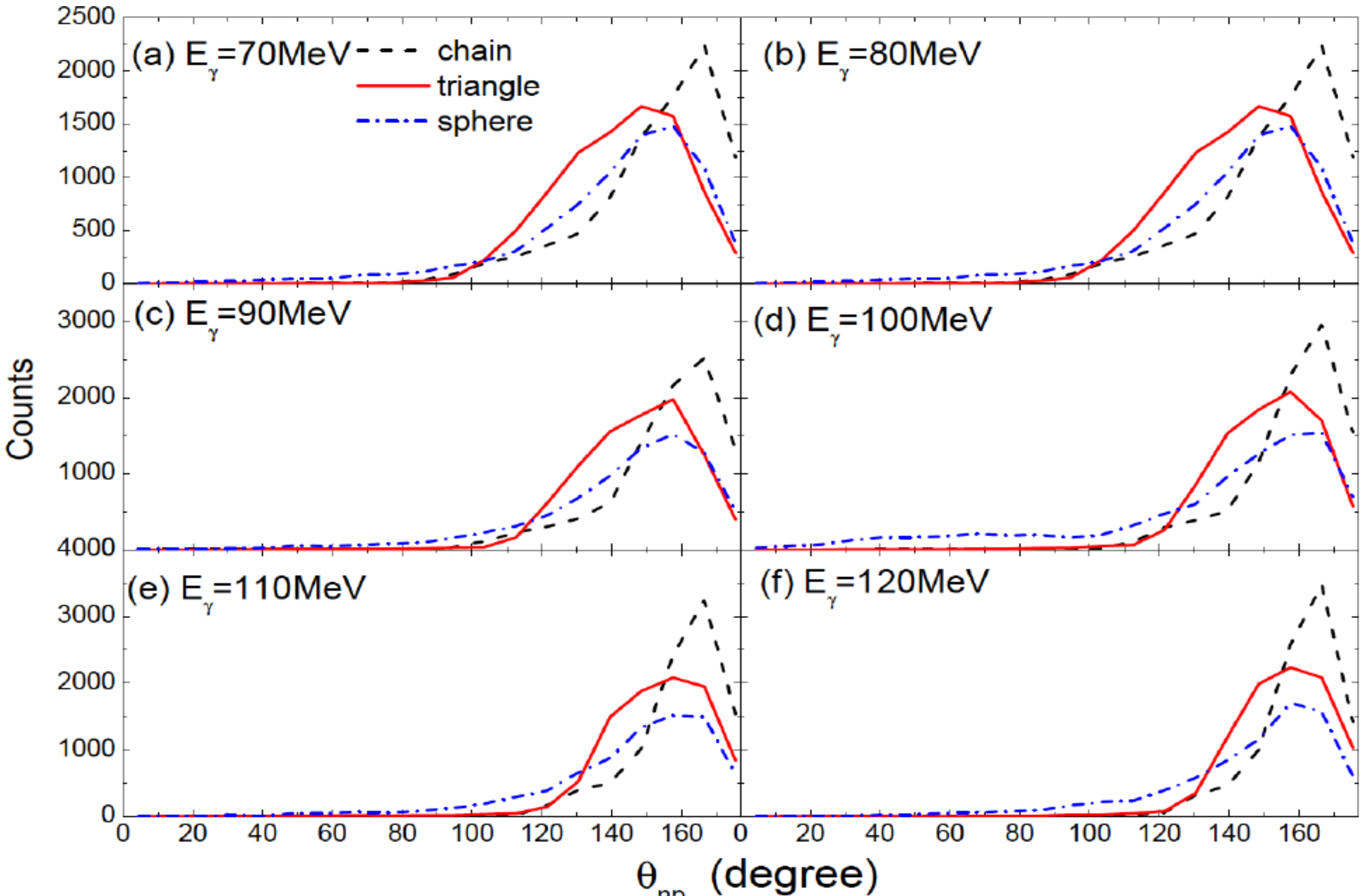
$$x_i = \rho sin(\alpha_i), \qquad y_i = \rho cos(\alpha_i)$$

where x_i and y_i are the Jacobi momenta, ρ is hyperradius, and α_i represents the hyperangle.

pair momentum of emitted proton and neutron

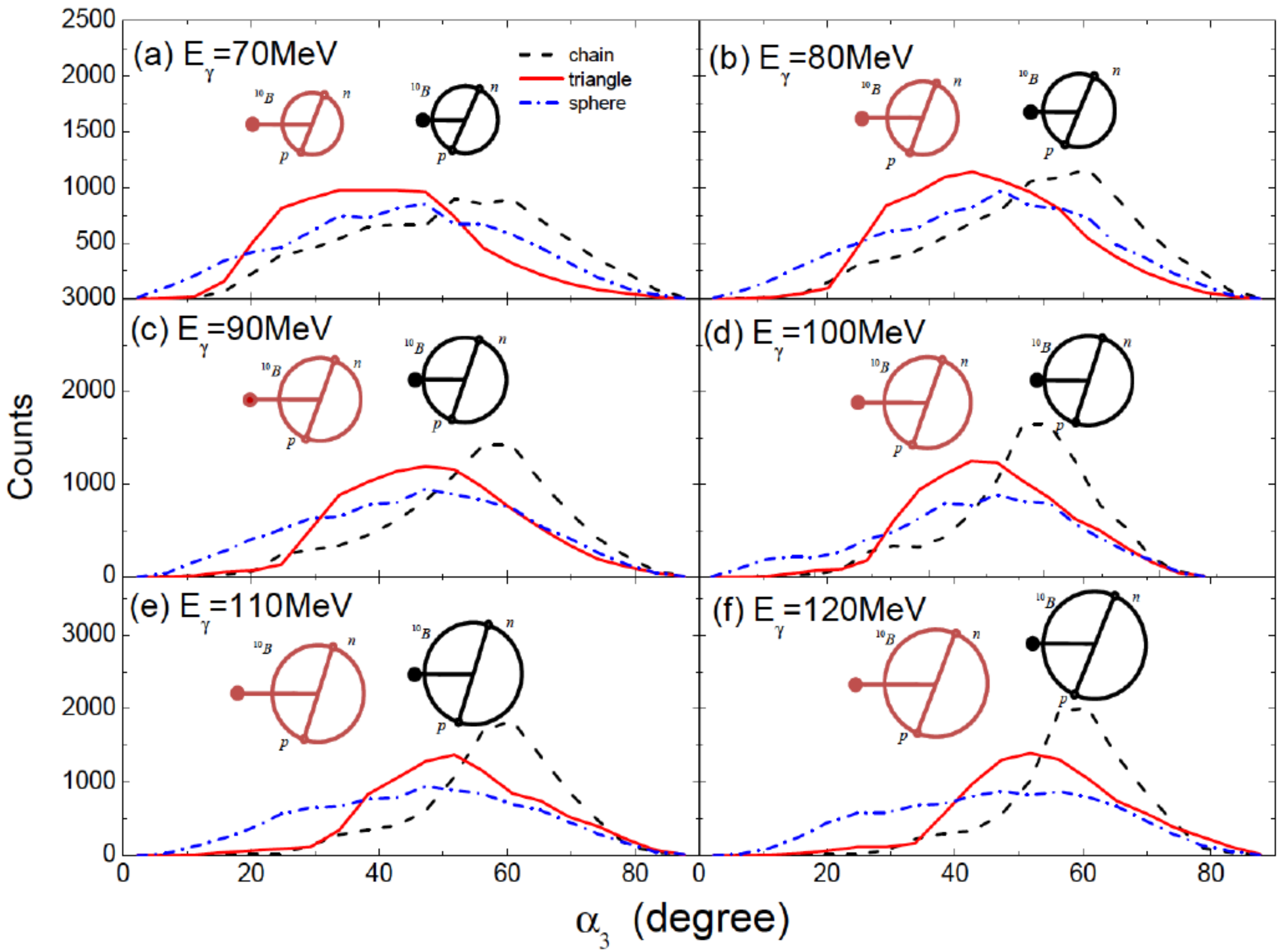


opening angle between neutron and proton

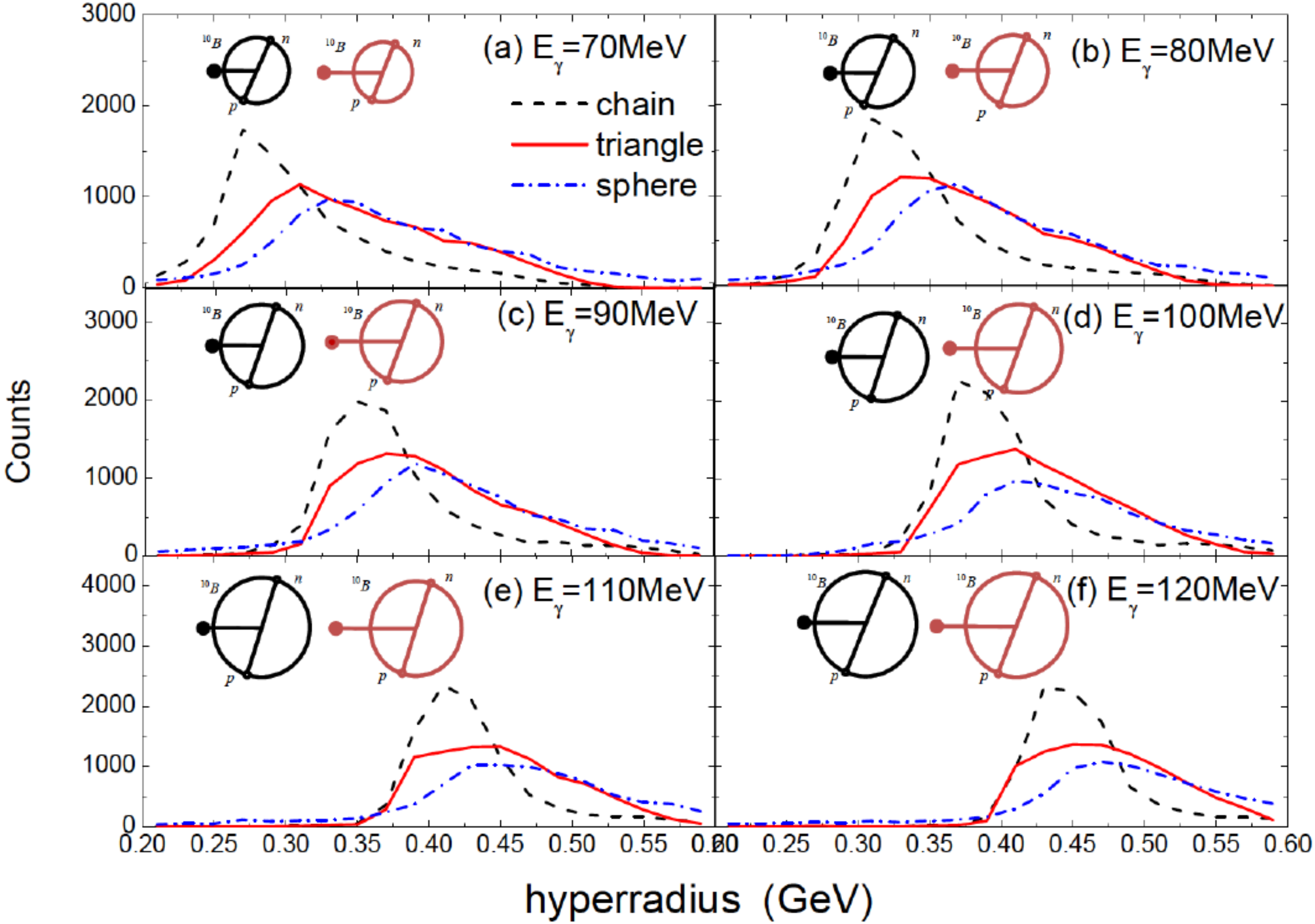


Hyperangle of residue

Usually the hyperangle is confined by (0,pi/2). If it is near 0, it indicates that the residual nucleus is far from p and n; If it is near to pi/2, it indicates that the residue nucleus is near the center-of-mass of the emitted p and n.



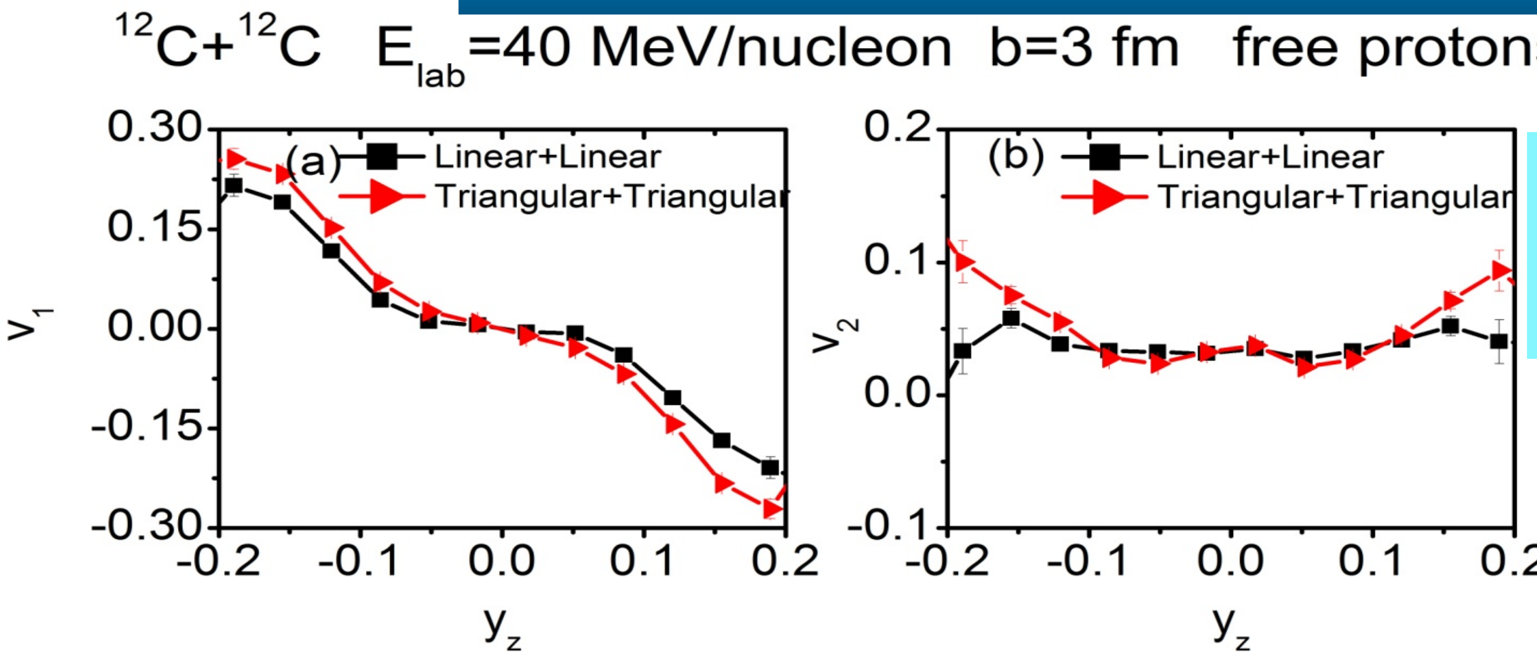
Hyperradius of residue



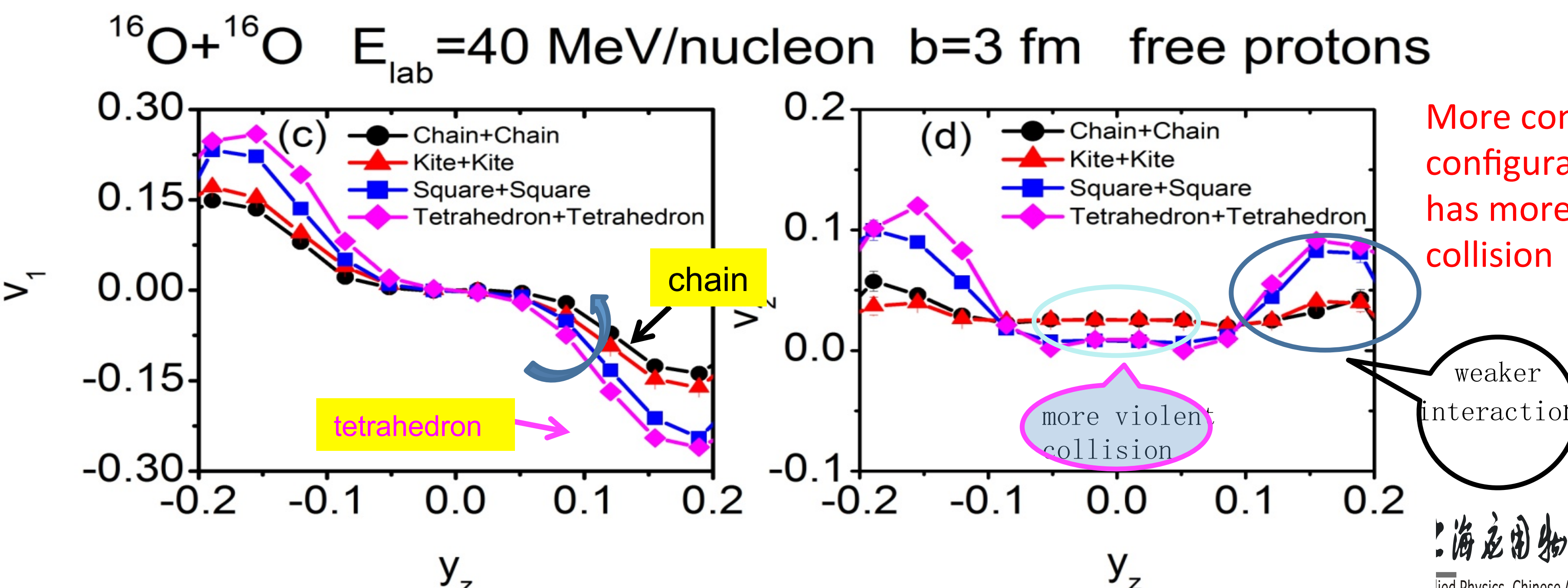
◆Alpha-cluster effect on flows for $^{16}O+^{16}O$ & $^{12}C+^{12}C$

Chen-Chen Guo, Wan-Bing He, Yu-Gang Ma,
CHIN. PHYS. LETT. 34, 092101 (2017)

The directed and elliptic flows



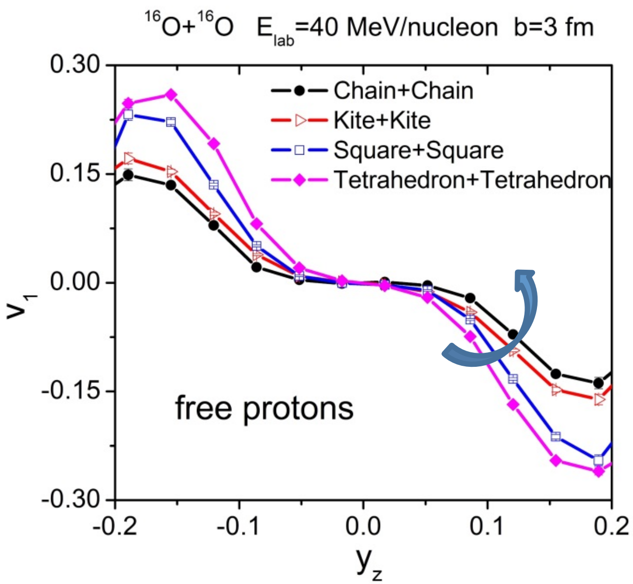
The sitatution in $^{12}C+^{12}C$ is similar to that in $^{16}O+^{16}O$

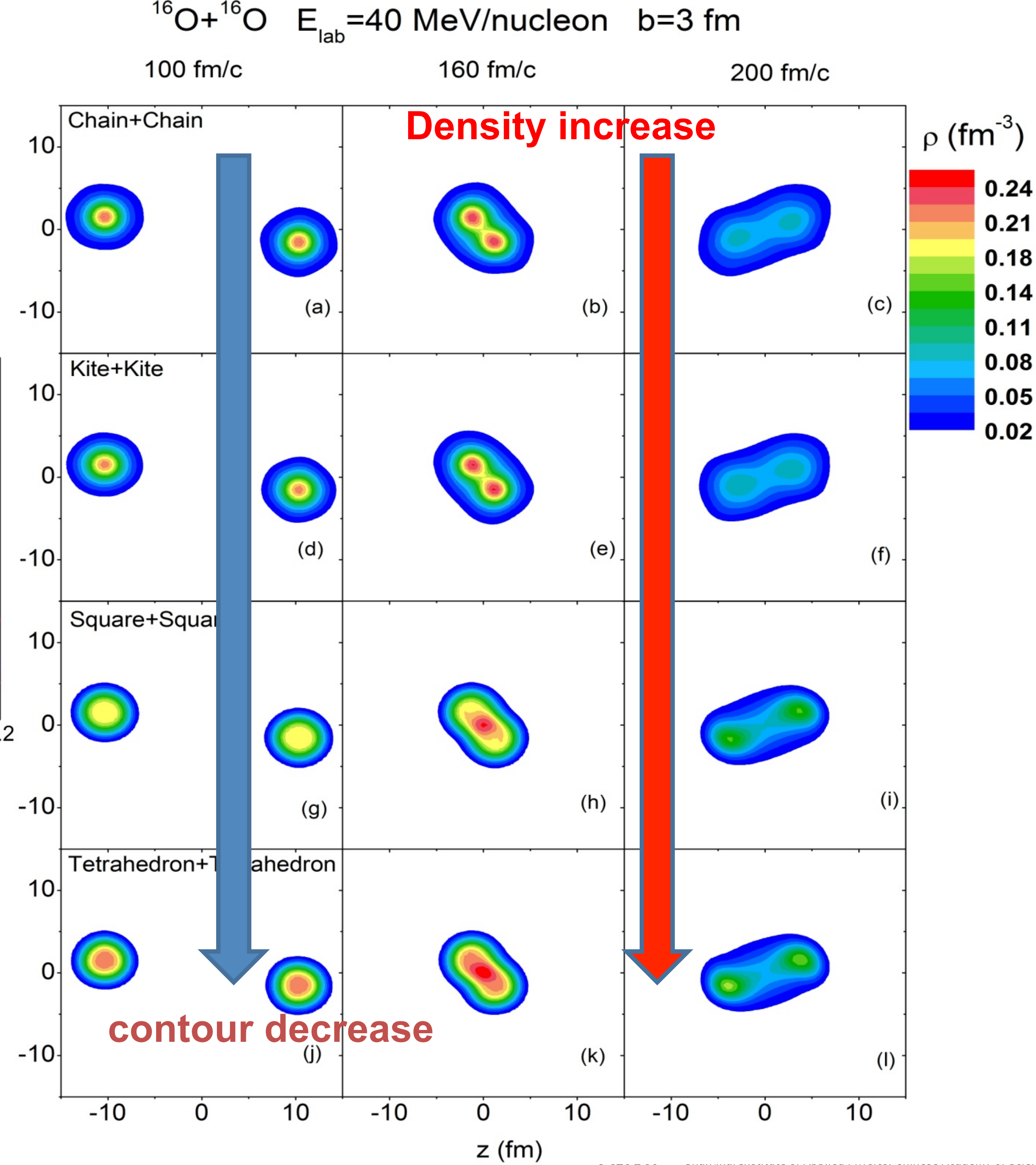


More compact configuration has more violent collision

Results :

cs, Chinese Academy of Science

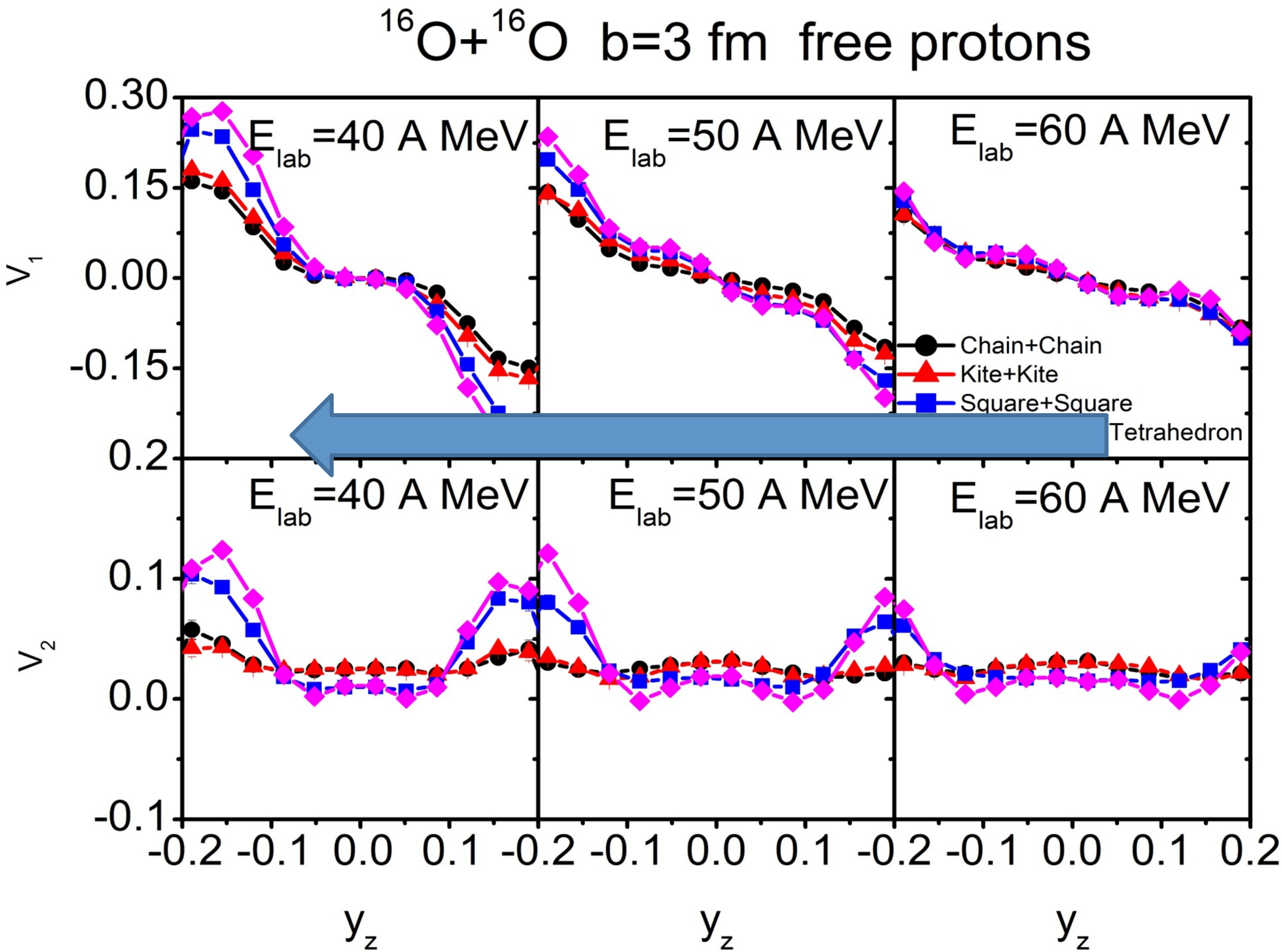




The initial distance between the centers of the projectile and target nuclei is set to 50 fm.

Results :

Beam energy dependence



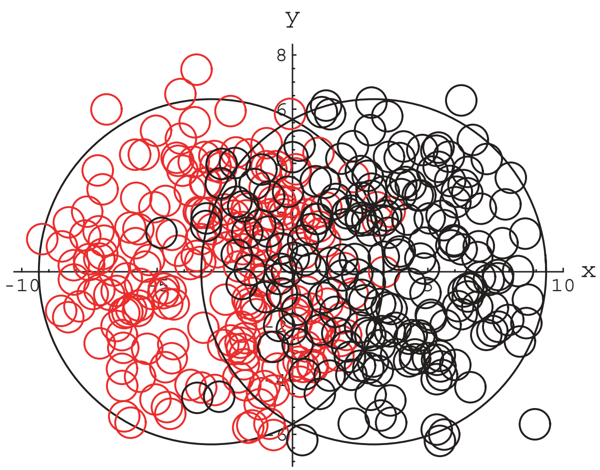
◆Alpha-cluster effect on flows for $^{12}C+^{197}Au$

S. Zhang, Y. G. Ma, J. H. Chen, W. B. He, and C. Zhong ,

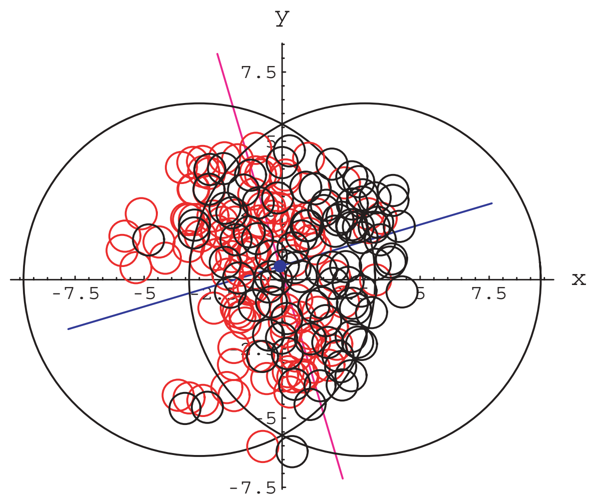
PHYSICAL REVIEW C 95, 064904 (2017)

Initial geometry and fluctuation

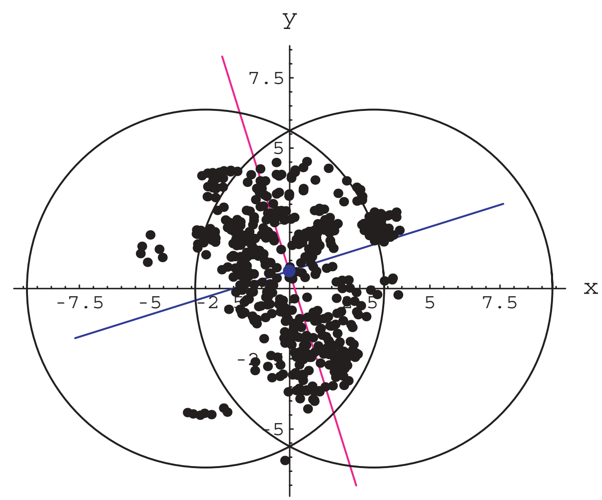
W. Broniowski et al., PRC-76-054905



Nucleon from nuclei A and B



Participant initial coordinates



Participant in center of mass frame after binary collision

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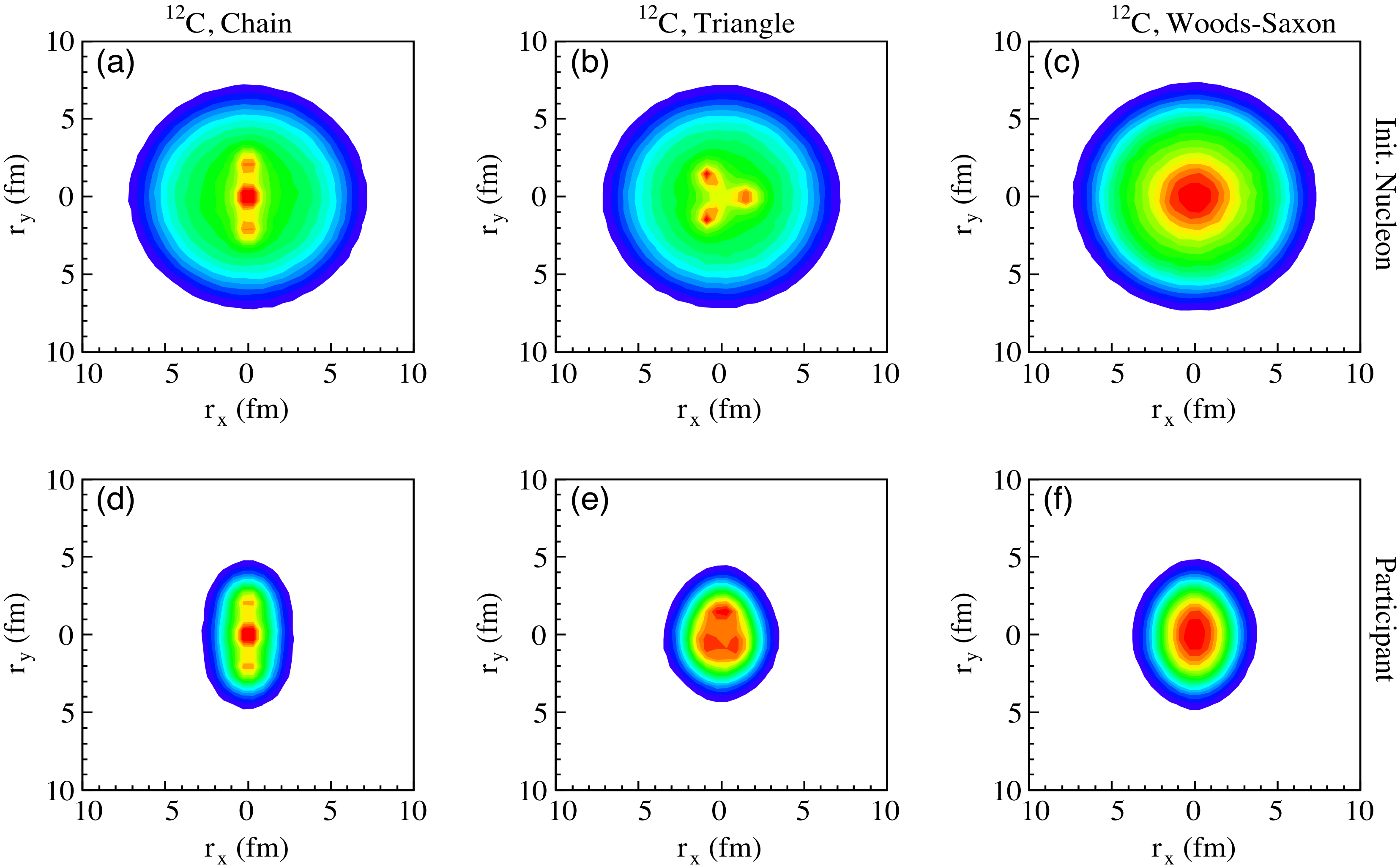
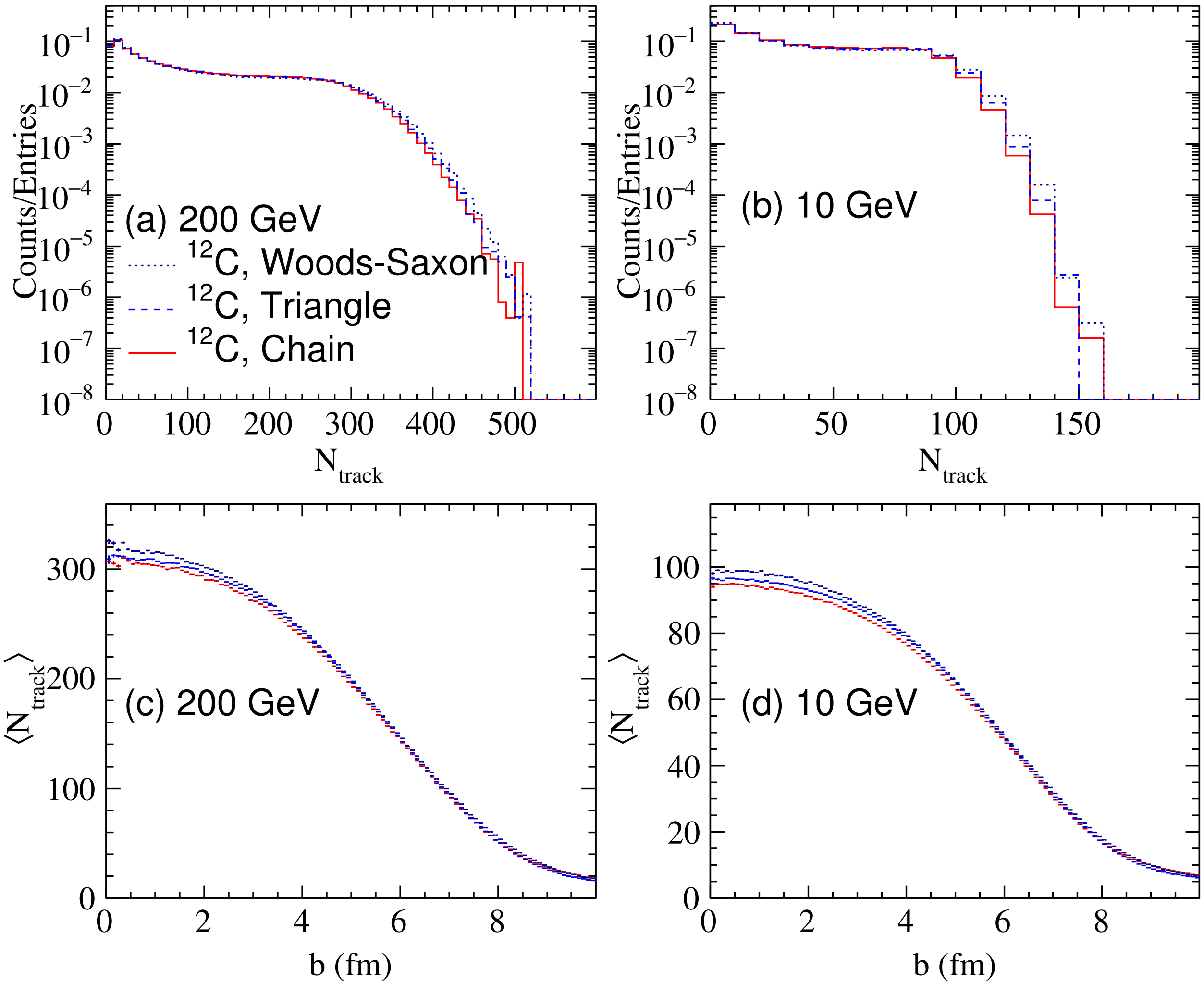
Initial nucleon dist.



Configuration of Chain and Triangle structure from EQMD, W. B. He, Y. G. Ma et al. PRL-113-032506

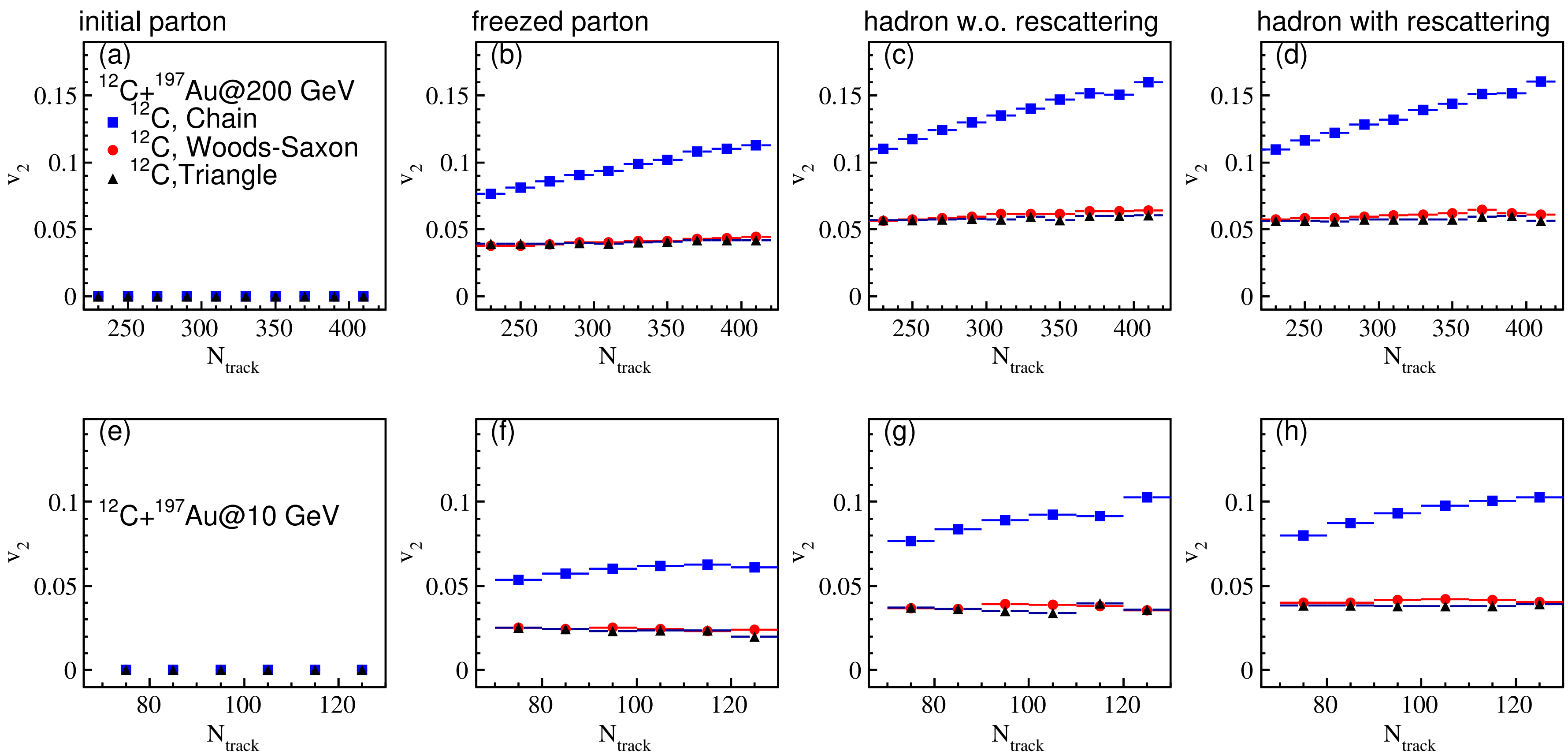
multiplicity dist.@AMPT



Central collisions

- ✓Ntrack>70, 10 GeV
- ✓Ntrack>210, 200 GeV

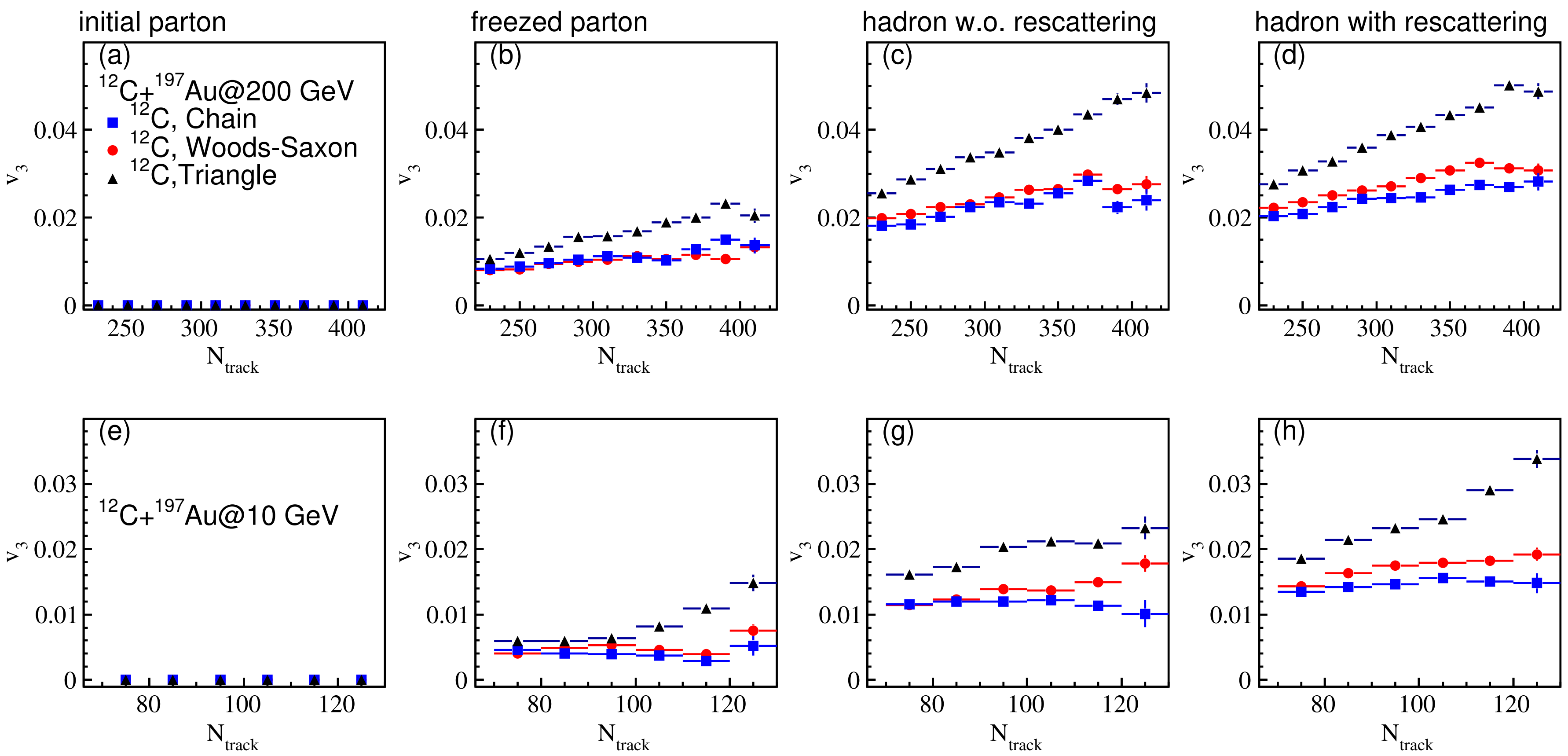
Elliptic flow evolution in central collision @AMPT



√Zero flow in initial stage→ hadron v2 formed in partonic interaction stage

√Chain structure of 12C contribute to elliptic flow

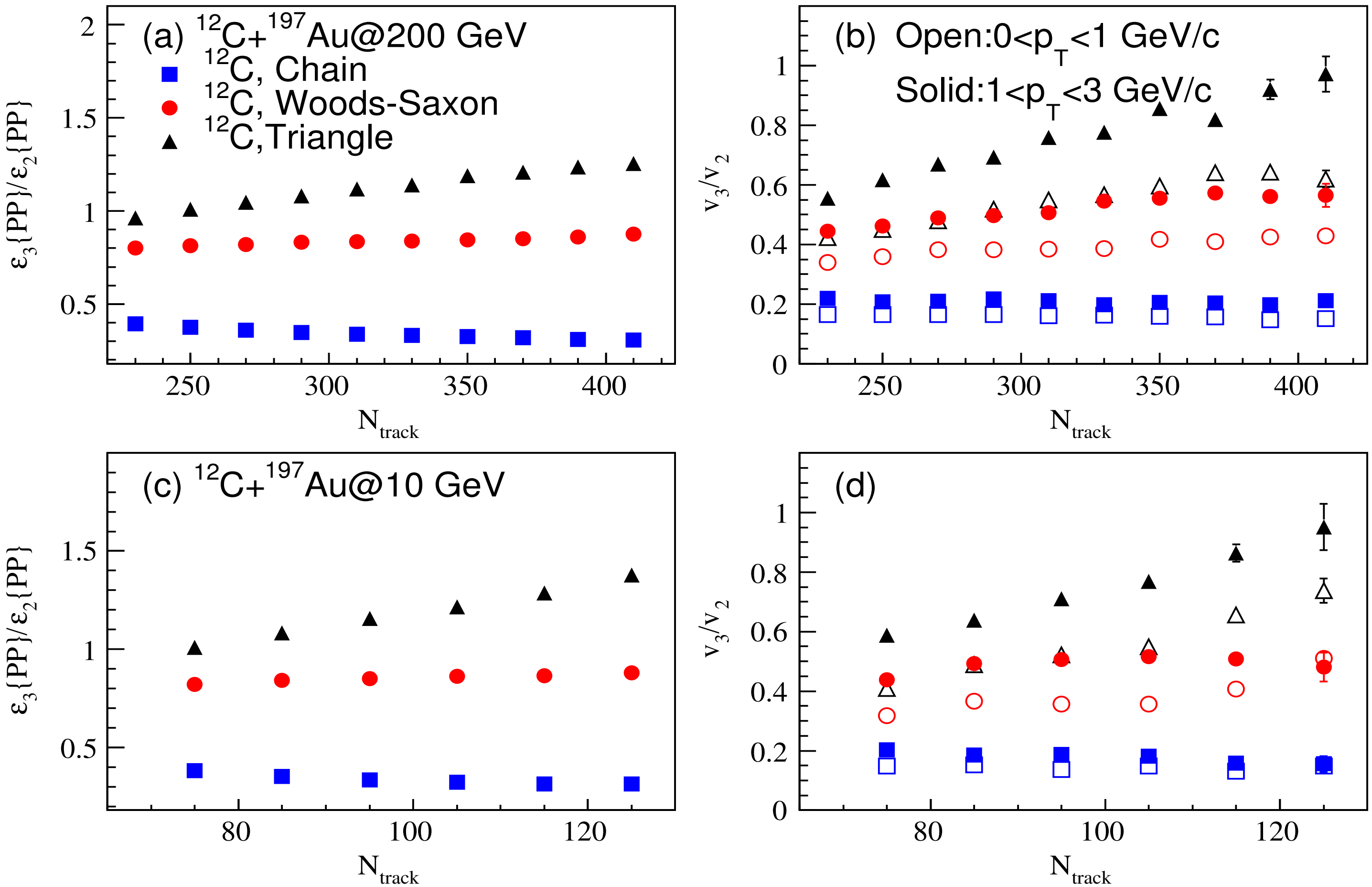
Triangular flow evolution in central collision @AMPT



✓Zero flow at initial stage→ hadron v3 formed in partonic interaction stage

✓Triangle structure of 12C contribute to triangular flow

Probe alpha-cluster by v3/v2 ratio



✓The ratio keep **flat trend** with increasing of Ntrack **for Woods-Saxon distribution and chain structure of 12C**

✓ The ratio **increases** with increasing of Ntrack **for triangle structure**.

Summary

- **Alpha-clustering structure is a very interesting topic in nuclear structure, it can be explored in low energy and high energy HIC or photon-induced reactions.**
- **EQMD model can give initial state of alpha-clustering structure and it shows that GDR is a good probe for the alpha-clustering structure.**
- **Photonuclear reaction in quasi-deuteron regime is also a good tool to investigate alpha-clustering structure through different observables in three-body decay.**
- **At Fermi energy, collective flow is sensitive to initial clustering structure.**
- **At relativistic HIC, collective flows and HBT correlation display the sensitivity to initial alpha-clustering structure (eg., 12C: Chain structure contribute to elliptic flow and Triangle structure affect triangular flow).**

Collaborators:
Xiguang Cao, Jinhui Chen, Wanbing He, Bosong Huang, Guoqiang Zhang, Song Zhang

Thank you for attentions !