重离子碰撞中核结构效应

Nuclear structure meets relativistic heavy-ion collisions

马余刚

复旦大学 核科学技术系/现代物理研究所

2023年08月1日 @ 大连

2023原子核结构与相对论重离子碰撞前沿交叉研讨会

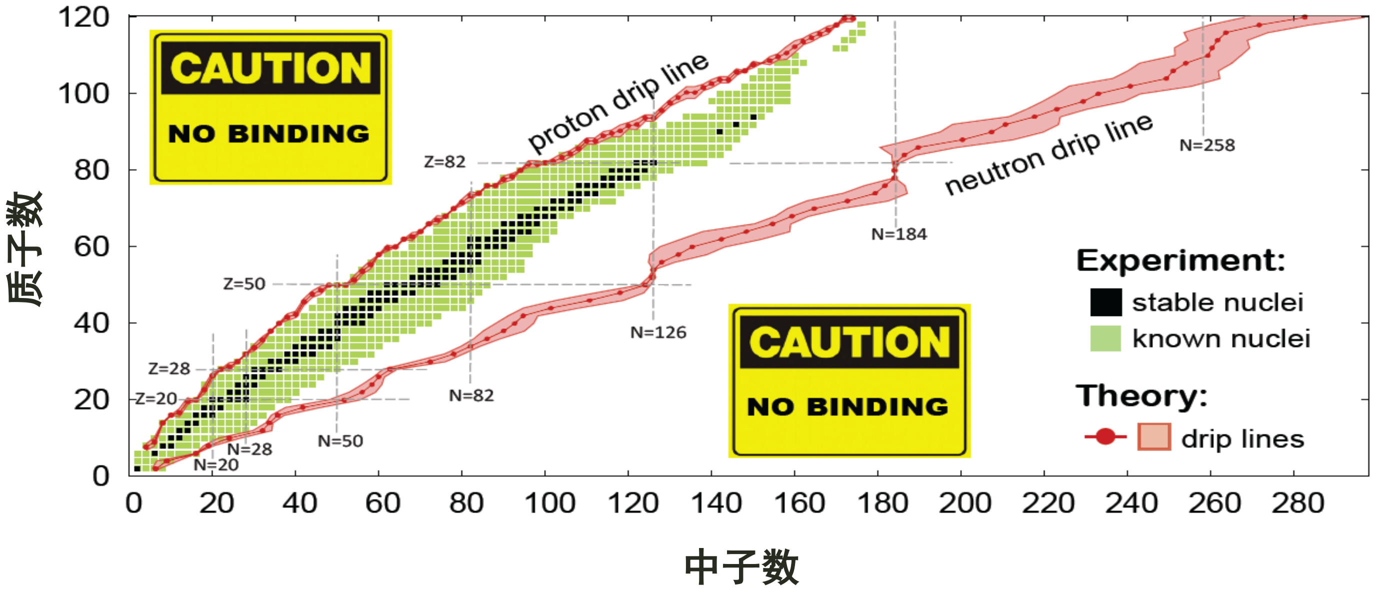
提纲

- 奇特核结构现象
- 重离子碰撞中的核结构效应: 中子皮、形变、α-团簇
- 总结

奇特核结构现象

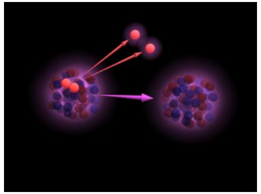
弱束缚核中出现的新现象与前沿物理问题

稳定核：～300；理论预言：～8000；已发现：～3400+

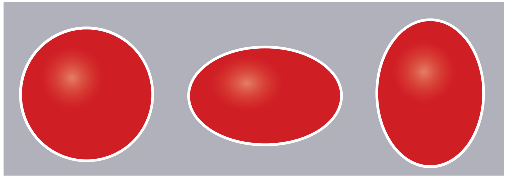


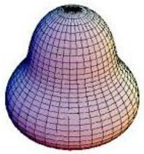
- 壳层结构的改变
- 幻数的消失与新幻数的出现
- 晕结构
- 原子核存在的极限
- 集团结构
- 奇异放射性
- 核反应的新机制与集体现象
- ……

奇异放射性

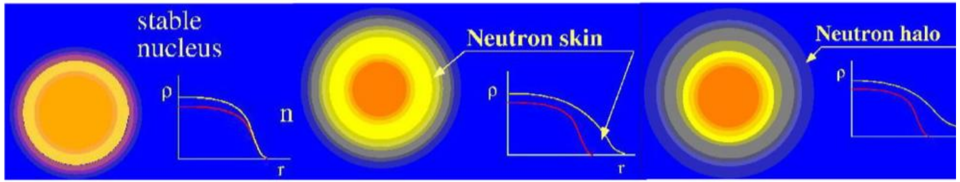


形变

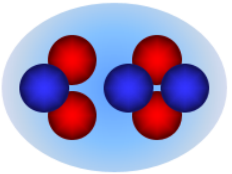




奇异结构



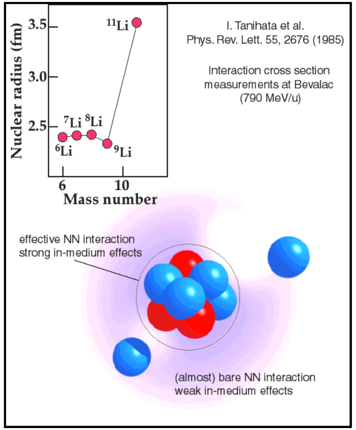
集团结构

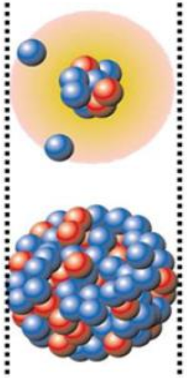


远离稳定线原子核的奇异结构

稳定核($N \approx Z$)

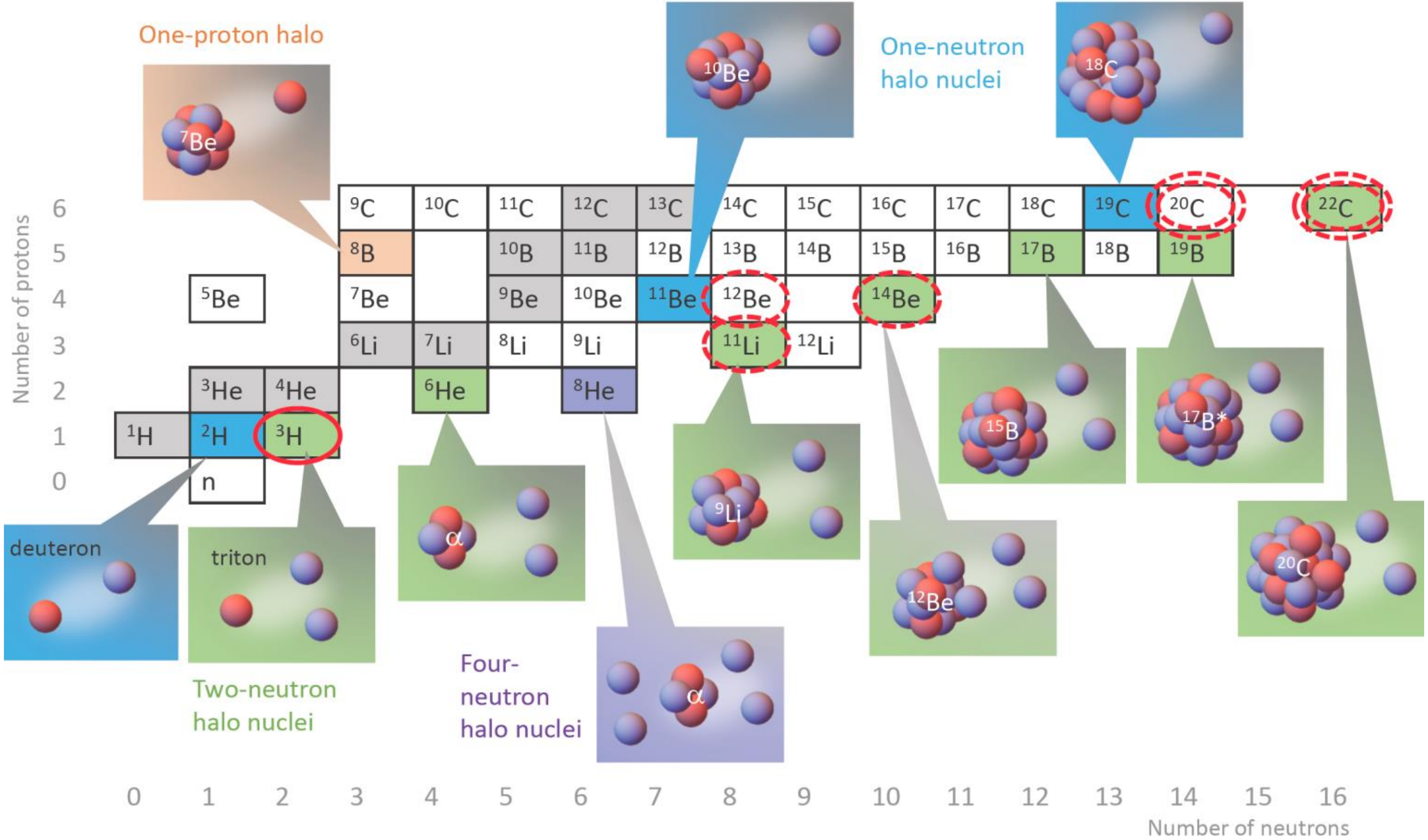
$R \approx 1.2 \times A^{1/3}$





^{11}Li

^{208}Pb



原子核的形变与奇异形状

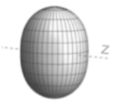
Collective shape of nuclei

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m}+\beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right)$$

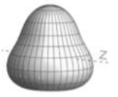
$1+\beta_2 Y_{2,0}(\theta,\phi)$

Quadrupole:
四极形变



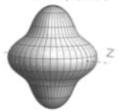
$1+\beta_3 Y_{3,0}(\theta,\phi)$

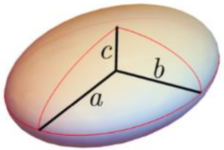
Octupole:
八极形变



$1+\beta_4 Y_{4,0}(\theta,\phi)$

Hexadecapole:
16极形变





$0 \le \gamma \le \pi/3$

Prolate: a=b<c → β_2, γ=0

Oblate: a<b=c → β_2, γ=π/3

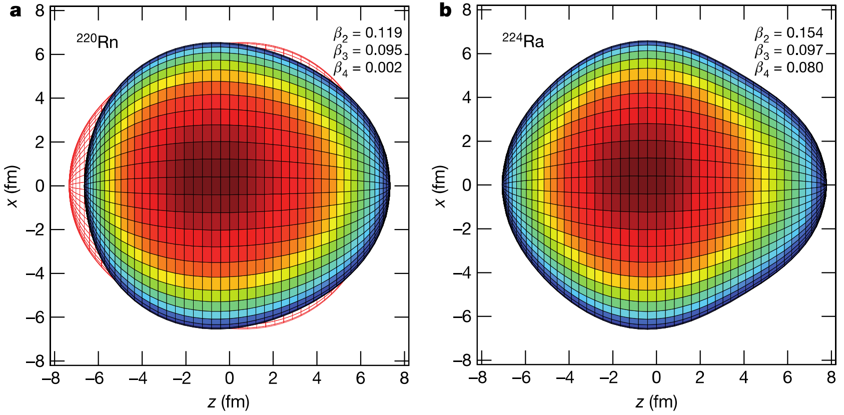
Triaxial: a<b<c → β_2, γ=π/6

ARTICLE

doi:10.1038/nature12073

Studies of pear-shaped nuclei using accelerated radioactive beams

L. P. Gaffney[1], P. A. Butler[1], M. Scheck[1,2], A. B. Hayes[3], F. Wenander[4], M. Albers[5], B. Bastin[6], C. Bauer[2], A. Blazhev[5], S. Bönig[2], N. Bree[7], J. Cederkäll[8], T. Chupp[9], D. Cline[3], T. E. Cocolios[4], T. Davinson[10], H. De Witte[7], J. Diriken[7,11], T. Grahn[12], A. Herzan[12], M. Huyse[7], D. G. Jenkins[13], D. T. Joss[1], N. Kesteloot[7,11], J. Konki[12], M. Kowalczyk[14], Th. Kröll[2], E. Kwan[15], R. Lutter[16], K. Moschner[5], P. Napiorkowski[14], J. Pakarinen[4,12], M. Pfeiffer[5], D. Radeck[5], P. Reiter[5], K. Reynders[7], S. V. Rigby[1], L. M. Robledo[17], M. Rudigier[5], S. Sambi[7], M. Seidlitz[5], B. Siebeck[5], T. Stora[4], P. Thoele[5], P. Van Duppen[7], M. J. Vermeulen[13], M. von Schmid[2], D. Voulot[4], N. Warr[5], K. Wimmer[18], K. Wrzosek-Lipska[7,14], C. Y. Wu[15] & M. Zielinska[14,19]



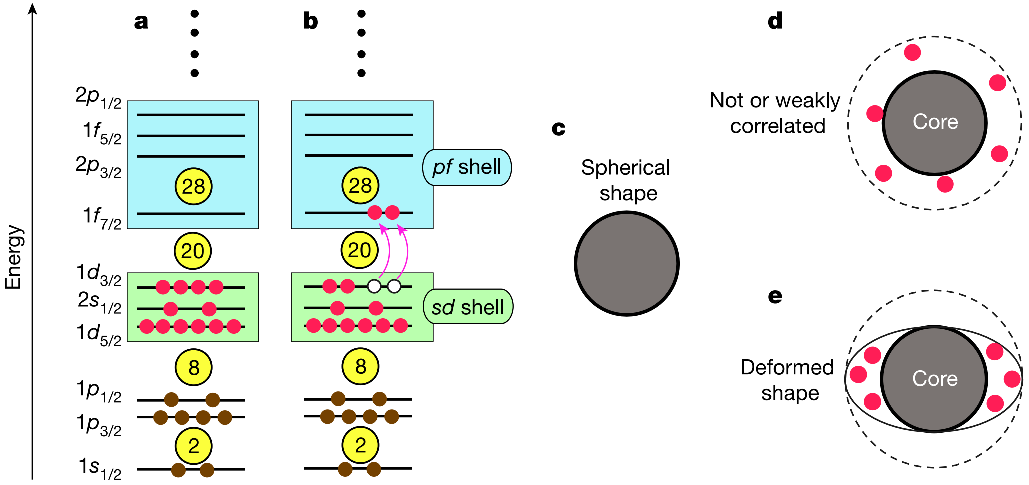
Article

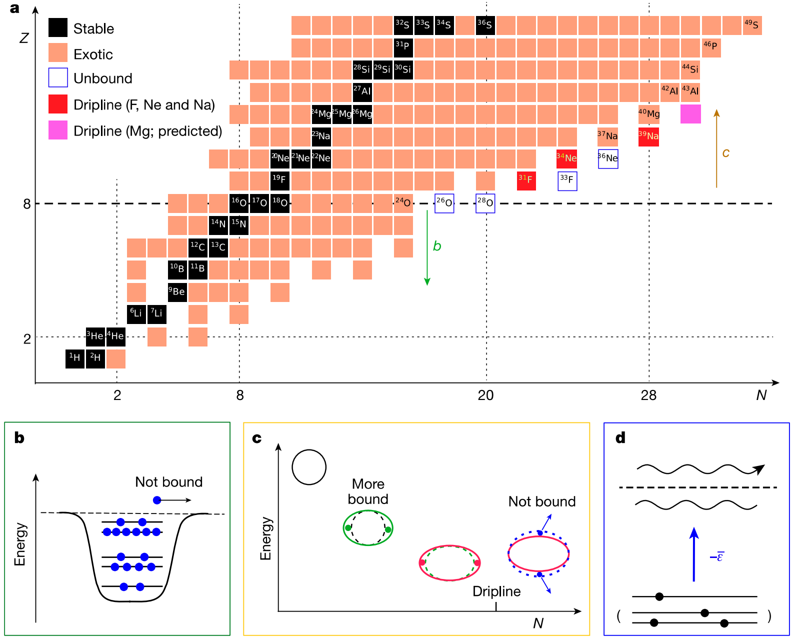
The impact of nuclear shape on the emergence of the neutron dripline

https://doi.org/10.1038/s41586-020-2848-x

Received: 31 December 2019

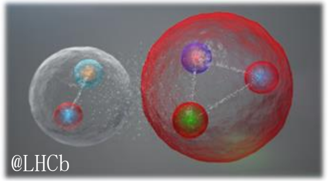
Naofumi Tsunoda[1], Takaharu Otsuka[2,3,4,5] ✉, Kazuo Takayanagi[6], Noritaka Shimizu[1], Toshio Suzuki[7,8], Yutaka Utsuno[1,5], Sota Yoshida[9] & Hideki Ueno[3]



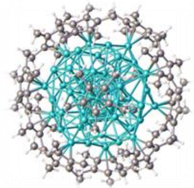


团簇现象

团簇(cluster)在物质各个层次都起着极为重要的作用。理解和描述团簇结构是当代重要的科学问题。

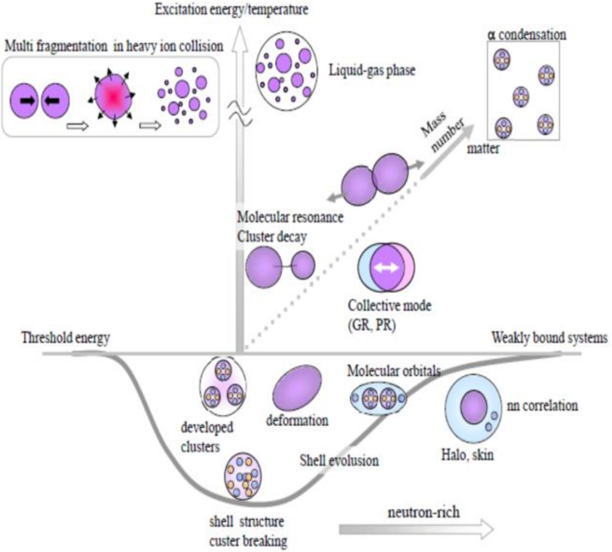


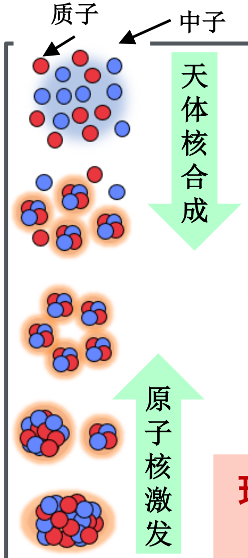
五夸克团簇



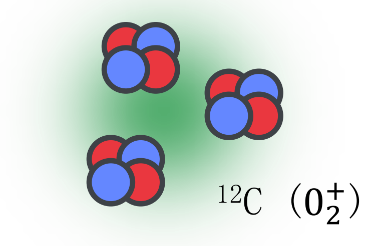
多原子团簇

星系团簇

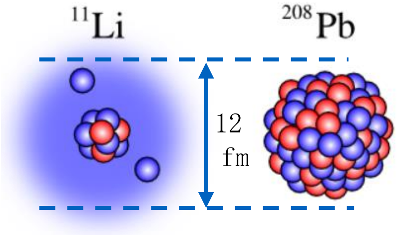




原子核激发过程中会发生“相变”，形成原子核团簇态。



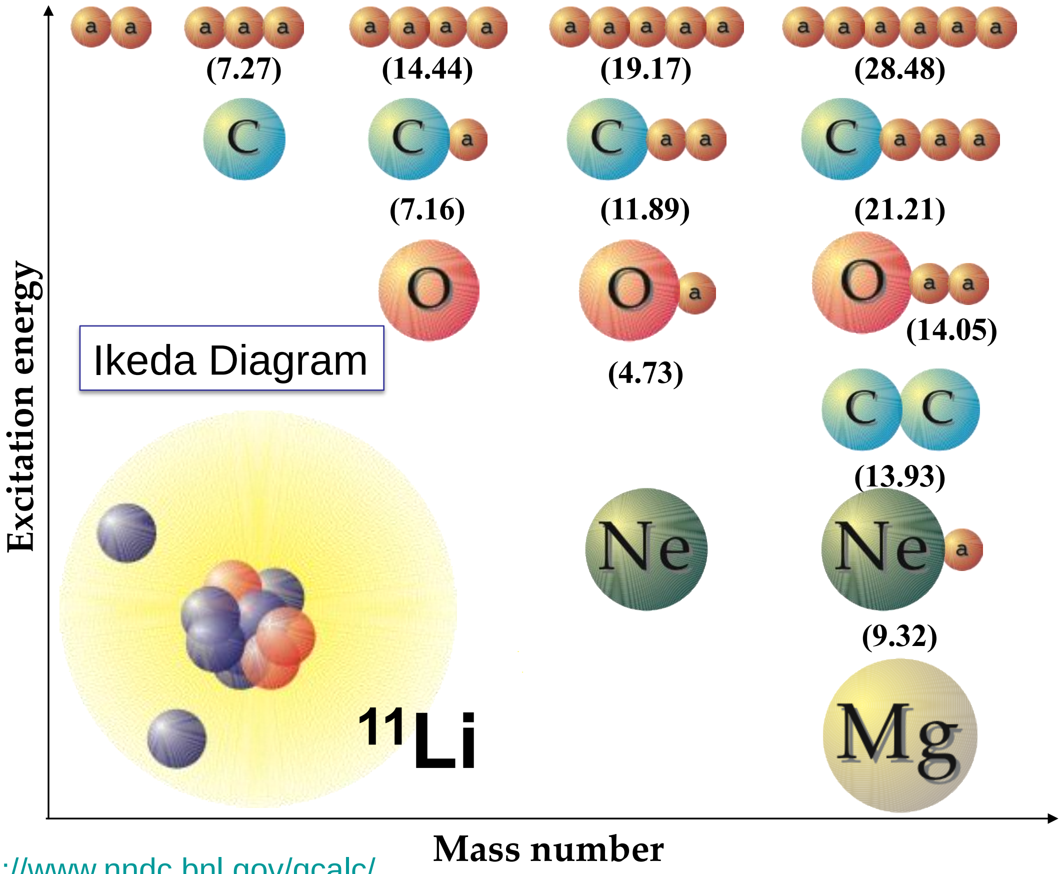
3α Bose-Einstein 凝聚态

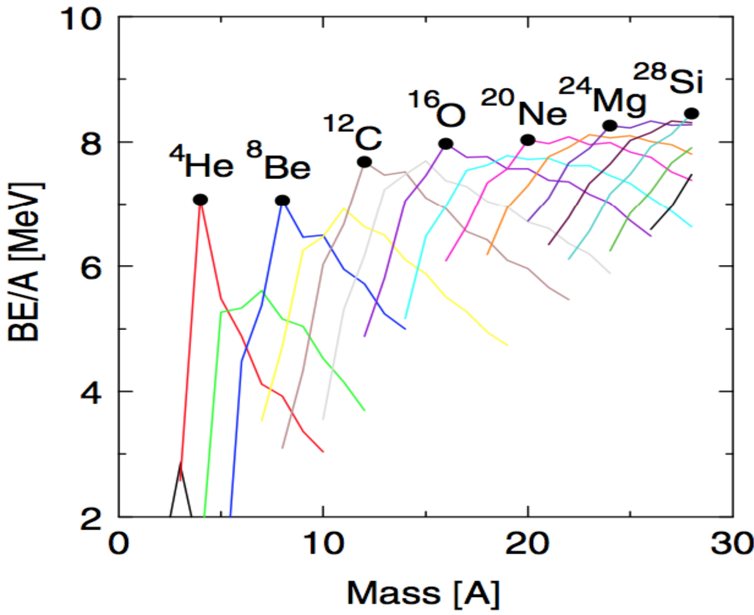


^{11}Li 的晕核结构

理论上精确描述这类原子核团簇结构，对于天体核合成反应和核结构理论有重要意义。

Alpha-Clustering





http://www.nndc.bnl.gov/qcalc/

sequence of reaction channels

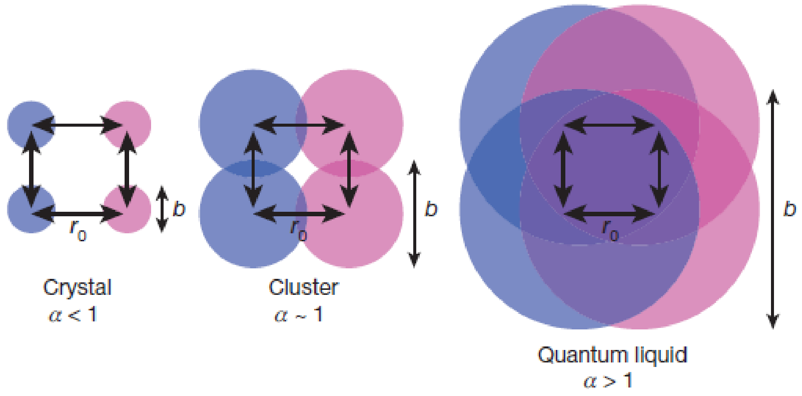
LETTER

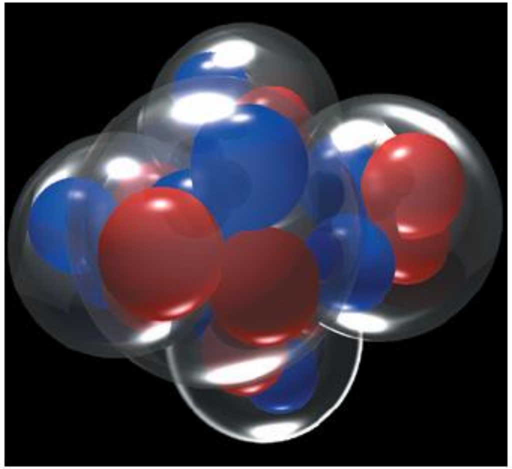
doi:10.1038/nature11246

How atomic nuclei cluster

J.-P. Ebran[1], E. Khan[2], T. Nikšić[3] & D. Vretenar[3]

Fully microscopic description based on the framework of energy-density functionals (EDFs).





NUCLEAR PHYSICS

Nucleons come together

MARTIN FREER

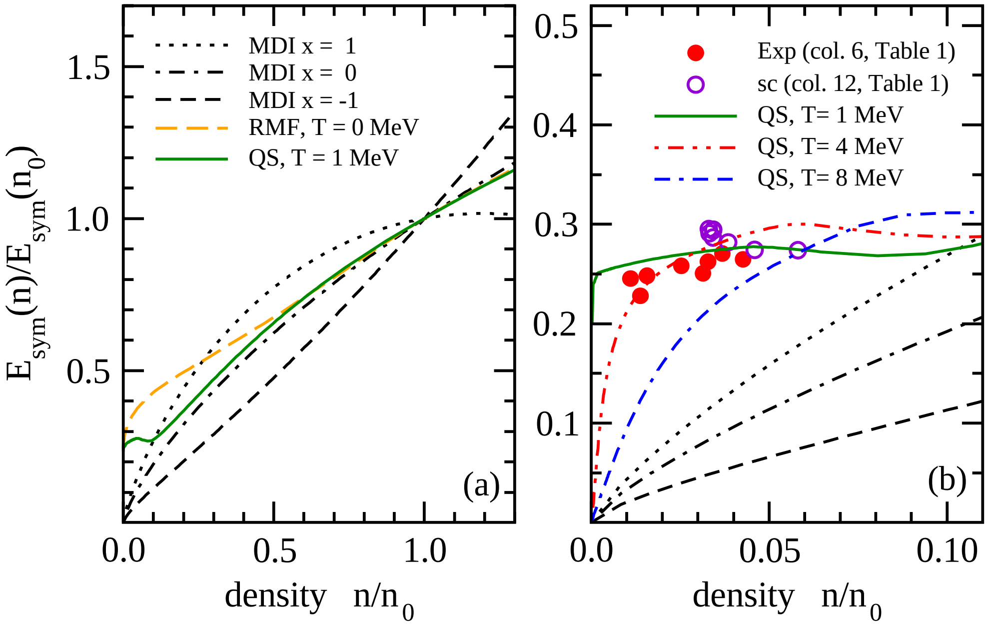
The transformation from the fermionic liquid to the bosonic crystal-like cluster structures reveals key features of the strong nucleon–nucleon interaction within nuclei, and the current work is a step forward in our understanding of this interaction. ■

So, is this the complete picture of nuclear clustering? Although the depth of the potential may emphasize the cluster symmetries, it does not describe the emergence of clustering close to the energy threshold for α-particle decay — the Ikeda picture[3]. There is, therefore, a missing component in this explanation of clustering. Weakly bound nuclei close to

Selected for a Viewpoint in *Physics*
PRL **104,** 202501 (2010) PHYSICAL REVIEW LETTERS week ending 21 MAY 2010

Symmetry Energy of Dilute Warm Nuclear Matter

J. B. Natowitz,[1] G. Röpke,[2] S. Typel,[3,4] D. Blaschke,[5,6] A. Bonasera,[1,7] K. Hagel,[1] T. Klähn,[5,8] S. Kowalski,[1] L. Qin,[1] S. Shlomo,[1] R. Wada,[1] and H. H. Wolter[9]



Physics
Physics **3**, 42 (2010)

Viewpoint

Getting a better handle on nuclear matter at low density

Lee G. Sobotka
Department of Chemistry, Washington University in St. Louis, St. Louis, MO 63130
Published May 17, 2010

New calculations of the effects of asymmetry in numbers of neutrons and protons in nuclei agree well with experiment and provide vital information in understanding nuclear matter at low density.

- **基于平均场方法的传统对称能理论计算无法给出正确的低温、低密度极限。**
- **量子统计方法将团簇的形成考虑在内，预测出的对称能与实验数据非常吻合。该方法给出了对称能的一致描述，将正确的低密度极限与饱和密度附近有效的准粒子方法结合起来。**

REPORT

NUCLEAR PHYSICS

Formation of α clusters in dilute neutron-rich matter

Junki Tanaka[1,2,3]*, Zaihong Yang[3,4]*, Stefan Typel[1,2], Satoshi Adachi[4], Shiwei Bai[5], Patrik van Beek[1], Didier Beaumel[6], Yuki Fujikawa[7], Jiaxing Han[5], Sebastian Heil[1], Siwei Huang[5], Azusa Inoue[4], Ying Jiang[5], Marco Knösel[1], Nobuyuki Kobayashi[4], Yuki Kubota[3], Wei Liu[5], Jianling Lou[5], Yukie Maeda[8], Yohei Matsuda[9], Kenjiro Miki[10], Shoken Nakamura[4], Kazuyuki Ogata[4,11], Valerii Panin[3], Heiko Scheit[1], Fabia Schindler[1], Philipp Schrock[12], Dmytro Symochko[1], Atsushi Tamii[4], Tomohiro Uesaka[3], Vadim Wagner[1], Kazuki Yoshida[13], Juzo Zenihiro[3,7], Thomas Aumann[1,2,14]

NUCLEAR PHYSICS

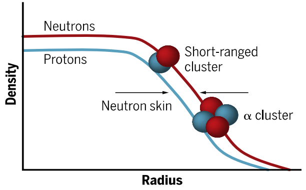
From nuclear clusters to neutron stars

Measurements of α cluster formation in nuclear "skins" can improve neutron star models

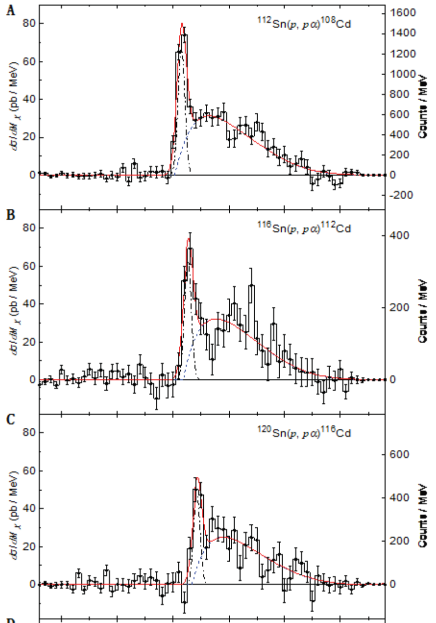
Probing neutron skins

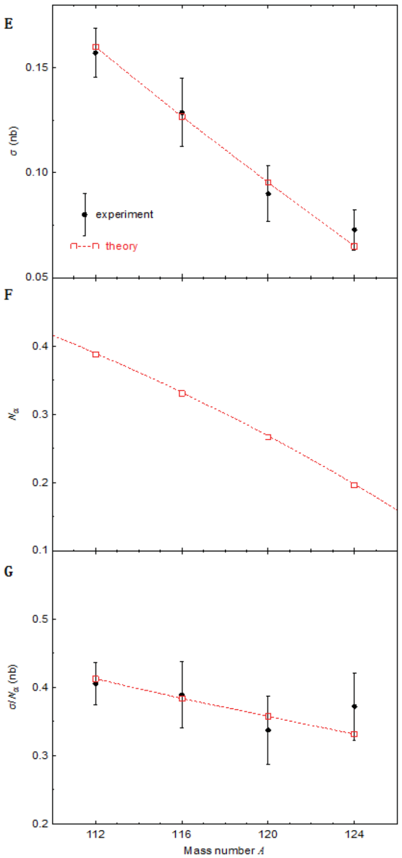
The neutron skin, the region where neutron density exceeds proton densities in nuclei, is affected by a cluster formation in the outer low-density regions (as measured by Tanaka *et al.*) and short-ranged clusters at higher-density regions.

Nucleon density in neutron-rich nuclei



- **通过使用准自由alpha簇敲除反应，获得了在丰中子锡同位素表面形成alpha簇的直接实验证据。**
- **观察到反应截面随着质量数的增加而单调下降，这与理论预测吻合，意味着alpha簇的形成与中子表皮之间存在紧密的相互作用。这一结果反过来要求修正中子皮厚度与对称能密度依赖性之间的相关性，这对于理解中子星至关重要。**





Tin isotope	Target thickness (mg/cm^2)	Isotopic enrichment (%)	Experimental cross sections (nb)	Theoretical cross sections (nb)	Effective number of α clusters	Theoretical Δr_{np} without α (fm)	Theoretical Δr_{np} with α (fm)	Relative Δr_{np} change (%)
^{112}Sn	40.2 (4)	95.1 (1)	0.157 (12)	0.160	0.3876	0.0495	0.0277	–44
^{116}Sn	39.3 (4)	97.8 (2)	0.129 (16)	0.127	0.3304	0.0843	0.0580	–31
^{120}Sn	39.9 (4)	99.6 (1)	0.090 (13)	0.095	0.2668	0.1179	0.0912	–23
^{124}Sn	40.7 (4)	97.4 (2)	0.073 (10)	0.065	0.1958	0.1505	0.1275	–15

中子皮的效应

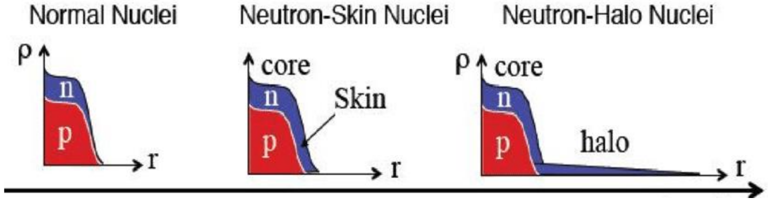
PHYSICAL REVIEW LETTERS **125,** 222301 (2020)

Probing the Neutron Skin with Ultrarelativistic Isobaric Collisions

Hanlin Li,[1] Hao-jie Xu,[2,*] Ying Zhou,[3] Xiaobao Wang,[2] Jie Zhao,[4] Lie-Wen Chen,[3,†] and Fuqiang Wang[2,4,‡]

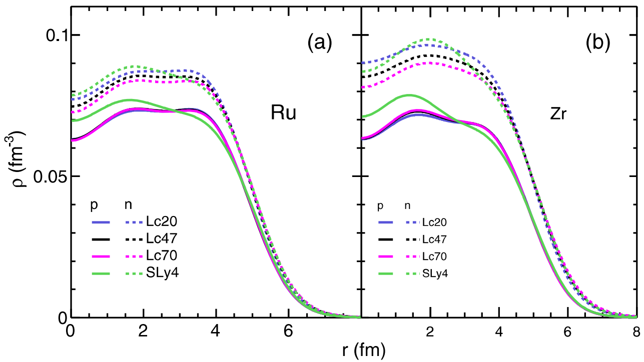
Determine the neutron skin type by STAR data

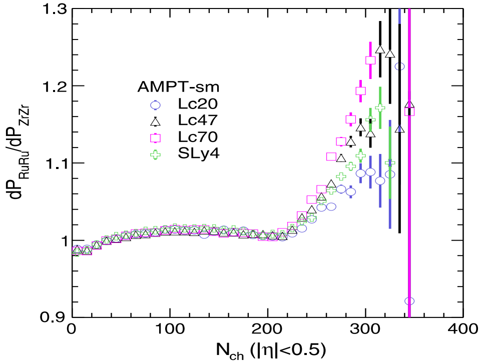
HJX, et.al., PLB819, 136453 (2021)

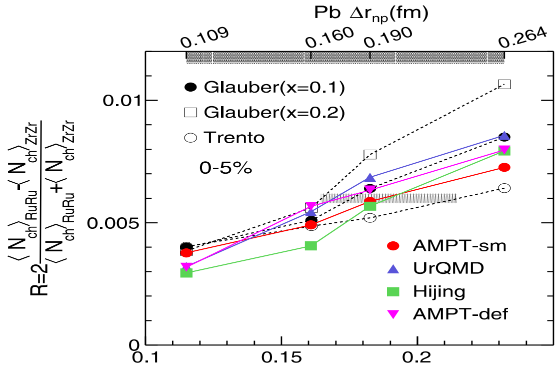


- Neutron-skin nuclei and neutron-halo nuclei for Zr

	^{96}Ru		^{96}Zr	
	R	a	R	a
p	5.085	0.523	5.021	0.523
skin-type n	5.085	0.523	5.194	0.523
halo-type n	5.085	0.523	5.021	0.592



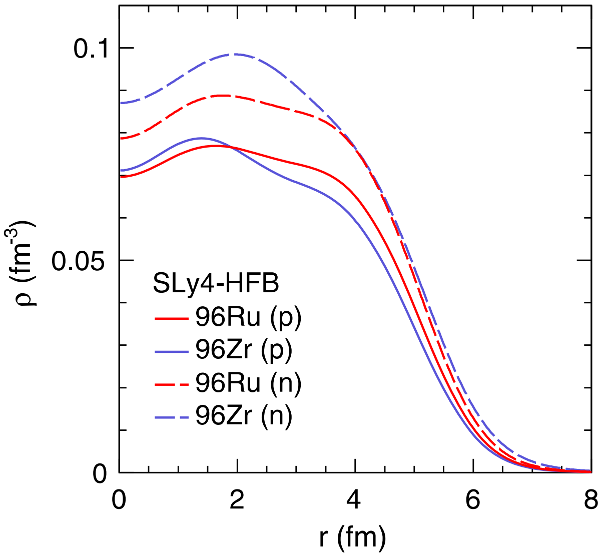


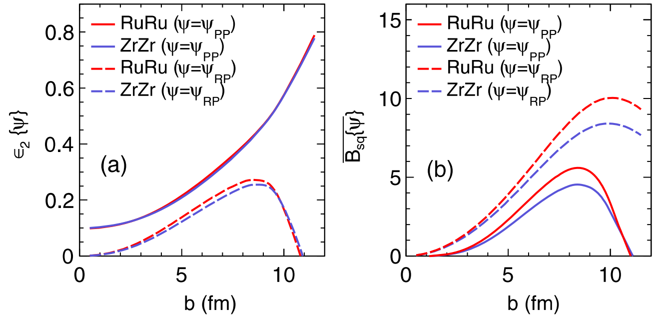


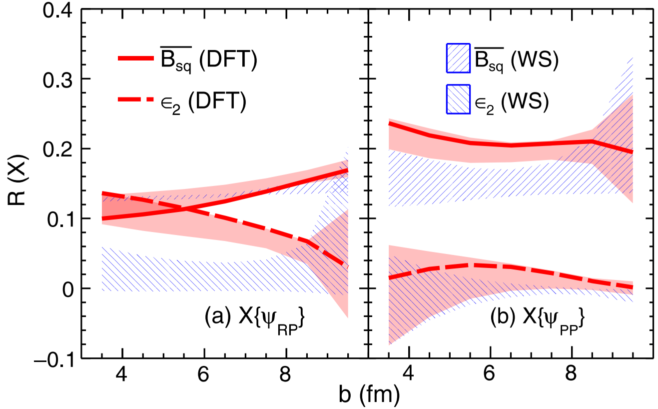
PHYSICAL REVIEW LETTERS **121,** 022301 (2018)

Importance of Isobar Density Distributions on the Chiral Magnetic Effect Search

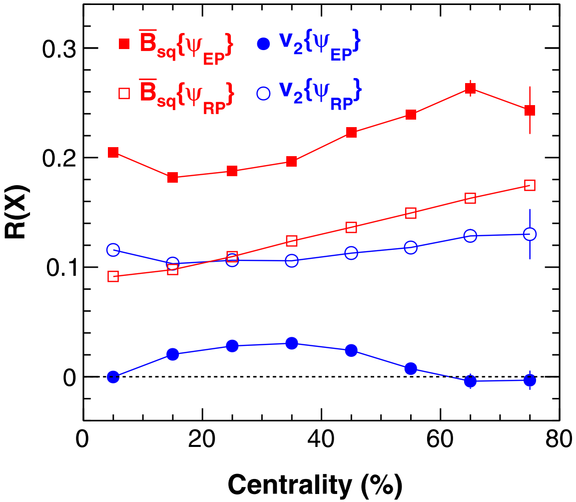
Hao-jie Xu,[1] Xiaobao Wang,[1] Hanlin Li,[2] Jie Zhao,[3] Zi-Wei Lin,[4,5] Caiwan Shen,[1] and Fuqiang Wang[1,3,*]







$$R(X) \equiv 2(X_{\mathrm{RuRu}} - X_{\mathrm{ZrZr}})/(X_{\mathrm{RuRu}} + X_{\mathrm{ZrZr}})$$

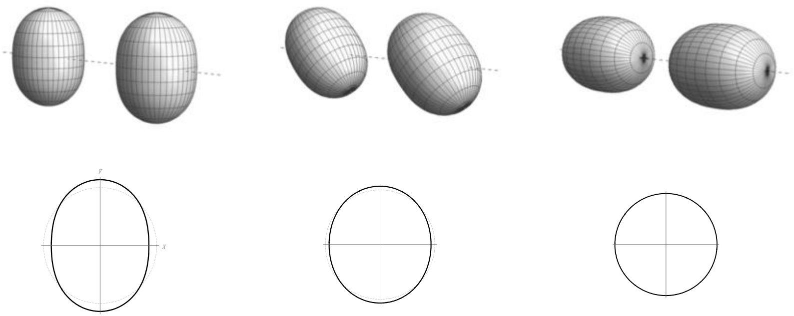


核形变的效应

See Jia JY, Zhang CJ et al. talks

How quadrupole deformation influence HI initial state

Body-Body $\mathcal{E}_2 = \epsilon_2 e^{i2\Phi} \propto \langle \boldsymbol{r}_\perp^2 e^{i2\phi} \rangle$ Tip-Tip



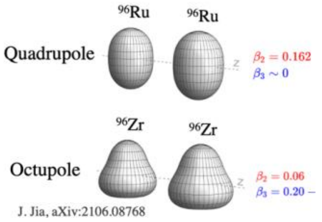
ε_2~$0.95\beta_2$ ε_2~$0.48\beta_2$ ε_2~0

$$\boldsymbol{\epsilon}_2 = \underbrace{\boldsymbol{\epsilon}_0}_{\text{undeformed}} + \underbrace{\boldsymbol{p}(\Omega_1, \Omega_2)}_{\text{phase factor}}\beta_2 + \mathcal{O}(\beta_2^2) \Longrightarrow \langle \epsilon_2^2 \rangle \approx \langle \epsilon_0^2 \rangle + 0.2\beta_2^2$$

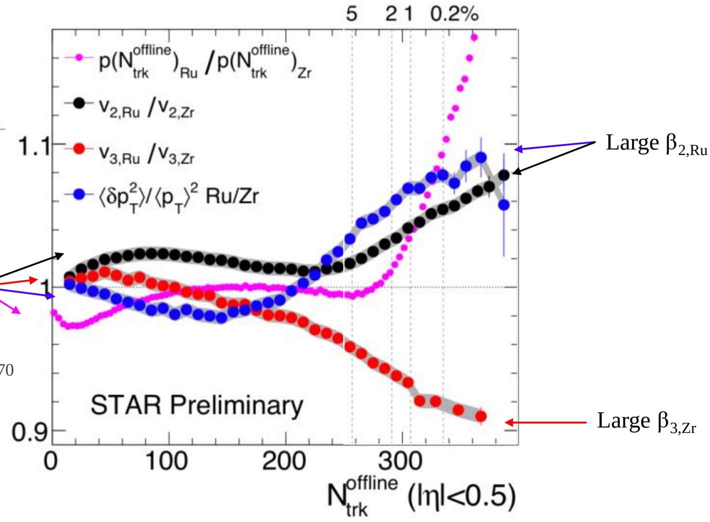
contains γ

Shape depends on Euler angle Ω=φθψ

Compare with isobar data



From 张春健 DNP STAR talk



STAR, arXiv:2109.00131
H. Xu et al., arXiv:1808.06711,1910.06170
2103.05595, 2111.14812
Q. Shou et al., arXiv:1409.8375
C. Zhang et al., arXiv:2109.01631
G. Giacalone et al., 2105.01638

Use these ratios to probe shape and radial structure of nuclei.

- Alpha团簇效应

EQMD模型

For transport model, one has to prepare energy-minimum states as initial ground nuclei. They are obtained by starting from a random configuration and by solving the damped equations of motion.

- Friction cooling :

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

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

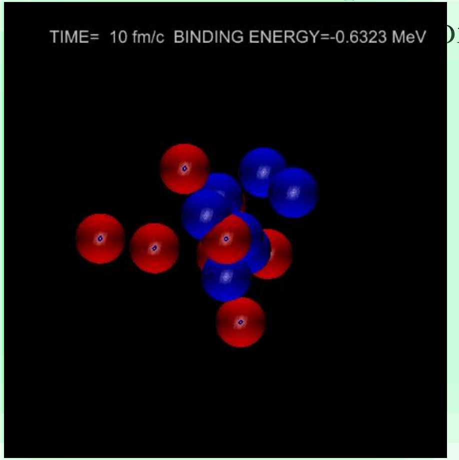
Add damping term

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

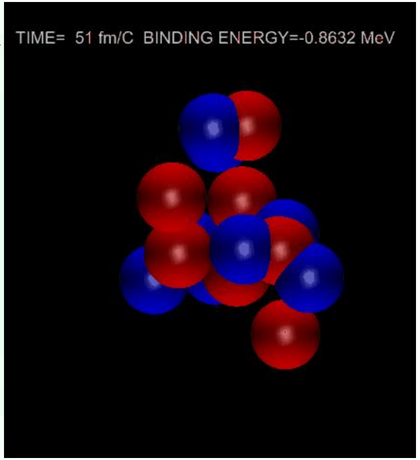
$$\frac{3\hbar}{4}\dot{\lambda}_i = -\frac{\partial H}{\partial \delta_i} + \mu_{\lambda}\frac{\partial H}{\partial \lambda_i}, \qquad \frac{3\hbar}{4}\dot{\delta}_i = \frac{\partial H}{\partial \lambda_i} + \mu_{\delta}\frac{\partial H}{\partial \delta_i}.$$

Equations of ... on

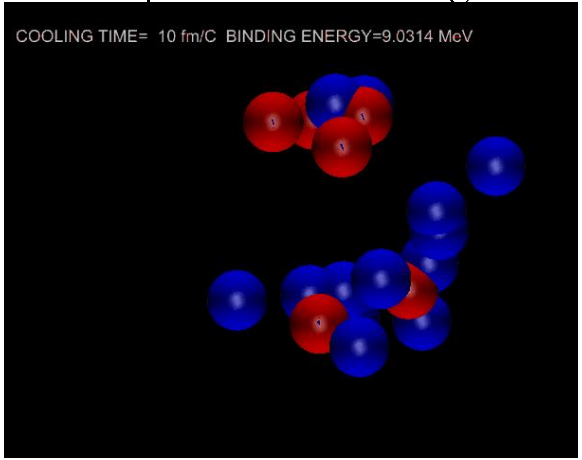
Equations of cooling



^{16}O initial state before cooling



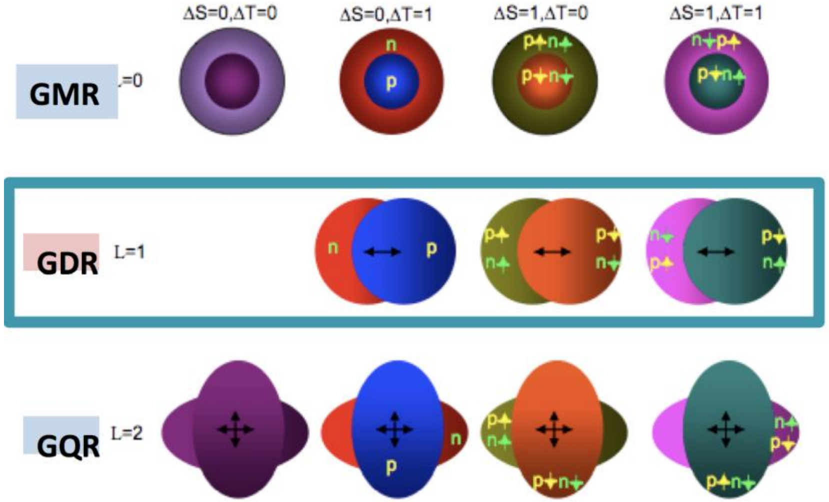
^{16}O cooling to ground state



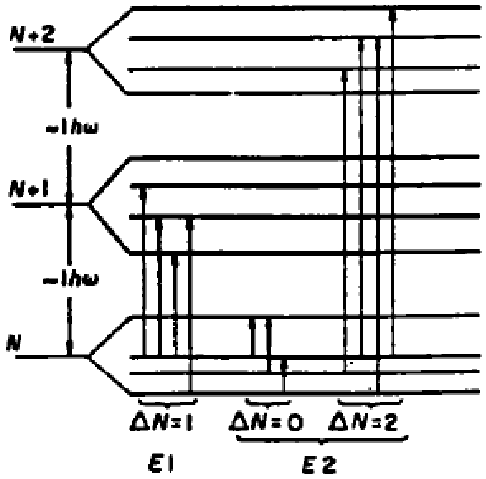
^{19}C cooling to halo structure

Giant Resonance

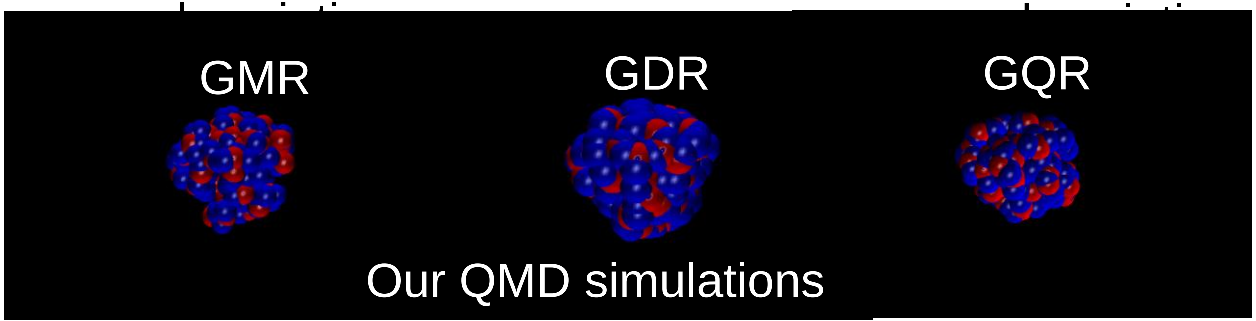
Giant resonances are typical collective excitations in nuclei



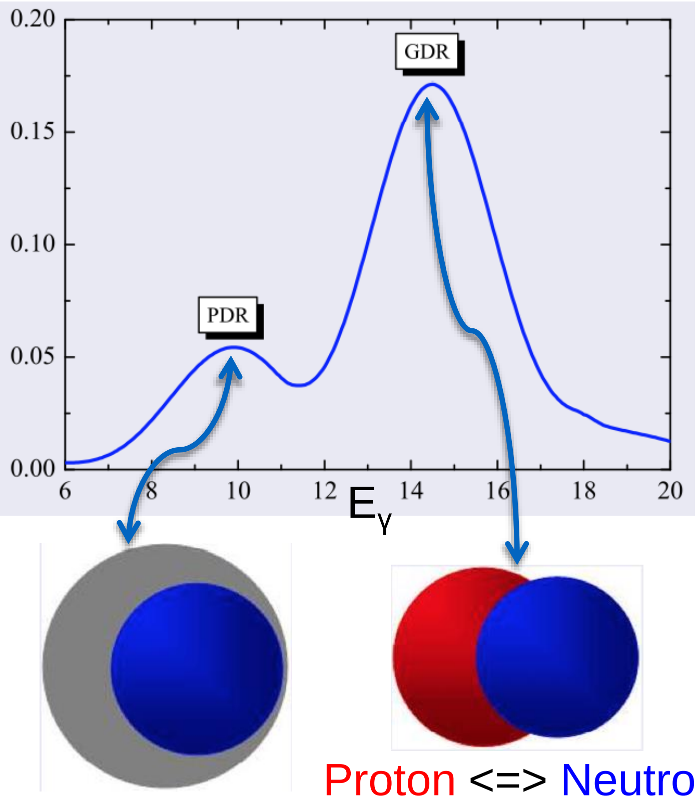
Macroscopic

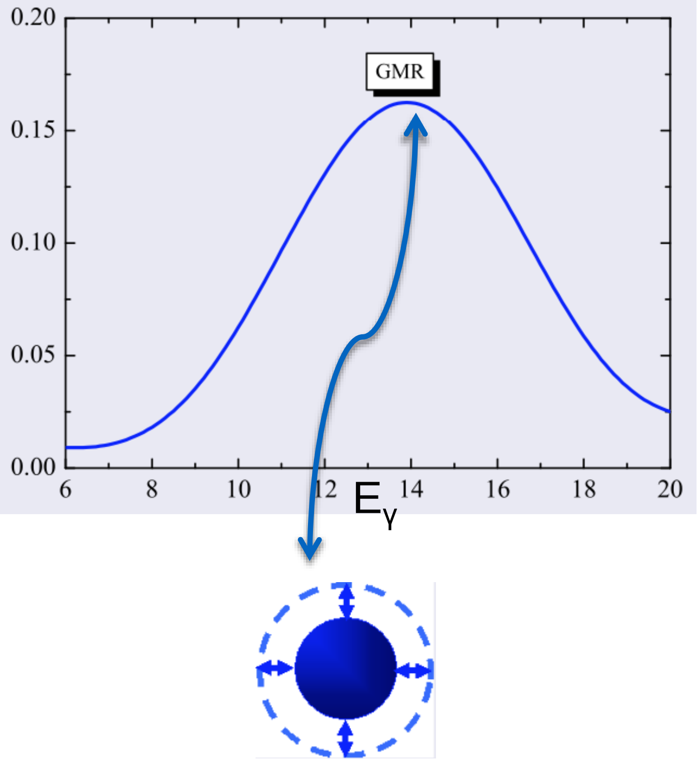


Microscopic



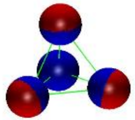
Three main excitation modes studied widely: GDR, PDR, GMR





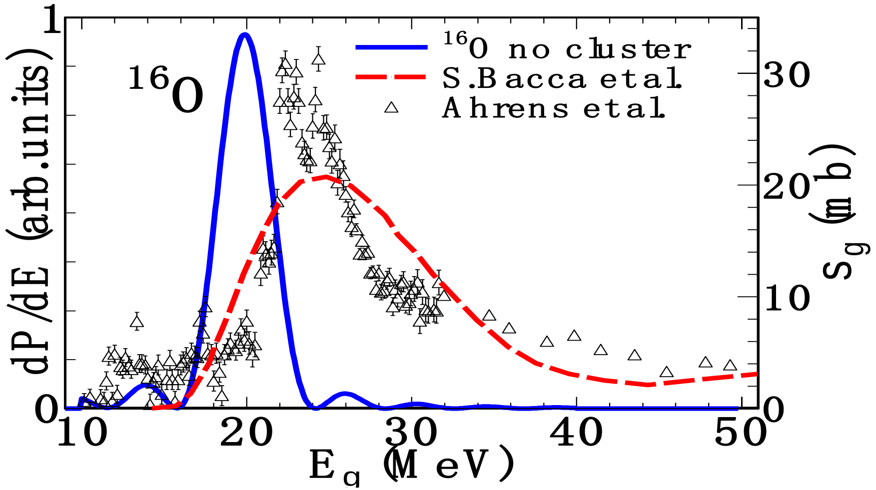
Proton <=> Neutron

Valence neutron <=> Core

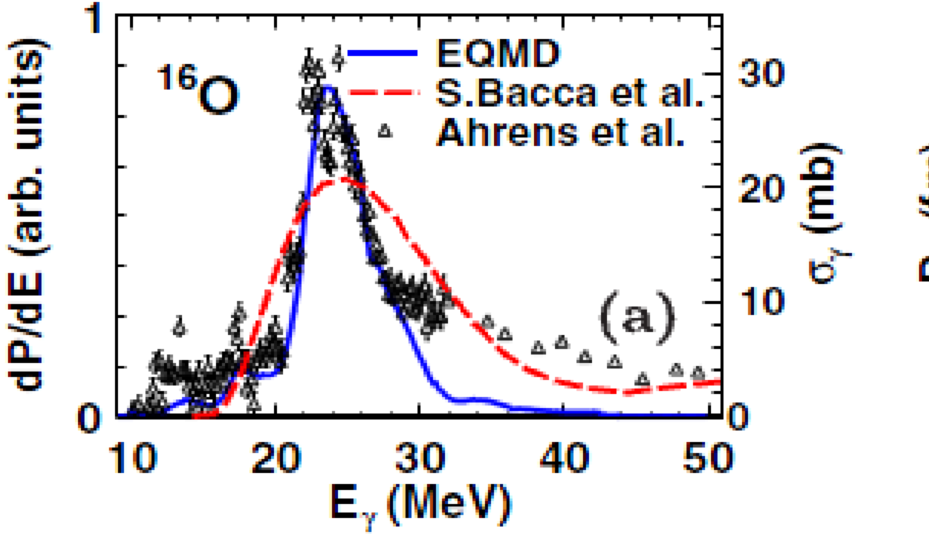


GDR of ^{16}O with different α configurations

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



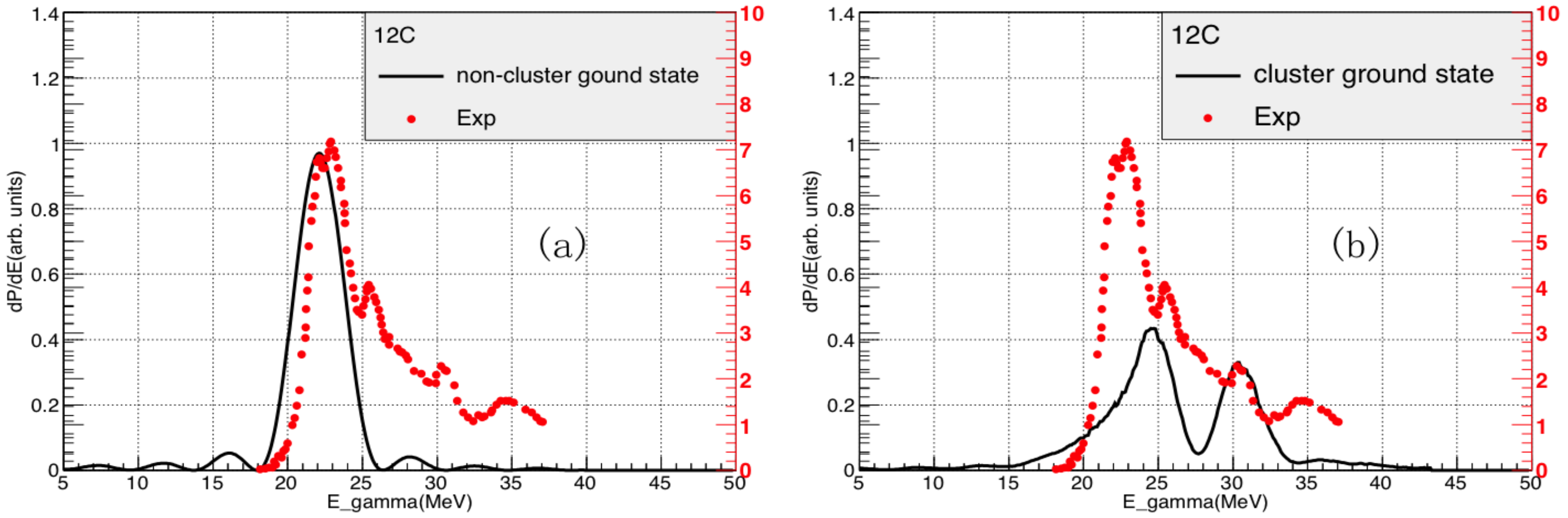
^{16}O ground state w/o alpha clusters



^{16}O ground state with tetrahedron structure

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.

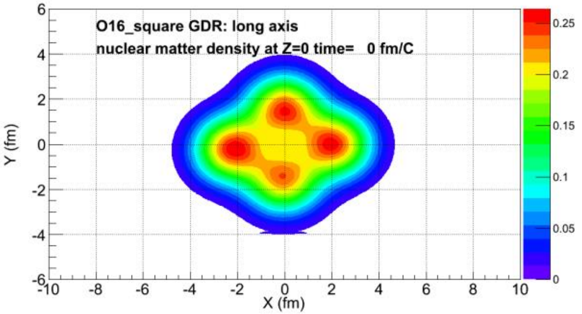
The data is from J. Ahrens, H. Borchert, K. H. Czock et al., Nucl. Phys. A251, 479 (1975).

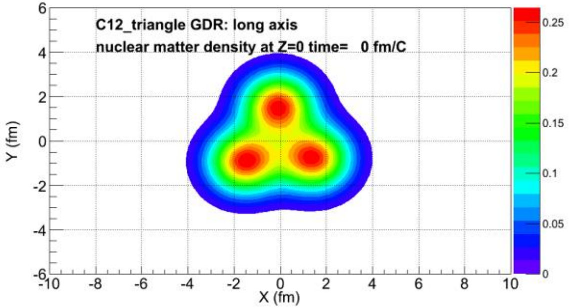
PRL 113, 032506 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

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]
[1]*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*
[2]*University of the Chinese Academy of Sciences, Beijing 100080, China*
[3]*Shanghai Tech University, Shanghai 200031, China*
(Received 6 May 2014; published 17 July 2014)

Correspondence between GDR and α cluster configurations





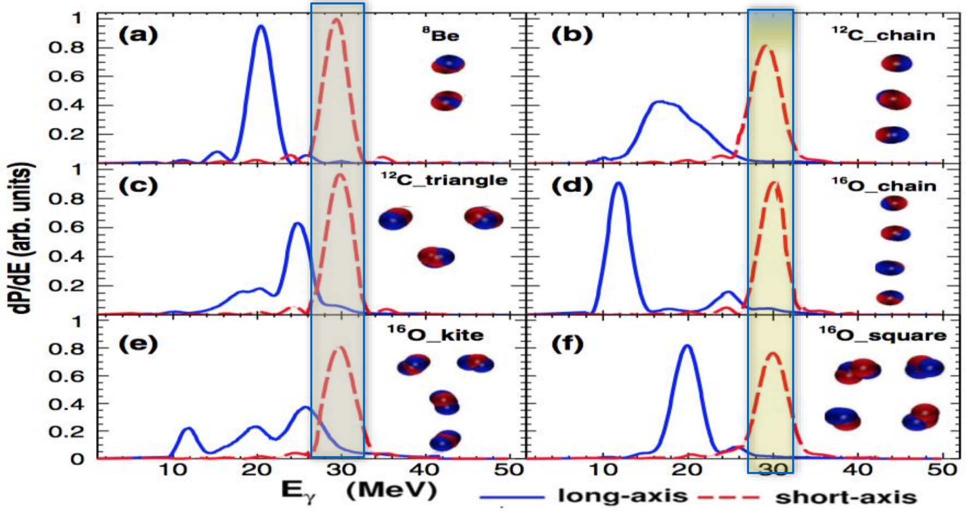
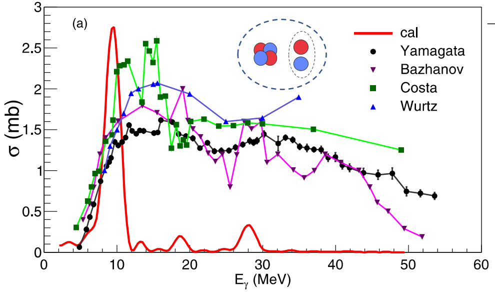


FIG. 2 (color online). ^{8}Be, ^{12}C, and ^{16}O GDR spectra with different cluster configurations. The corresponding α cluster configuration in the present EQMD model calculation is drawn in each panel, in which blue and red balls indicate protons and neutrons, respectively. The dynamical dipole evolution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

非alpha共轭核的GDR

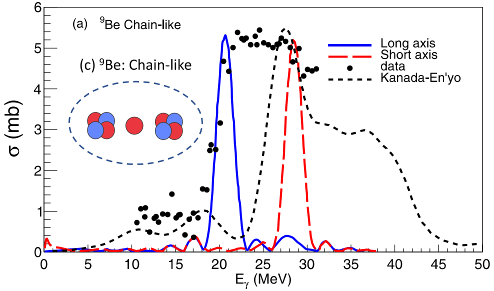


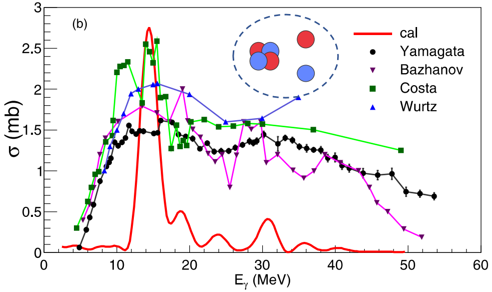
PHYSICAL REVIEW C **103**, 054318 (2021)

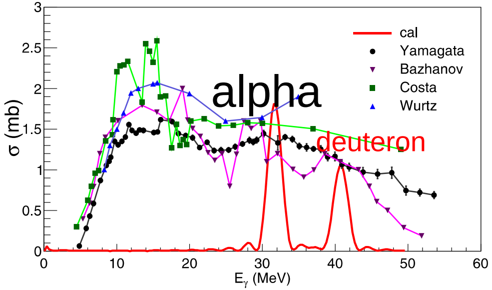
Dipole excitation of ^{6}Li and ^{9}Be studied with an extended quantum molecular dynamics model

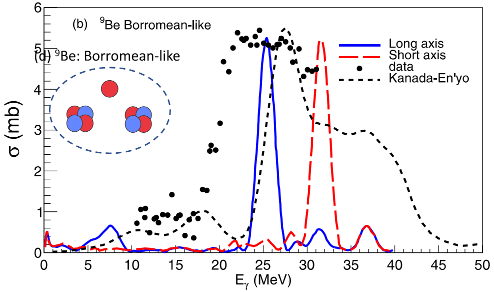
Bo-Song Huang (黄勃松)*
Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

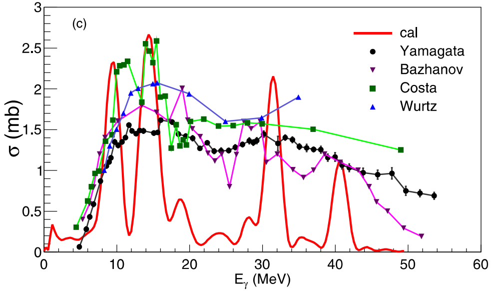
Yu-Gang Ma (马余刚)†
Key Laboratory of Nuclear Physics and Ion-Beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China





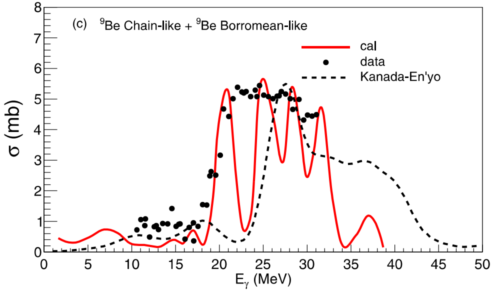






^{6}Li 比分组合的结果:
1. : 1.17 : 0.9 : 1.
a+d / a+n+p/ a/d

^{9}Be 比分组合的结果:
1. : 0.9 : 1.1 : 0.75
2 peaks of chain+2 peaks of Borromean



- Alpha-clustering effect on nucleon correlation by Photonuclear reaction

PHYSICAL REVIEW C **95**, 034606 (2017)

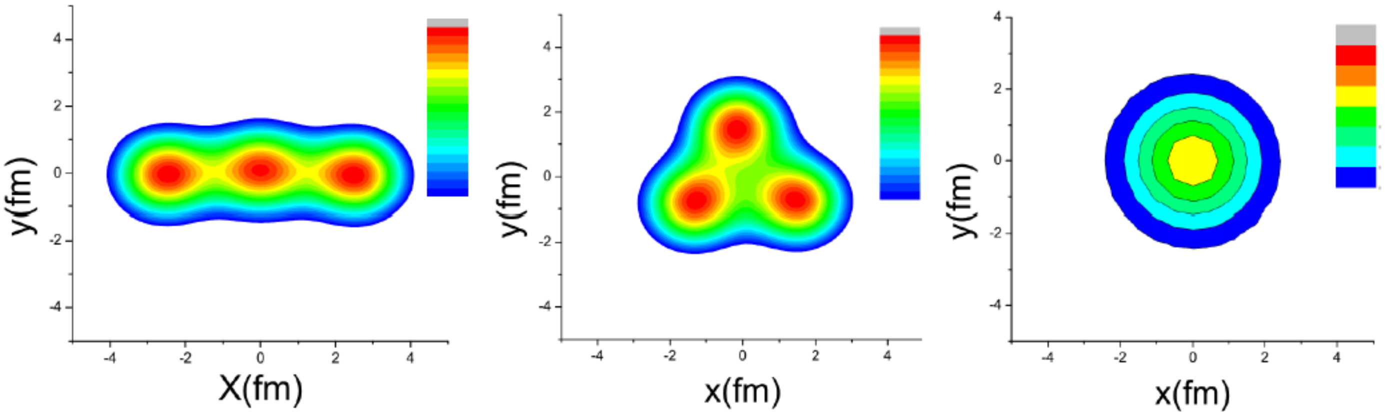
Photonuclear reaction as a probe for α-clustering nuclei in the quasi-deuteron region

B. S. Huang (黄勃松),[1,2] Y. G. Ma (马余刚),[1,3,*] and W. B. He (何万兵)[1,4]

If photons hit alpha cluster, what happens?

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

(a) chain **(b)triangle** **(c)spherical**



Quasi-deuteron: ~70-140MeV

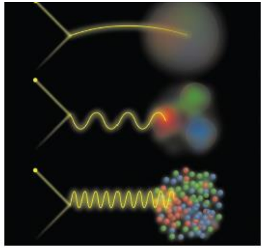


TABLE I: RMS radius and binding energy of different configurations of 12C and the ground state data.

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

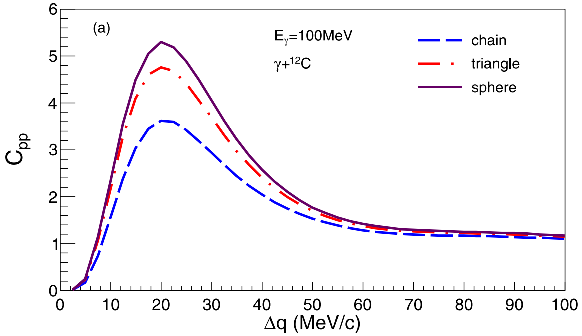
Effects on momentum correlation function via photonuclear reactions

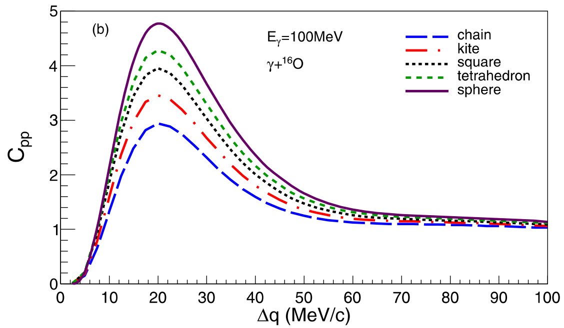
质子-质子关联

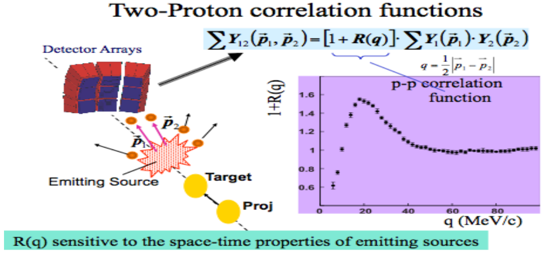
PHYSICAL REVIEW C **101**, 034615 (2020)

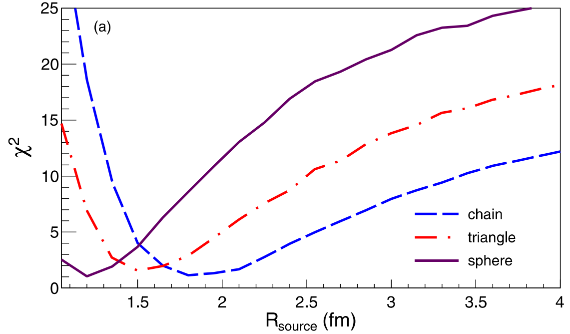
Two-proton momentum correlation from photodisintegration of α-clustering light nuclei in the quasideuteron region

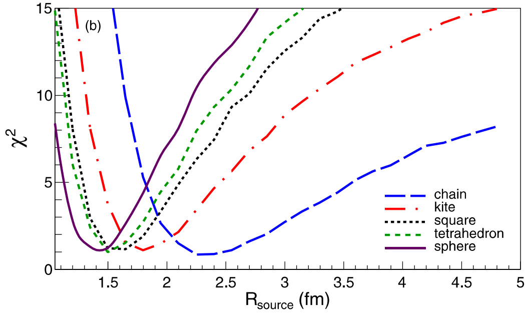
Bo-Song Huang (黄勃松)* and Yu-Gang Ma (马余刚)†











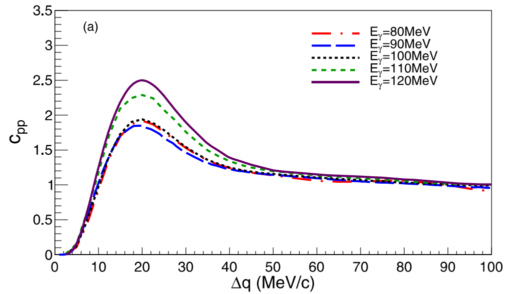


TABLE II. Same as Table I but for ^{16}O configurations.

Configuration	r_{RMS} (fm)	E_{bind}/A (MeV)	R_{source} (fm)	B.R.$_{2p}$
Chain	3.782	7.26	2.40	0.40%
Kite	3.254	7.22	1.75	0.70%
Square	2.908	7.29	1.60	0.85%
Tetrahedron	2.761	7.79	1.50	1.30%
Sphere	2.6	8.15	1.40	5.13%
Exp. data	2.6991(52)	7.976		

Configuration	r_{RMS} (fm)	E_{bind}/A (MeV)	R_{source} (fm)	B.R.$_{2p}$
Chain	2.71	7.17	1.85	0.45%
Triangle	2.35	7.12	1.55	0.75%
Sphere	2.23	7.60	1.25	5.05%
Exp. data	2.4702(22)	7.68		

- pp的动量关联函数的强度与alpha-clustering构型依赖敏感
- 可以定量提取发射源的半径
- **从关联函数提取出发射源的尺寸，其排序与构型的大小自洽**

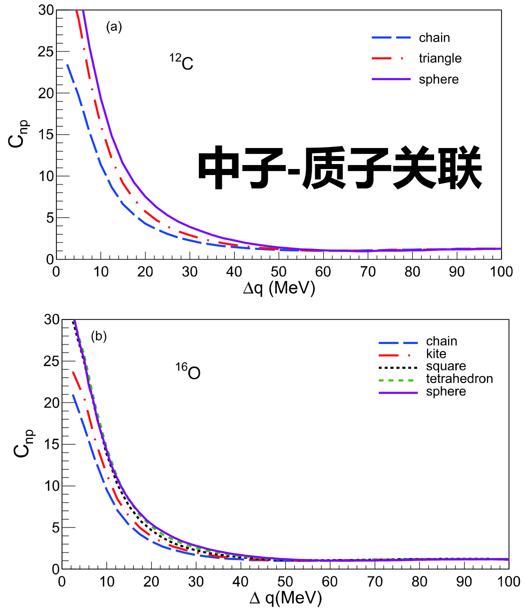
非全同粒子的发射次序

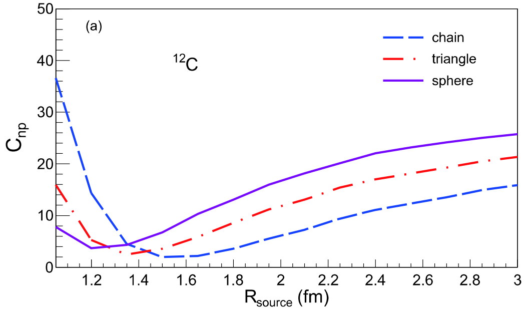
Chinese Physics C Vol. 44, No. 9 (2020) 094105

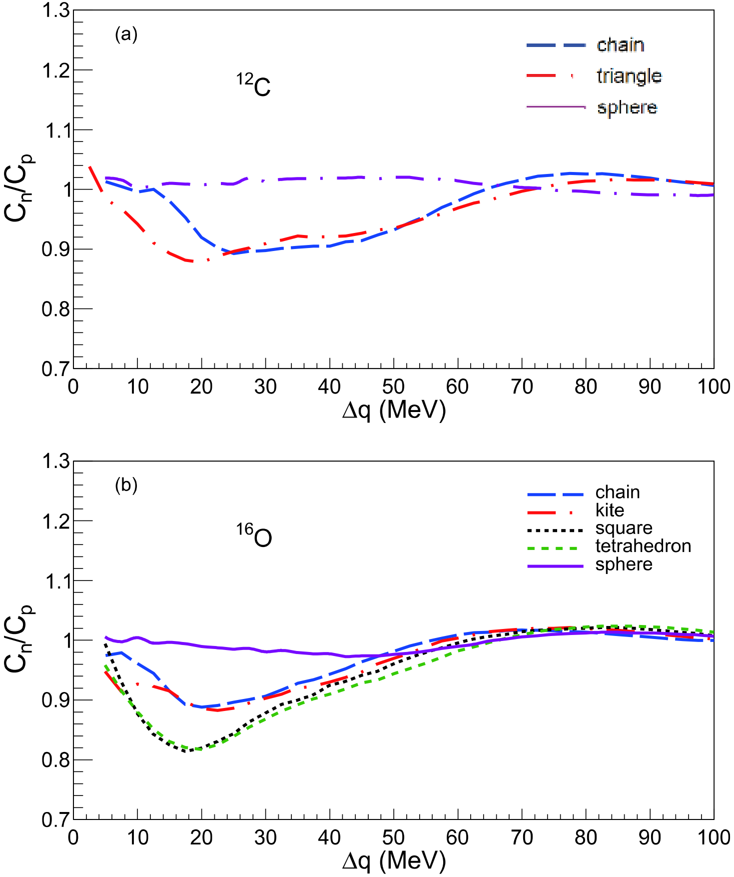
Emission time sequence of neutrons and protons as probes of α-clustering structure*

Bo-Song Huang(黄勃松)[1,2;1)] Yu-Gang Ma(马余刚)[1,2;2)]

中子-质子关联







$R(V_n>V_p) < R(V_n<V_p)$

Fig. 5. (color online) Ratio of correlation functions between C_n and C_p where C_n represents C_{np} gated with $v_n > v_p$ and C_p represents C_{np} gated with $v_n < v_p$ for 100 MeV induced three-body photodisintegration of ^{12}C (a) and ^{16}O (b). Dif-

R. Lednicky et al., How to measure which sort of particles was emitted earlier and which later, PLB 373, 30 (1996)

- **The α-clustering nuclei：** the neutron is on average emitted later than the proton
- **Non-clustering spherical structure:** neither the proton nor neutron has priority in the average emission time sequence。

Alpha-clustering effect on flows in $^{12}C+^{197}Au$@ 10GeV & 200A GeV

PHYSICAL REVIEW C **95**, 064904 (2017)

Nuclear cluster structure effect on elliptic and triangular flows in heavy-ion collisions

S. Zhang,[1] Y. G. Ma,[1,2,3,*] J. H. Chen,[1] W. B. He,[4] and C. Zhong[1]

Eur. Phys. J. A (2018) **54**: 161
DOI 10.1140/epja/i2018-12597-y

THE EUROPEAN PHYSICAL JOURNAL A

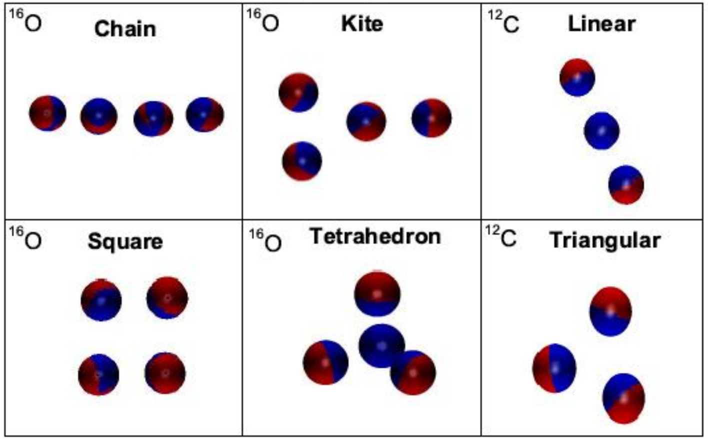
Regular Article – Theoretical Physics

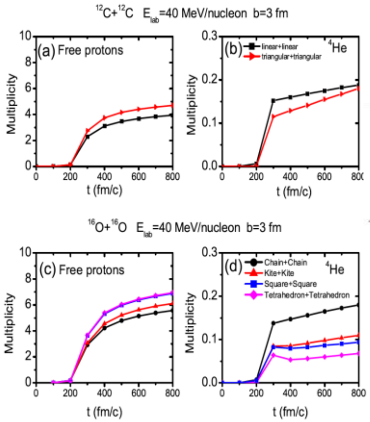
Collective flows of α-clustering $^{12}C + ^{197}Au$ by using different flow analysis methods

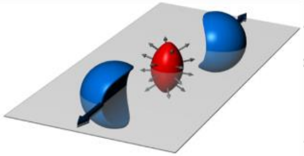
S. Zhang[1,2], Y.G. Ma[1,2,3,4,a], J.H. Chen[1,2], W.B. He[1], and C. Zhong[1,2]

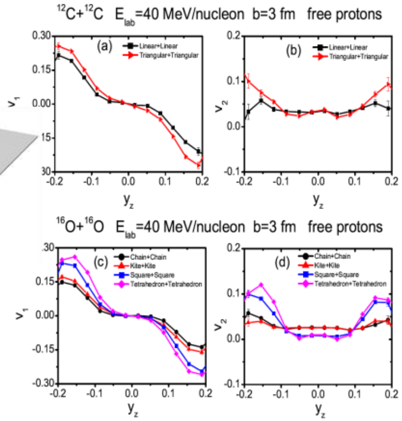
alpha集团效应对集体流的影响@低能: C+C, O+O

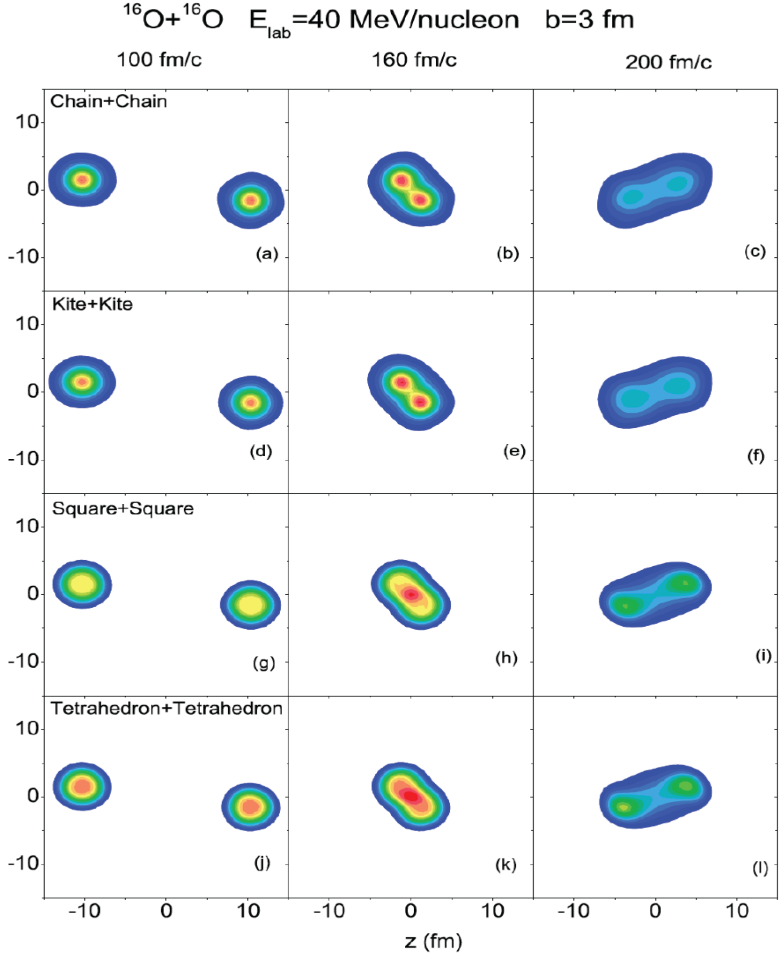
Different α clustering configurations in ^{16}O and ^{12}C







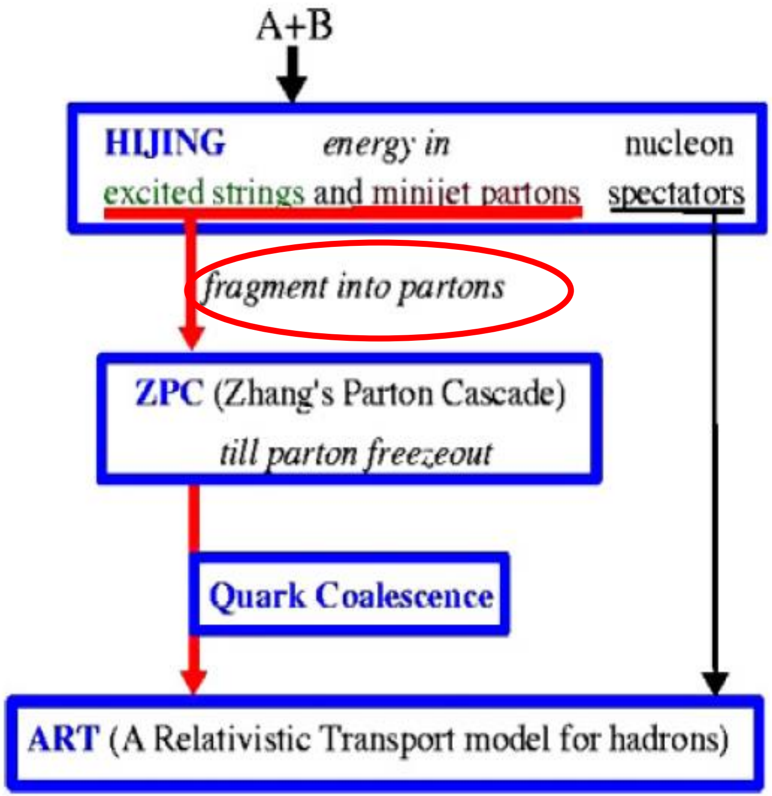


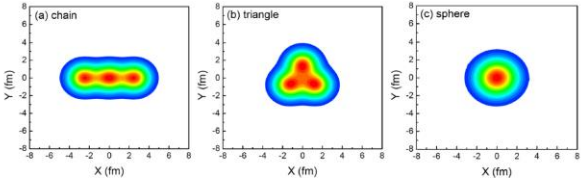


C.C. Guo, Y. G. Ma et al., Phys. Rev. C 99, 044607 (2019)

AMPT model {Melting version of AMPT}

A Multi-Phase Transport model, Ko & Lin et al.





EQMD distri. → AMPT distri.

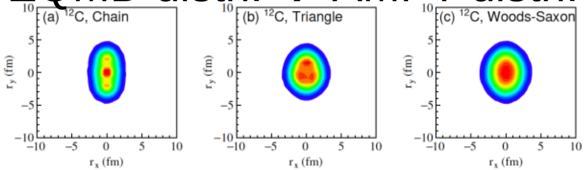
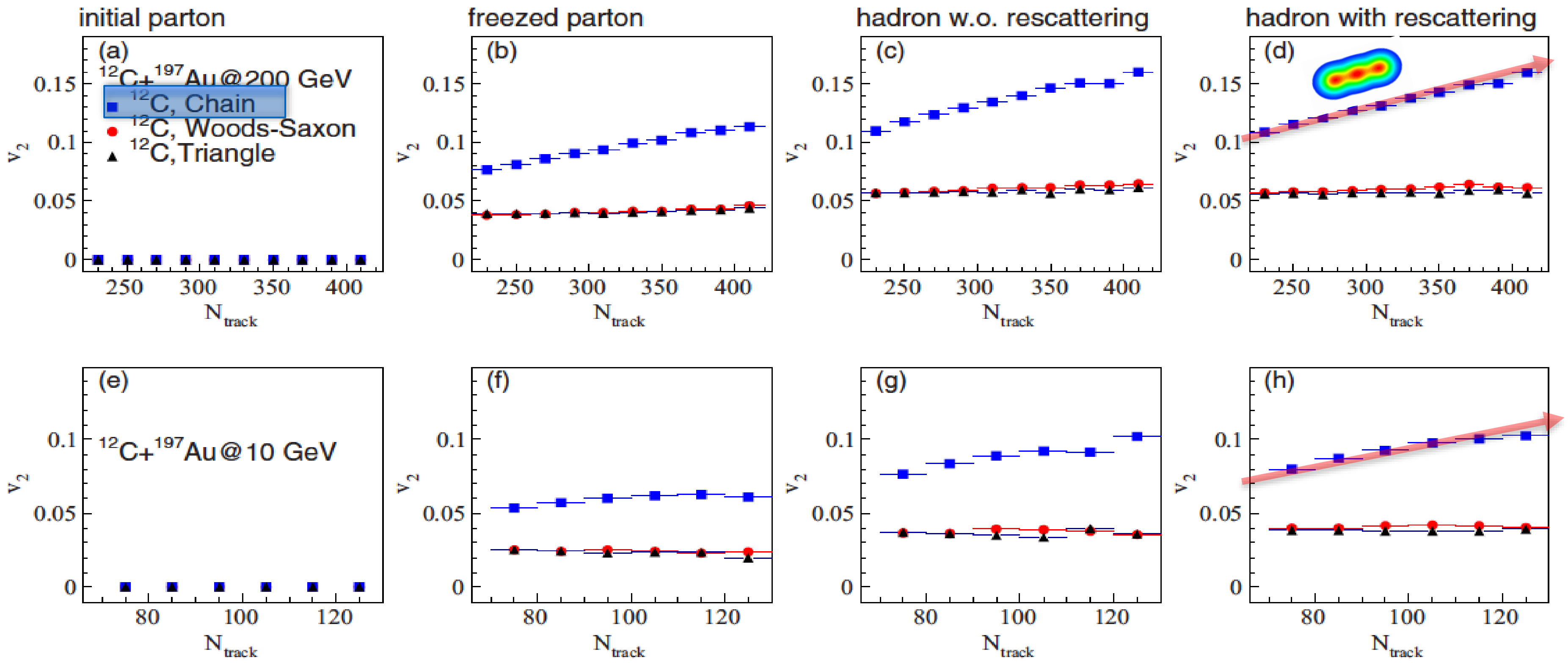


FIG. 1: Participant distributions of $^{12}C + ^{197}Au$ central collisions with different initial configurations of ^{12}C.

The distribution of the radial center of the α clusters in ^{12}C is assumed to be a Gaussian function, $e^{-0.5(\frac{r-r_c}{\sigma_{r_c}})^2}$, here r_c is the average radial center of an α cluster and σ_{r_c} is the width of the distribution. And the nucleon inside each α cluster will be given by Woods-Saxon distribution. The parameters of r_c and σ_{r_c} can be obtained from the EQMD calculation [41–43]. For the triangle structure, $r_c = 1.8$ fm and $\sigma_{r_c} = 0.1$ fm. For the chain structure, $r_c = 2.5$ fm, $\sigma_{r_c} = 0.1$ fm for two α clusters, and the other one will be at the center in ^{12}C.

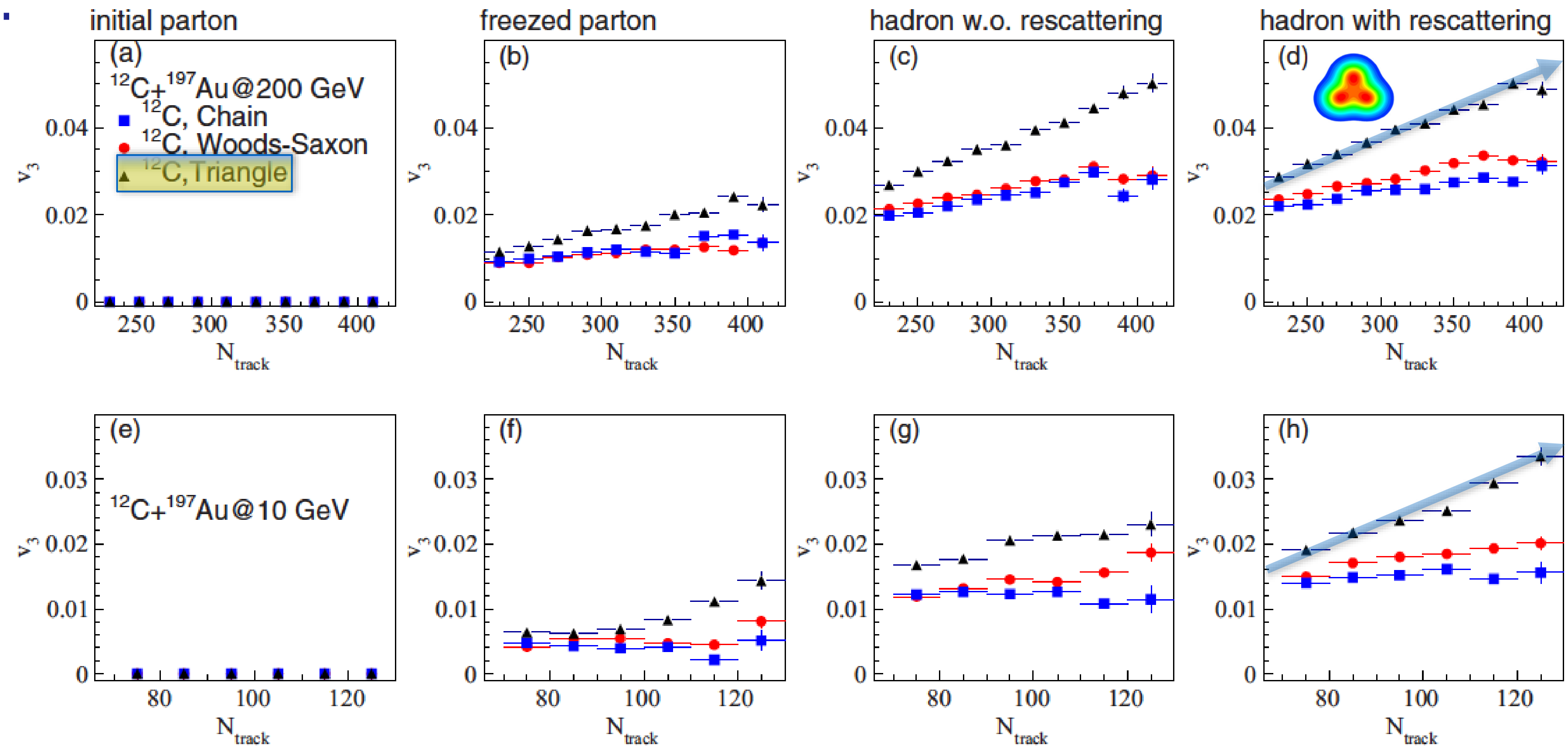
→ **Hadron rescattering**

Elliptic flow@^{12}C+Au



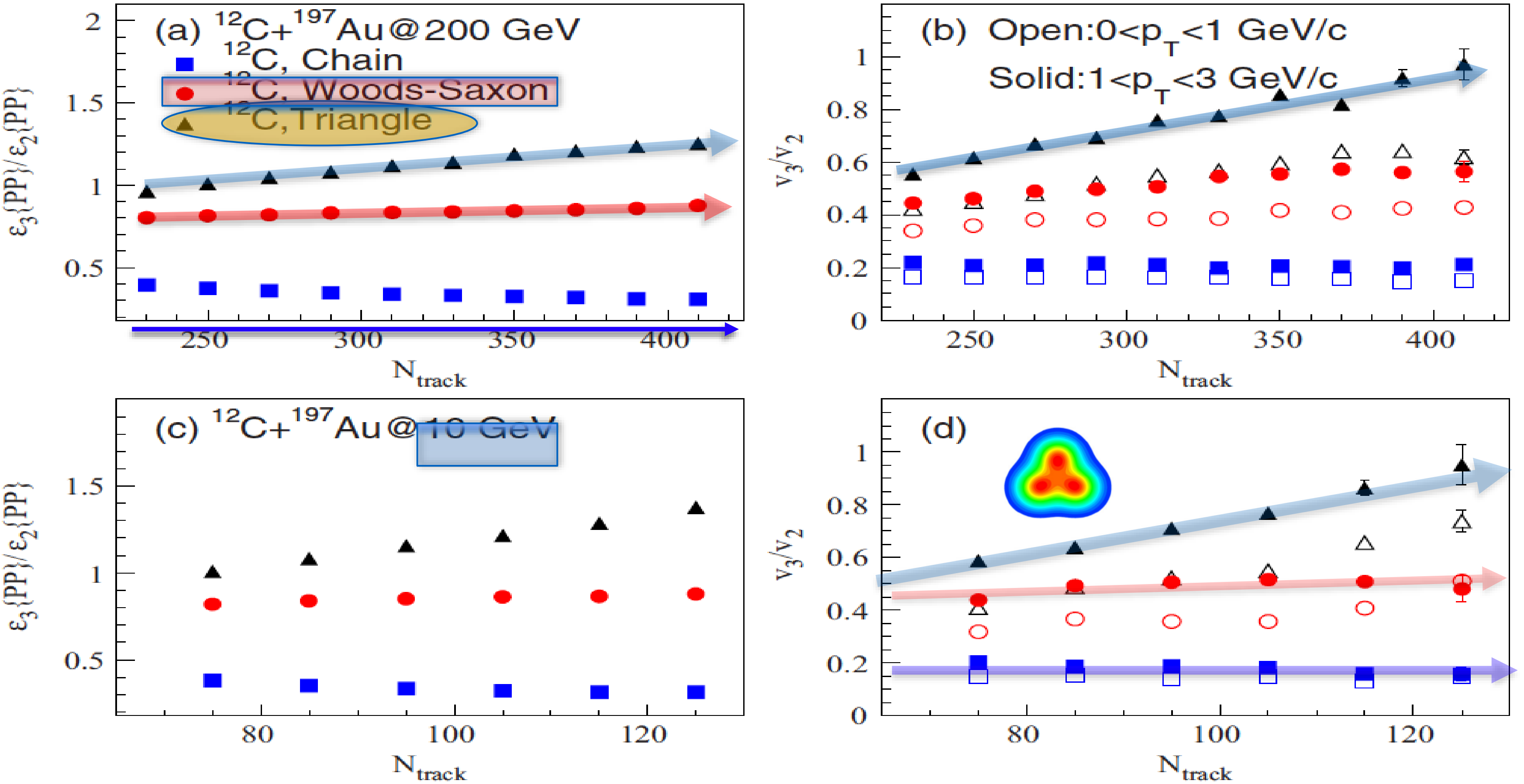
Elliptic flow (v2) is significant for **linear 3-alpha ^{12}C structure**

Triangular flow @ ^{12}C+Au



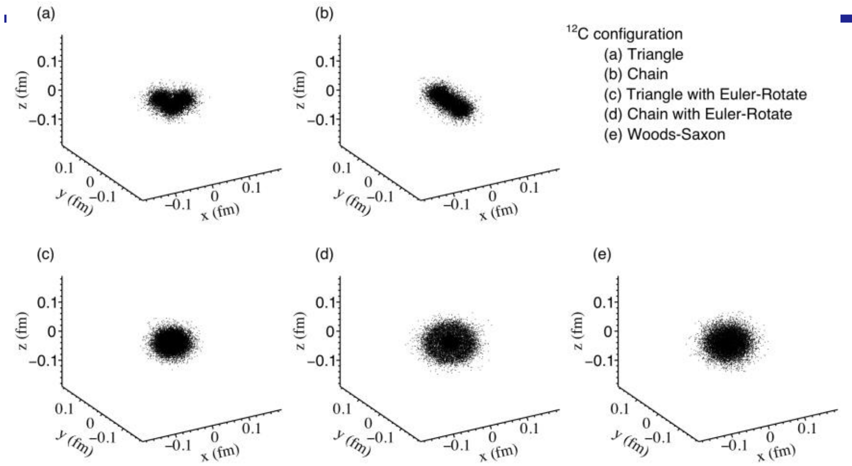
Triangular flow (v3) is significant for triangle 3-alpha 12C structure

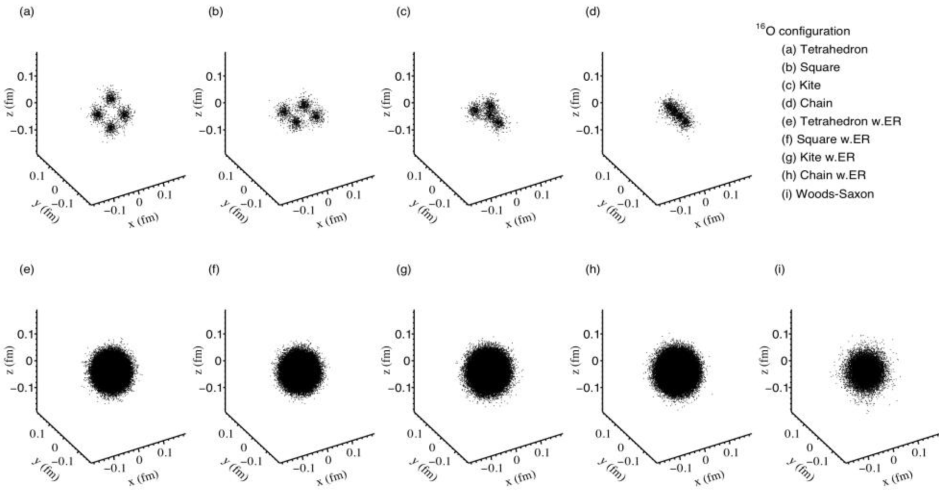
A sensitive probe to structure: e3/e2 & v3/v2

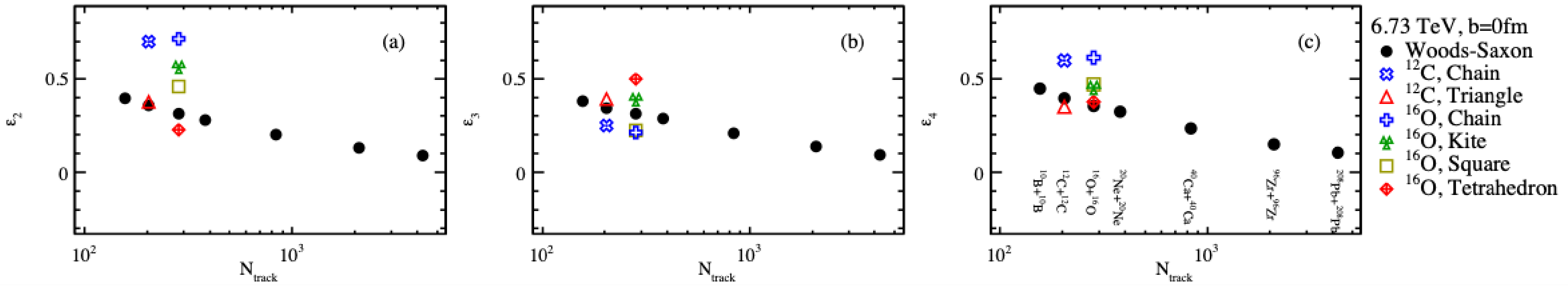


V3/v2 increases with the multiplicity → triangle 3-alpha 12C

α-clustering effect on eccentricity



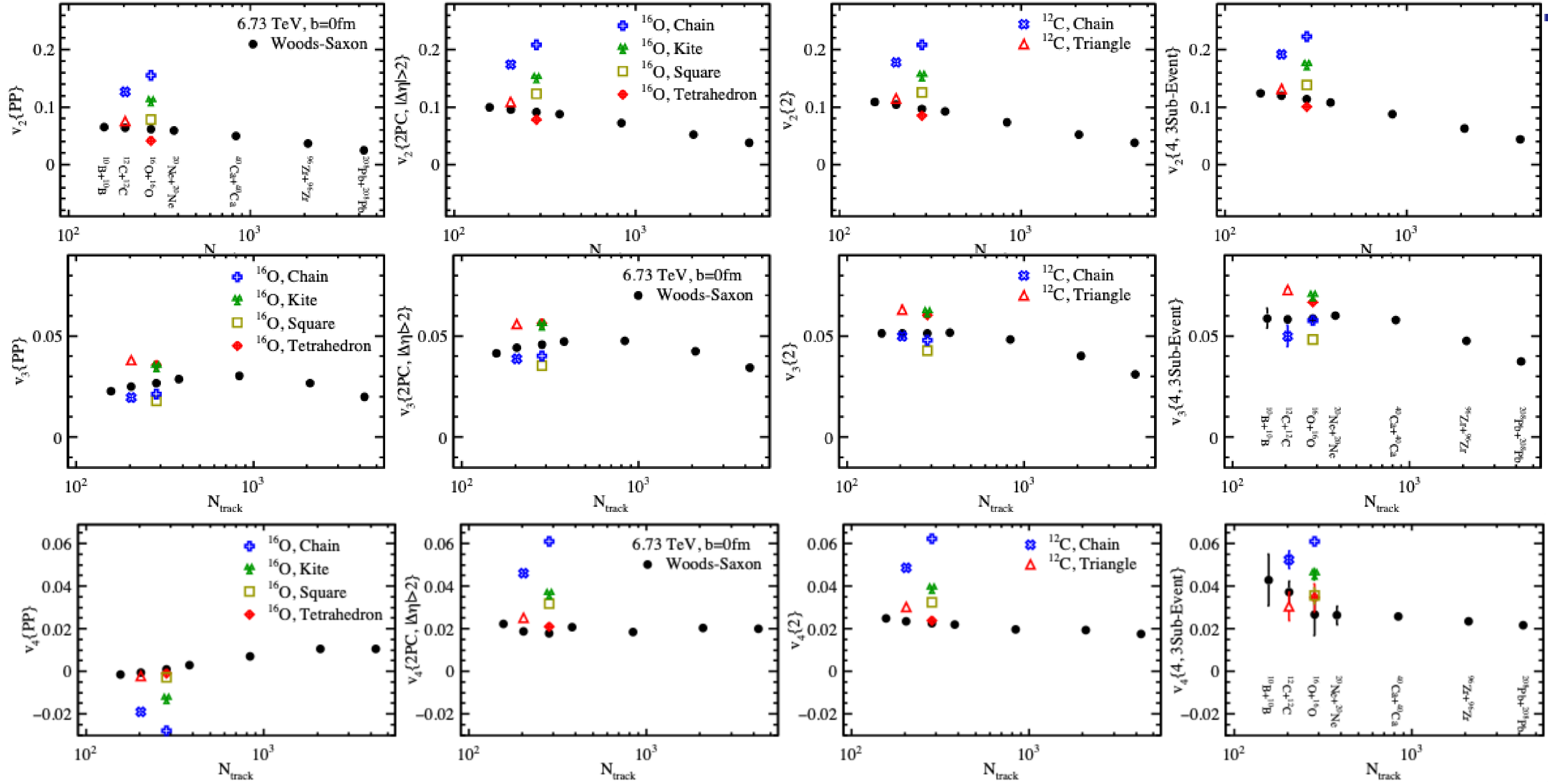




✓Sensitive to fluctuation

✓Also to intrinsic geometry (α-cluster structure)

α-clustering effect on collective flow



✓ Smoothly changing with increasing size of collision system (most central, Woods-Saxon distribution)

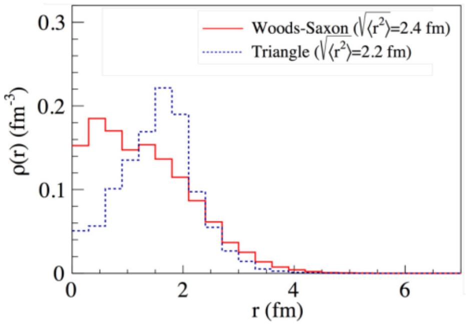
✓ Deviation from Woods-Saxon case for α-clustered initial system

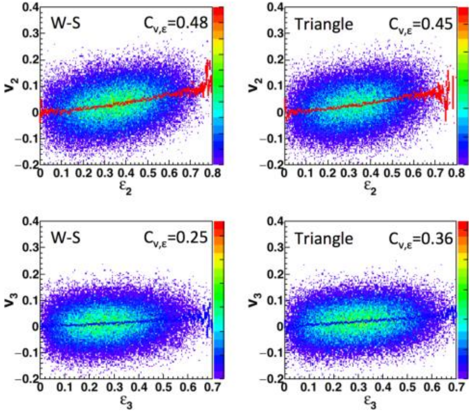
$^{12}C + ^{197}Au$系统中集体流的涨落(I)

PHYSICAL REVIEW C **102**, 014910 (2020)

Anisotropy fluctuation and correlation in central α-clustered $^{12}C + ^{197}Au$ collisions

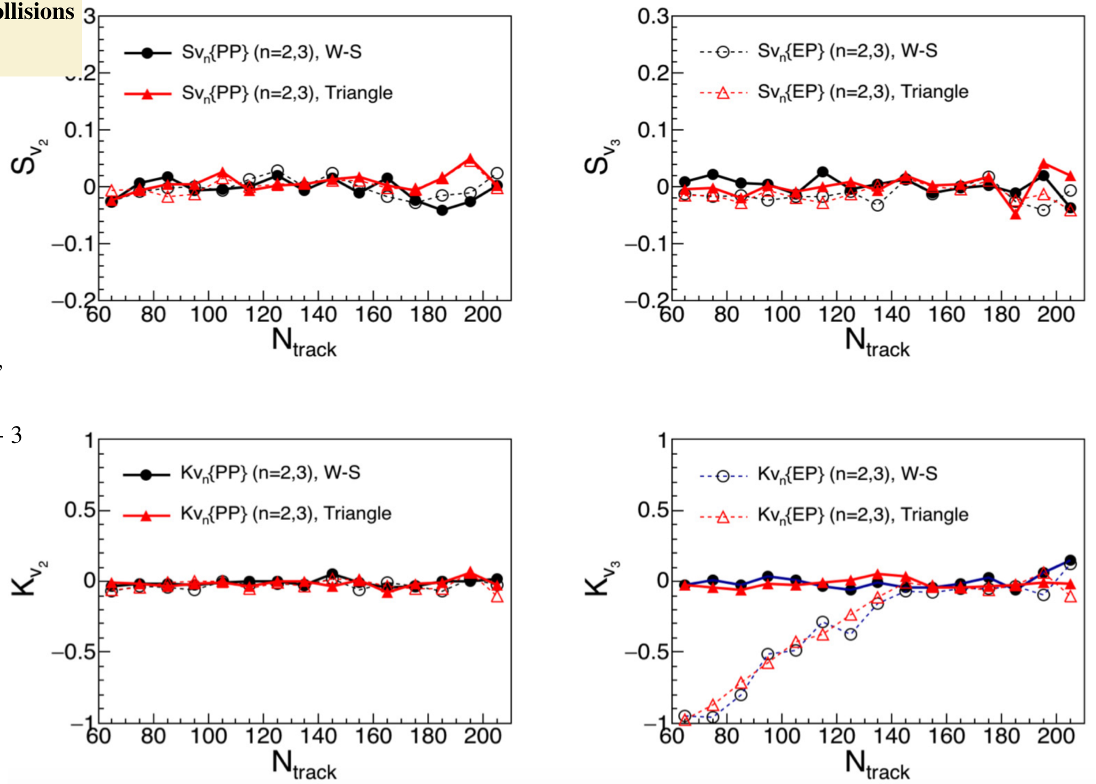
L. Ma[1,*] Y. G. Ma[1,2,†] and S. Zhang[1,‡]





$$S_{\varepsilon_n} = \frac{\langle(\varepsilon_n - \langle\varepsilon_n\rangle)^3\rangle}{\langle(\varepsilon_n - \langle\varepsilon_n\rangle)^2\rangle^{3/2}},$$

$$K_{\varepsilon_n} = \frac{\langle(\varepsilon_n - \langle\varepsilon_n\rangle)^4\rangle}{\langle(\varepsilon_n - \langle\varepsilon_n\rangle)^2\rangle^2} - 3$$



具有α-cluster构型的情形，涨落的中心度依赖性明显不同于在WS情形

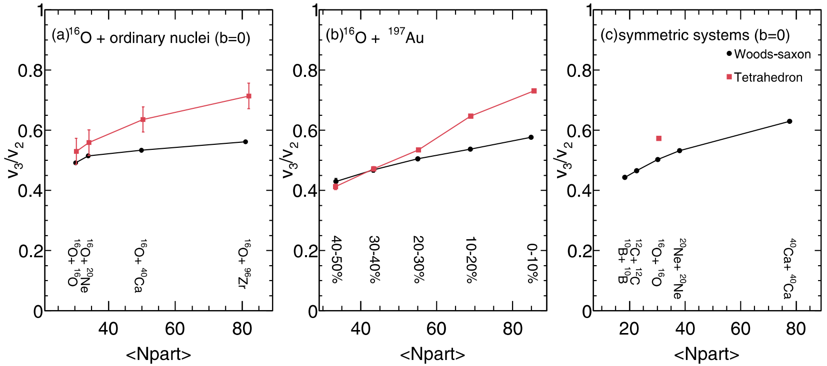
Alpha-cluster核碰撞的流、多重性关联

PHYSICAL REVIEW C **102**, 054907 (2020)

Signatures of α-clustering in ^{16}O by using a multiphase transport model

Yi-An Li (李逸安),[1,2,3] Song Zhang (张松),[2,*] and Yu-Gang Ma (马余刚)[2,1,†]

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$



- ✓ 非对称系统扫描，v_3/v_2两种构型具有明显的差别，WS构型非常平坦
- ✓ ^{16}O $+^{197}$ Au中心度依赖，高多重数下v_3/v_2的比，两种构型具有明显的差别
- ✓ 对称系统扫描，明显看到四面体构型的 ^{16}O $+^{16}$ O系统的v_3/v_2偏离系统学

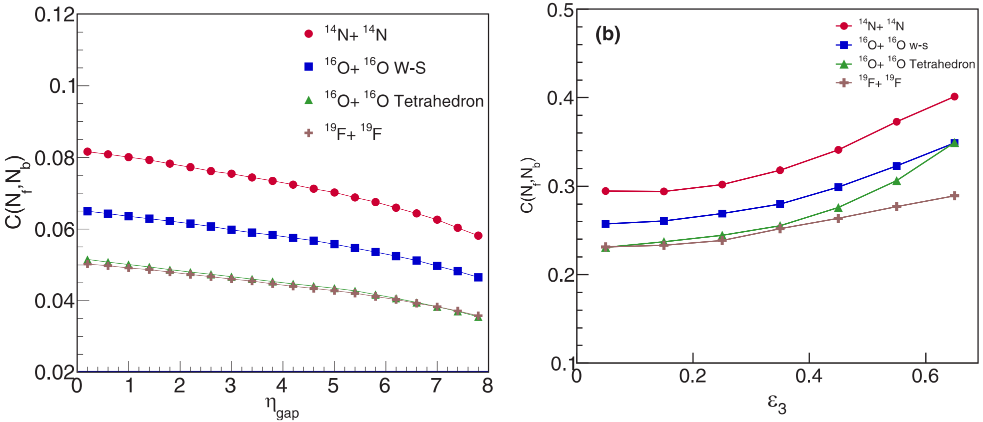
PHYSICAL REVIEW C **104**, 044906 (2021)

System evolution of forward-backward multiplicity correlations in a multiphase transport model

Yi-An Li (李逸安)
Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China;
Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China;
and School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

Dong-Fang Wang (王东方), Song Zhang (张松),* and Yu-Gang Ma (马余刚)†
Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China

$$C(N_f, N_b) = \frac{\langle N_f N_b\rangle - \langle N_f\rangle\langle N_b\rangle}{\langle N_f\rangle\langle N_b\rangle}$$



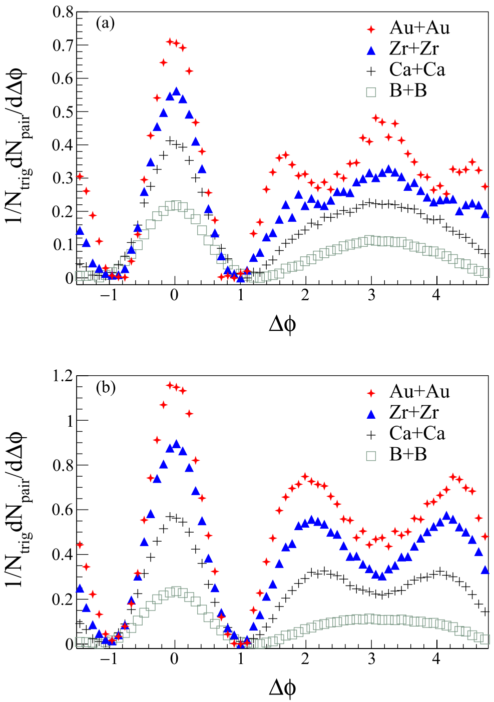
- ✓ 对称系统扫描，明显看到四面体构型的 ^{16}O $+^{16}$ O系统的C(Nf,Nb)偏离排序

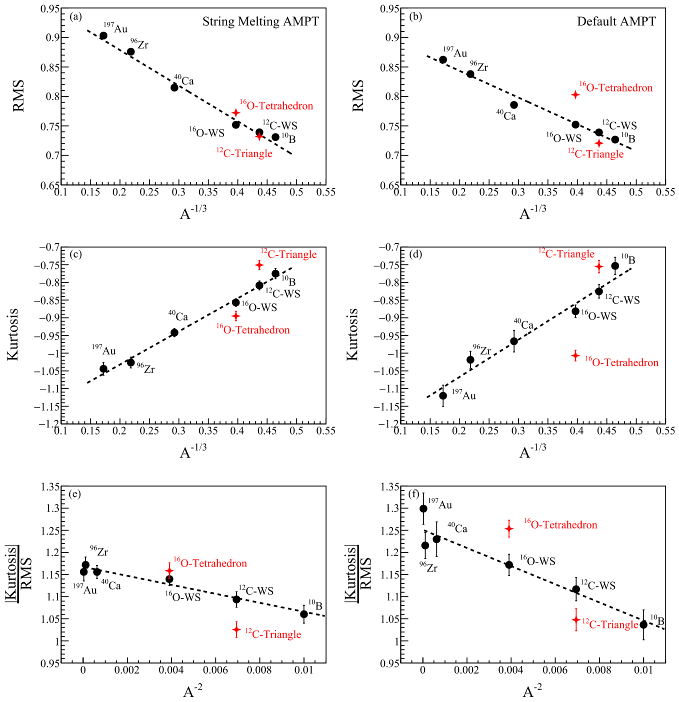
System dependence of away-side broadening and α-clustering light nuclei structure effect in dihadron azimuthal correlations

Yuan-Zhe Wang (王远哲)[a], Song Zhang (张松)[a,b], Yu-Gang Ma (马余刚)[a,b,*]

[a] *Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China*
[b] *Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China*

Physics Letters B 831 (2022) 137198

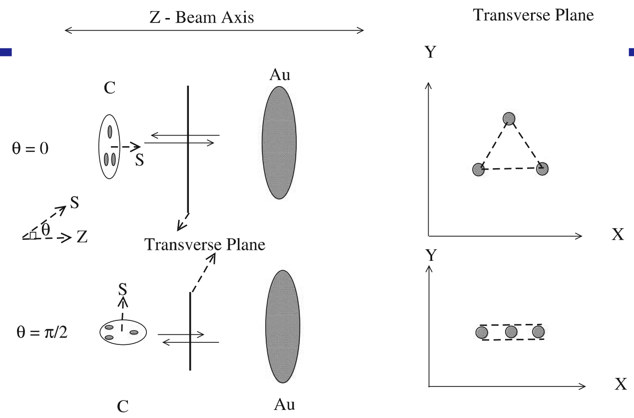


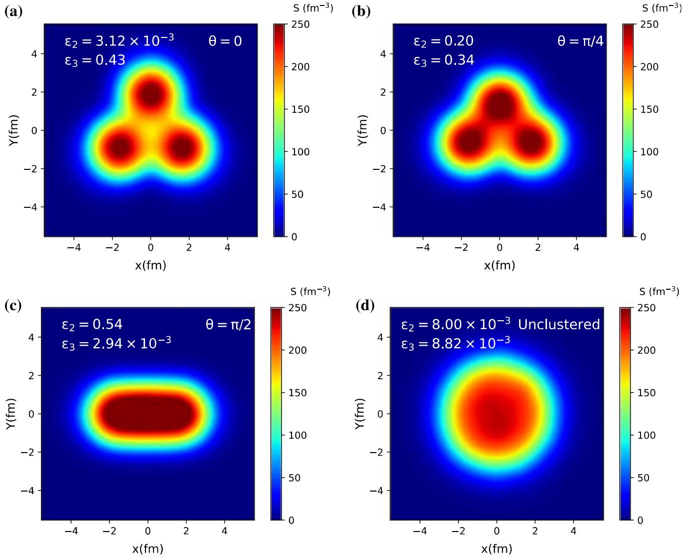


Ratio of Kurtosis to RMS on away-side, potential observable to distinguish -cluster structure from normal nuclear structures

System scan of two-particle azimuthal correlation and α-cluster effect

Alpha cluster与热光子

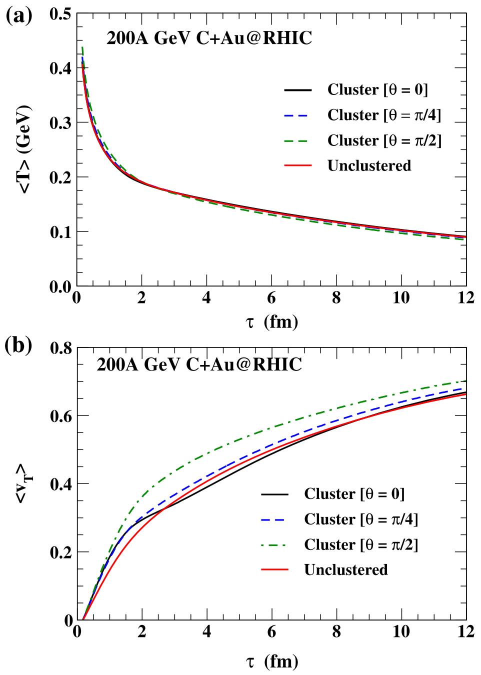


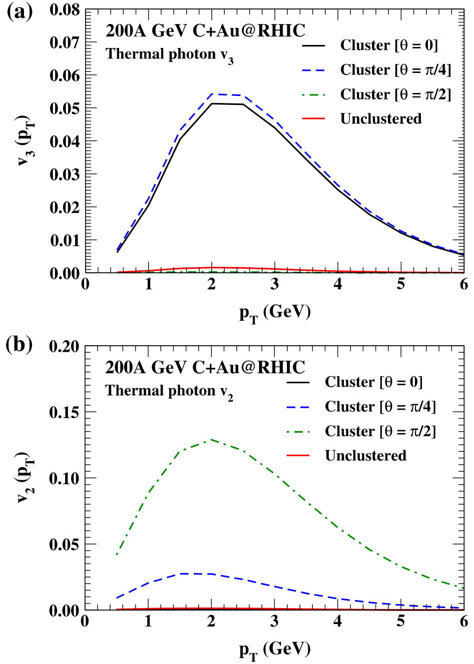


Eur. Phys. J. A (2021) 57:134
https://doi.org/10.1140/epja/s10050-021-00441-8
THE EUROPEAN PHYSICAL JOURNAL A
Check for updates
Regular Article -Theoretical Physics

Thermal photons as a sensitive probe of α-cluster in C + Au collisions at the BNL Relativistic Heavy Ion Collider

Pingal Dasgupta[1], Guo-Liang Ma[1,a], Rupa Chatterjee[2,b], Li Yan[1,c], Song Zhang[1], Yu-Gang Ma[1,d]

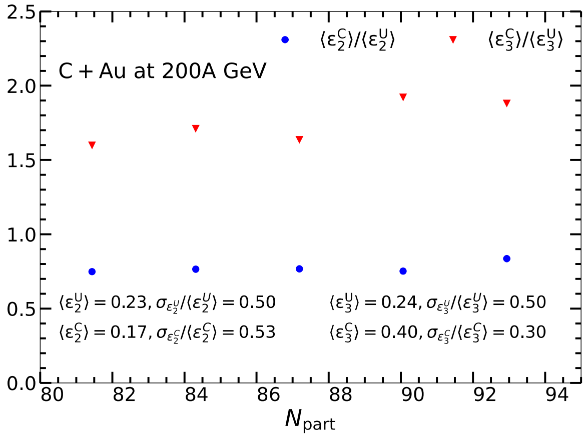


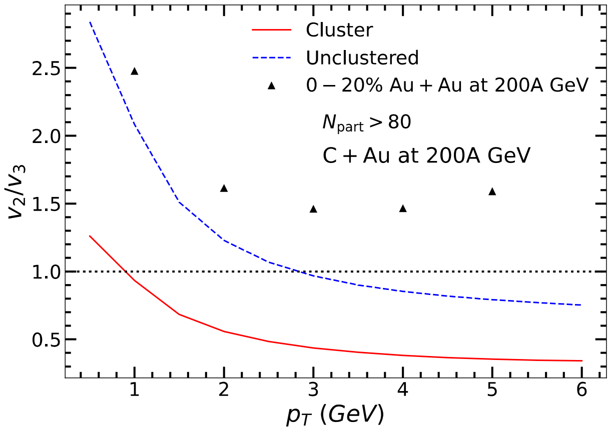


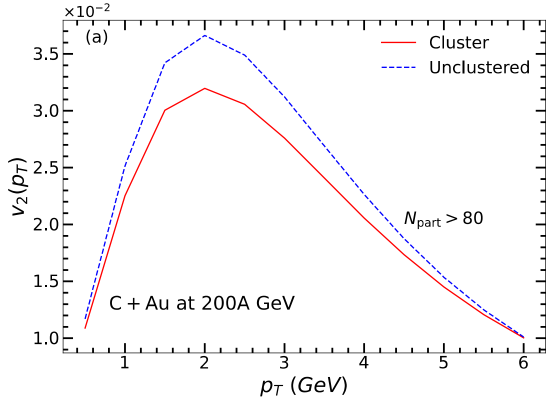
PHYSICAL REVIEW C **107**, 044908 (2023)

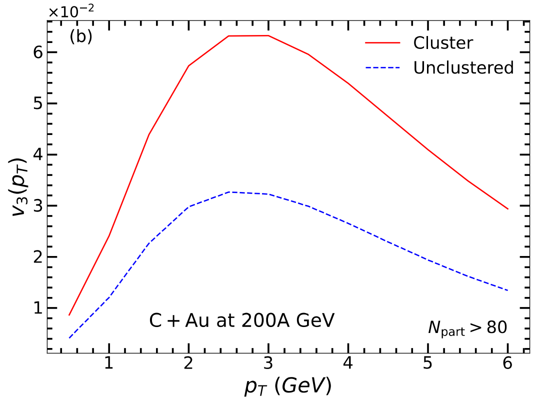
Production and anisotropic flow of thermal photons in collisions of α-clustered carbon with heavy nuclei at relativistic energies

Pingal Dasgupta,[1,2] Rupa Chatterjee,[3,4,*] and Guo-Liang Ma (马国亮)[1,2,†]
[1]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China





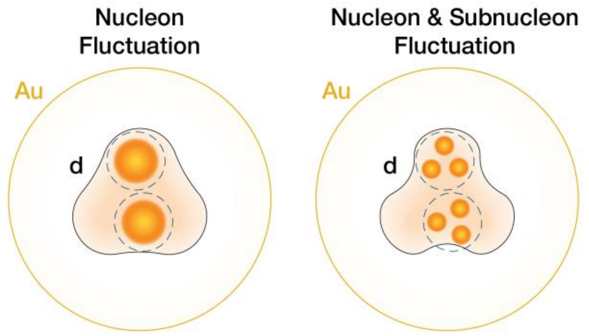


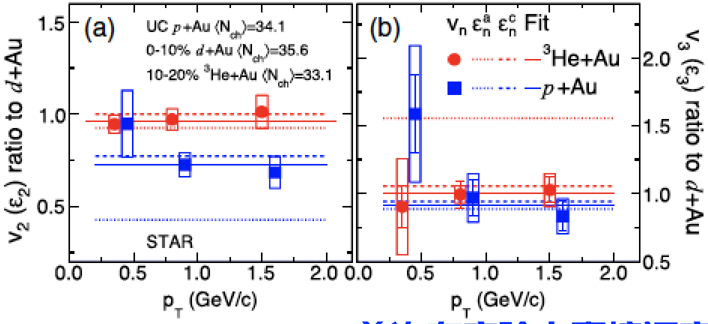


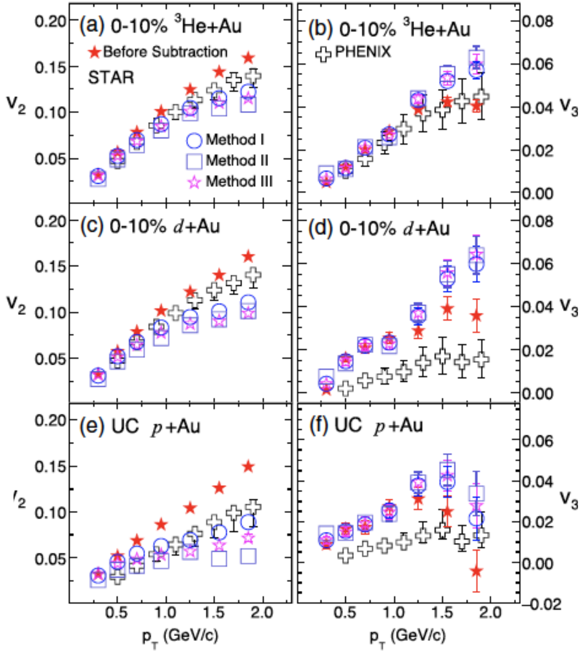
- Initial state models (MCG or TRENTO) show similar difference in initial eccentricities between clustered and unclustered case.
- The photon v3 for the clustered case is found to be twice as large as the same obtained for the unclustered case. The v2 does not show much difference for the two cases.
- The ratio v2/v3 for the unclustered case is found to be about twice large as the clustered case.

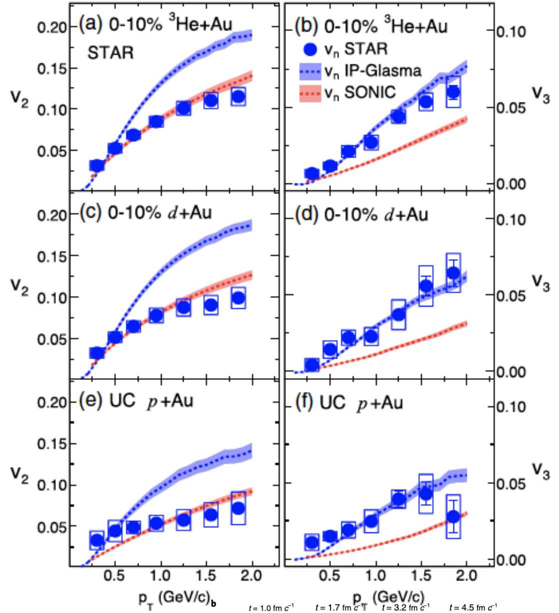
小系统碰撞集体流：QGP的形状测量

小系统碰撞中QGP的形状是跟大系统核-核碰撞中的一样由核子位置信息主导，还是由核子中的亚核子结构信息来确定？

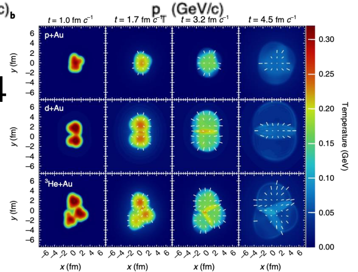








PNENIX, Nat. Phys.15 (2019) 214



首次在实验上直接证实小碰撞系统中QGP的形状由亚核子结构主导。

STAR Collaboration, Physical Review Letters 130, 242301 (2023)

- Alpha-clustering effect on HBT radii in head-on $^{12}C+^{197}Au$@ 200A GeV

Formulation of HBT correlation

Eur. Phys. J. A (2020) 56:52
https://doi.org/10.1140/epja/s10050-019-00002-0

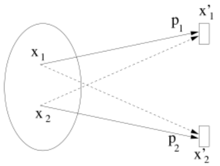
THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Theoretical Physics

Clustering structure effect on Hanbury-Brown–Twiss correlation in ^{12}C+^{197}Au collisions at 200 GeV

Junjie He[1,2], Song Zhang[3,a], Yu-Gang Ma[1,3,b], Jinhui Chen[3], Chen Zhong[3]

- 1956 Hanbury Brown and Twiss
- 1960 Goldhaber-Goldhaber-Lee-Pais effect



$$C(\vec{q},\vec{K}) = 1 \pm \left| \frac{\int d^4x e^{i\vec{q}\cdot(\vec{x}-\vec{\beta}t)} S(x,K)}{\int d^4x S(x,K)} \right|^2, \quad (1)$$

$$C(\vec{q},\vec{K}) = 1 + \lambda(\vec{K})\exp(-\sum_{i,j=o,s,l} R^2_{ij}(\vec{K})q_iq_j). \quad (2)$$

$$R^2_s(K_\perp,\Phi,Y) = \langle\tilde{x}^2\rangle\sin^2\Phi + \langle\tilde{y}^2\rangle\cos^2\Phi - \langle\tilde{x}\tilde{y}\rangle\sin 2\Phi, \quad (3)$$

$$\begin{aligned} R^2_o(K_\perp,\Phi,Y) = &\langle\tilde{x}^2\rangle\cos^2\Phi + \langle\tilde{y}^2\rangle\sin^2\Phi + \beta^2_\perp\langle\tilde{t}^2\rangle \\ &- 2\beta_\perp\langle\tilde{t}\tilde{x}\rangle\cos\Phi - 2\beta_\perp\langle\tilde{t}\tilde{y}\rangle\sin\Phi \\ &+ \langle\tilde{x}\tilde{y}\rangle\sin 2\Phi, \end{aligned} \quad (4)$$

$$R^2_l(K_\perp,\Phi,Y) = \langle(\tilde{z}-\beta_l\tilde{t})^2\rangle, \quad (5)$$

where $\tilde{x}_\mu = x_\mu - \langle x_\mu\rangle$, $\beta_\perp = p_T/E$, and $\beta_l = p_z/E$.

$$\Phi' = \Phi - \Psi_{EP}, \quad (6)$$

$$\Psi_{EP} = \frac{\text{atan2}(\langle r^2\sin(2\phi_{\text{part}})\rangle, \langle r^2\cos(2\phi_{\text{part}})\rangle) + \pi}{2}, \quad (7)$$

$$dY/d(\Phi-\Psi_{EP}) = a_0 + a_1 cos[2(\Phi-\Psi_{EP})], \quad (8)$$

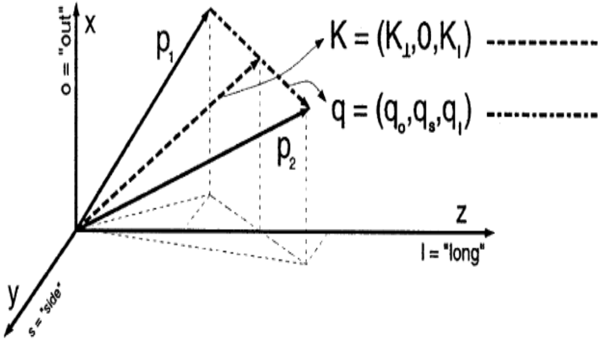
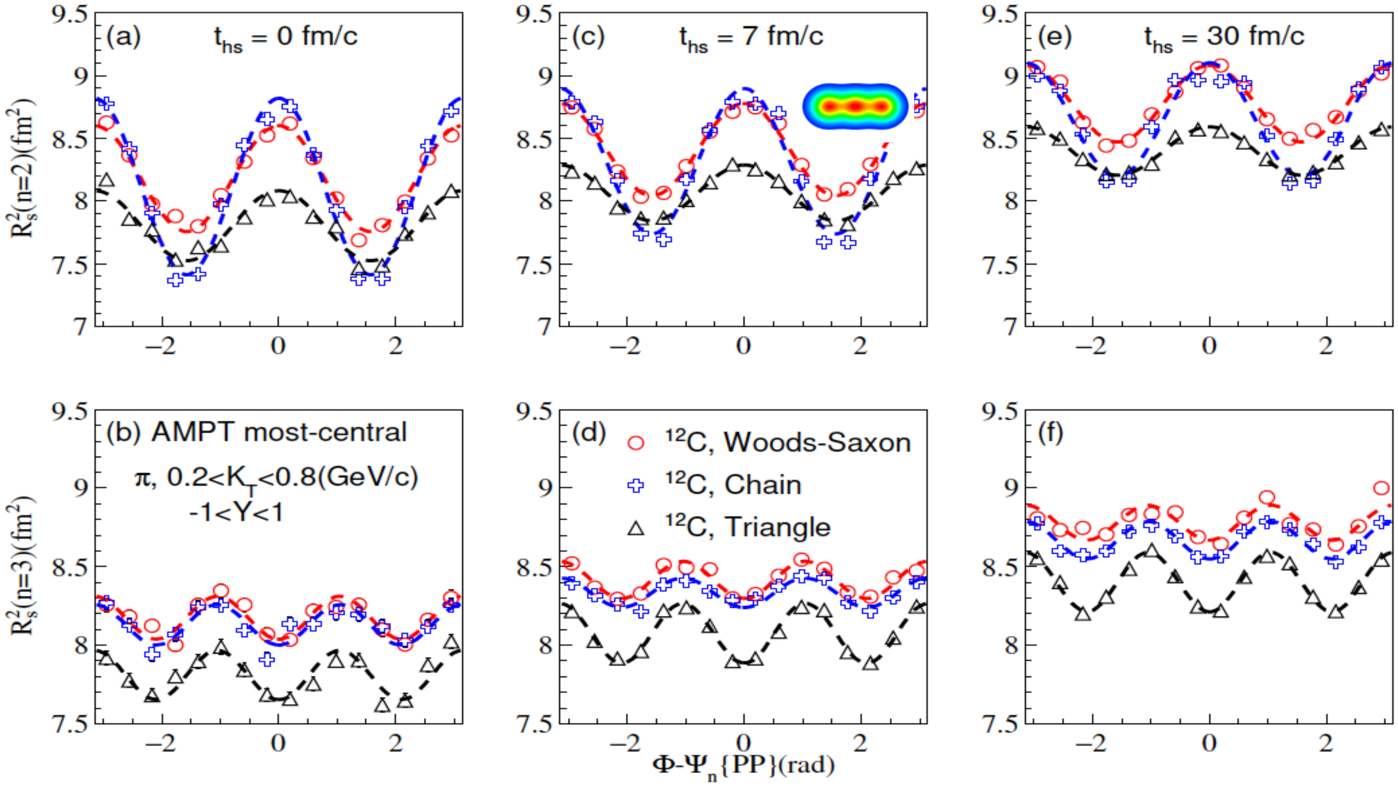


Fig. 3.1. The osl coordinate system takes the longitudinal (long) direction along the beam axis. In the transverse plane, the "out" direction is chosen parallel to the transverse component of the pair momentum $\boldsymbol{K}_\perp$, the remaining Cartesian component denotes the "side" direction.

Azimuthal dependent HBT radii (1)

Hadron rescattering time (AFTER hadronization)

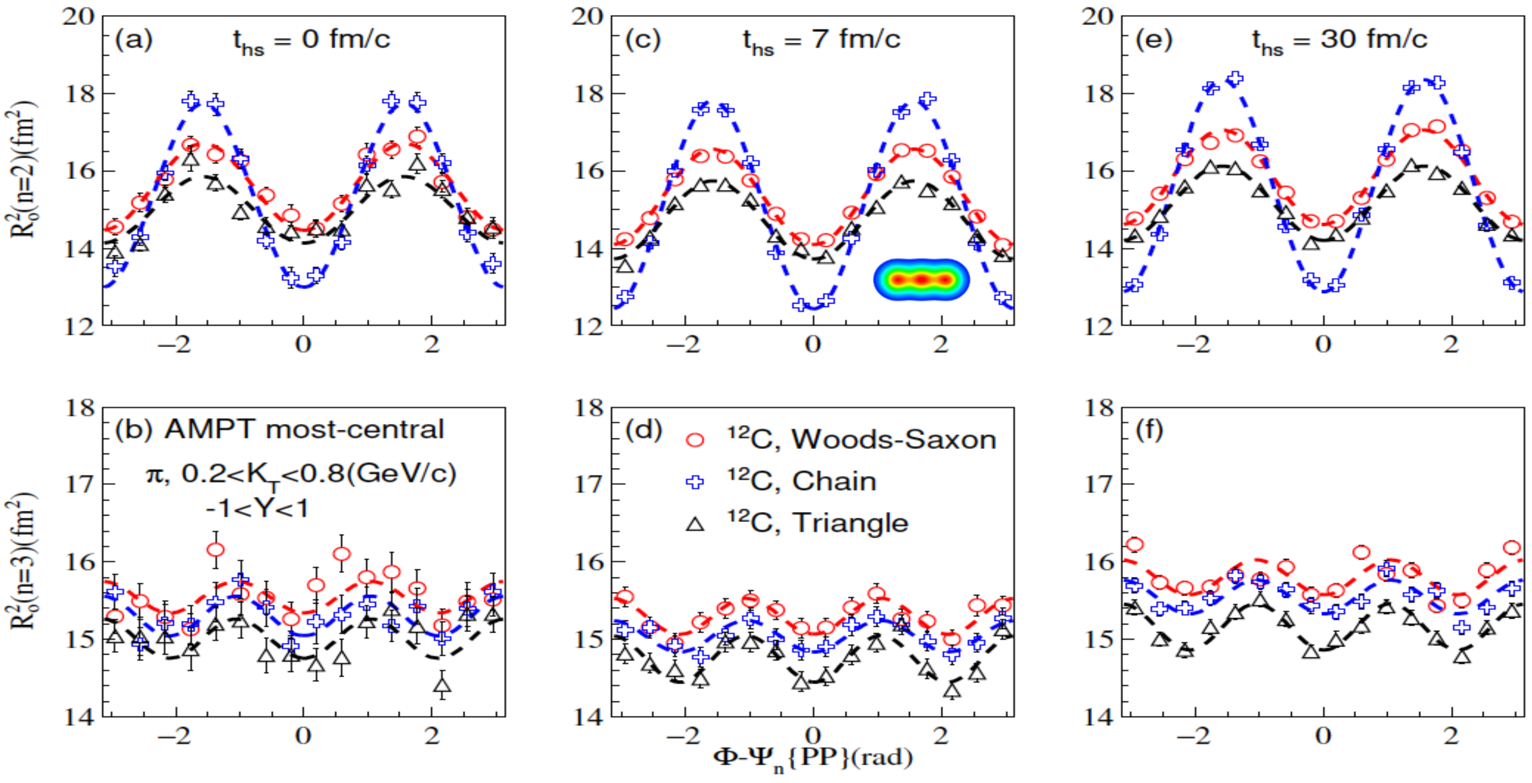


Pion-pion correlation

pion-pion correlation for the Chain structure shows a stronger azimuthal dependence

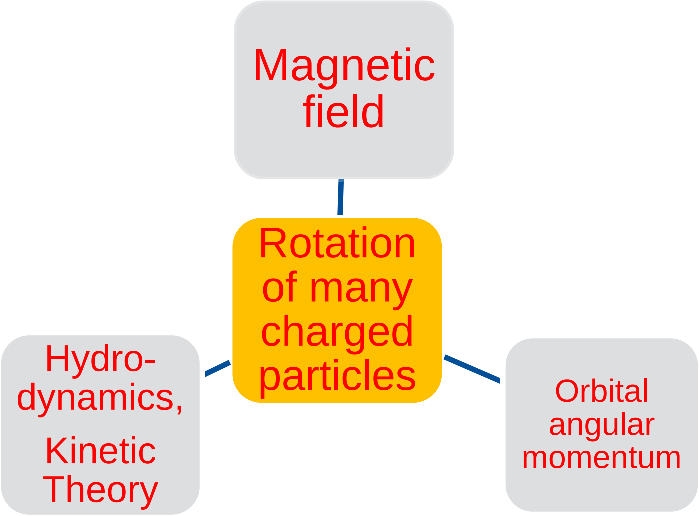
Azimuthal dependent HBT radii (2)

Hadron rescattering time



R0^2 of Pi-pi correlation for the chain structure shows a stronger azimuthal dependence!

□Alpha-clustering effect on EM fields in $^{12}C+^{197}Au$@ 200A GeV

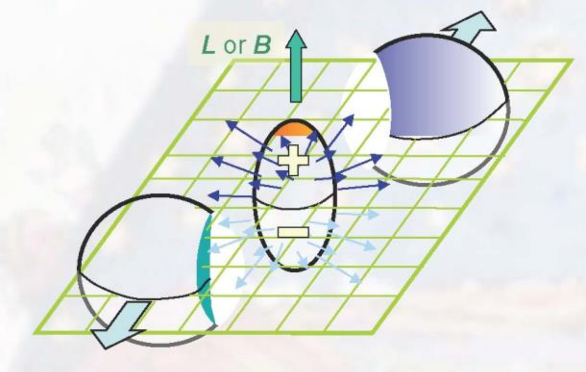


Magnetic fields in heavy ion collision

- **High energy HIC**

$$v = \sqrt{(s-m_n^2)/s} \sim 1 - \frac{m_n^2}{2s}$$
$$\gamma = 1/\sqrt{1-v^2/c^2} \sim \frac{\sqrt{s}}{m_n}$$

- **Electric field in cms frame of nucleus,** $\mathbf{E} = \frac{Ze}{R^2}\hat{\mathbf{r}}$



- **Boost to Lab frame (v_z= 0.99995 c for 200GeV),** Scale of strong interaction

$$\mathbf{B} = -\gamma \mathbf{v}_z \times \mathbf{E} \rightarrow eB \rightarrow 2\gamma v_z \frac{Ze^2}{R^2} \sim \boxed{1.3 m_\pi^2} \sim 2.6 \times 10^{18}\ \mathrm{Gs}$$

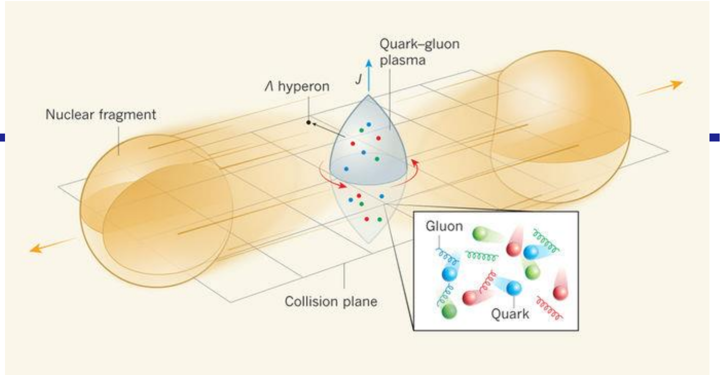
Kharzeev, McLerran, Warringa (2008), Skokov (2009); Deng & Huang (2012),; Bloczynski,Huang, Zhang, Liao (2012); ……

PHYSICAL REVIEW C **99**, 054906 (2019)

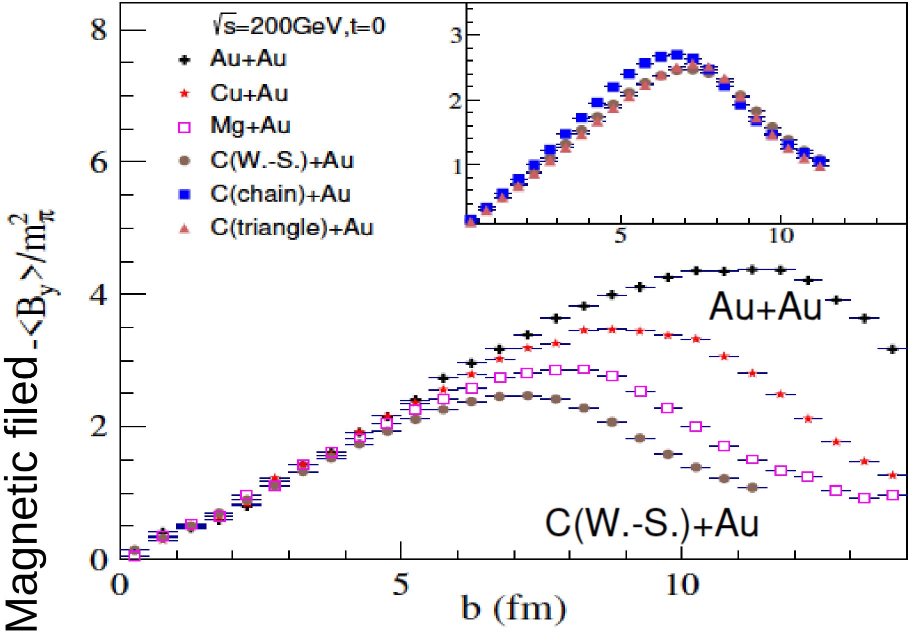
Electromagnetic field from asymmetric to symmetric heavy-ion collisions at 200 GeV/c

Yi-Lin Cheng (程艺琳)
Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
and University of Chinese Academy of Sciences, Beijing 100049, China

Song Zhang (张松),* Yu-Gang Ma (马余刚),† Jin-Hui Chen (陈金辉), and Chen Zhong (钟晨)



Chain structure shows a little stronger magnetic field

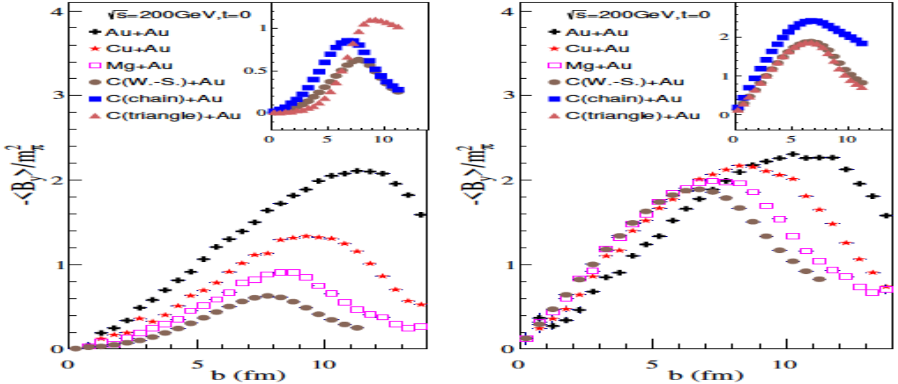


Lienard-Wiechert potential to calculate the electromagnetic fields for A + ^{197}Au@200GeV, AMPT model

$$e\vec{E}(t,\vec{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\vec{R}_n - R_n\vec{v}_n}{(R_n - \vec{R}_n\cdot\vec{v}_n)^3}(1-v_n^2),$$

$$e\vec{B}(t,\vec{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\vec{V}_n \times \vec{R}_n}{(R_n - \vec{R}_n\cdot\vec{v}_n)^3}(1-v_n^2),$$

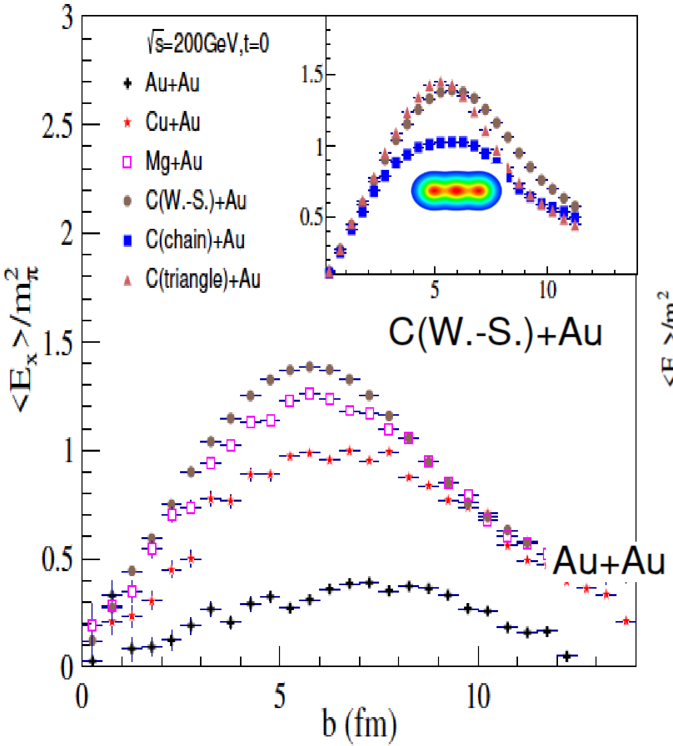
Projectile-side   Target (Au)-side



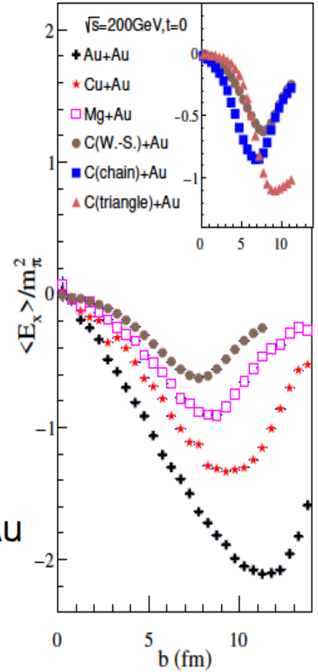
The larger (the more asy. N/Z) the projectile, the stronger the <-By>

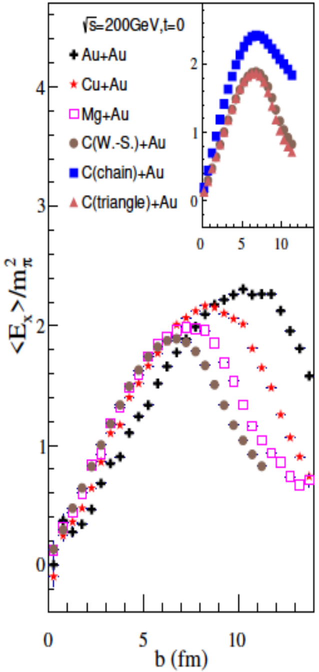
Electric field

Chain structure shows weaker electric field



Projectile-side   Target (Au)-side





- ✓ <E_x>: the asymmetric projectile and target nuclear collisions produce stronger electric field than symmetrical collision system
- ✓ -<B_y>: the magnetic field will be in the reverse trend
- ✓ α-cluster effect at semi-central collisions for chain structure

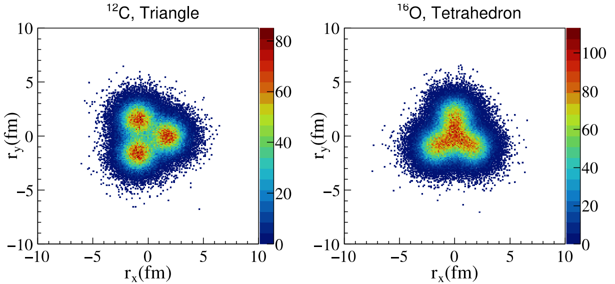
The larger (more asym. N/Z) the projectile, the weaker the <Ex>

Alpha-cluster初态与机器学习

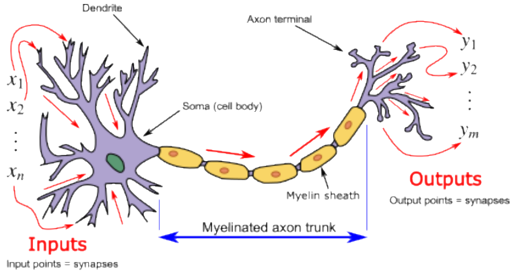
PHYSICAL REVIEW C **104**, 044902 (2021)

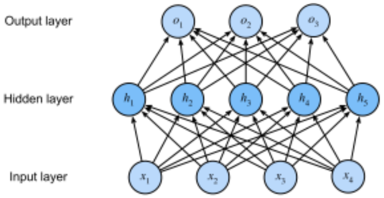
Machine-learning-based identification for initial clustering structure in relativistic heavy-ion collisions

Junjie He (何俊杰),[1,2] Wan-Bing He (何万兵),[3,*] Yu-Gang Ma (马余刚),[3,†] and Song Zhang (张松)[3]

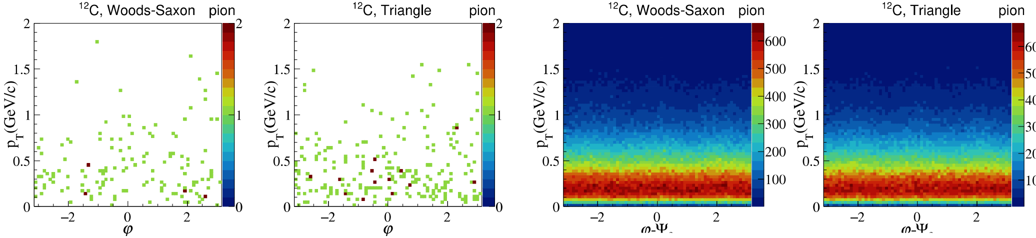


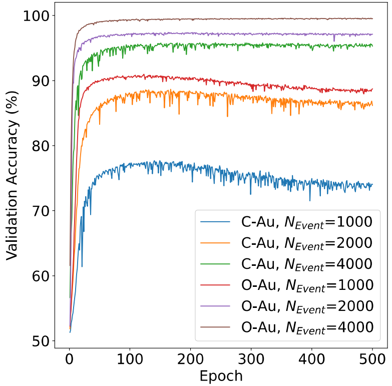
5.1 团簇构型的 ^{12}C 和 ^{16}O 在横平面的核子分布，取样自 10000 个事件。

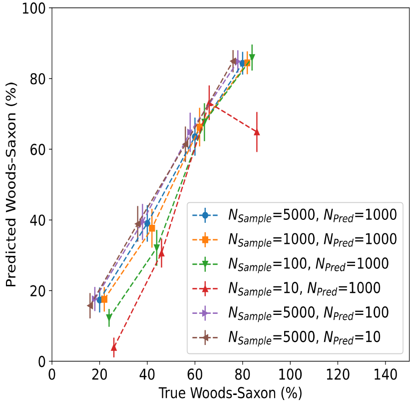




- 8×10^5 central $^{12}C/^{16}O + ^{197}Au$ collisions for each configuration at $\sqrt{s_{NN}} = 200$ GeV from AMPT
- Cut: $|y| < 1$







PHYSICAL REVIEW C **107**, 064909 (2023)

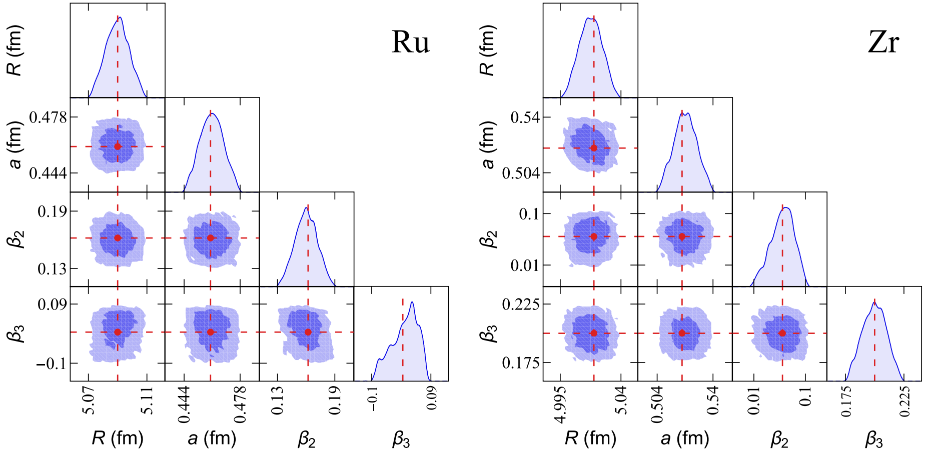
Examination of nucleon distribution with Bayesian imaging for isobar collisions

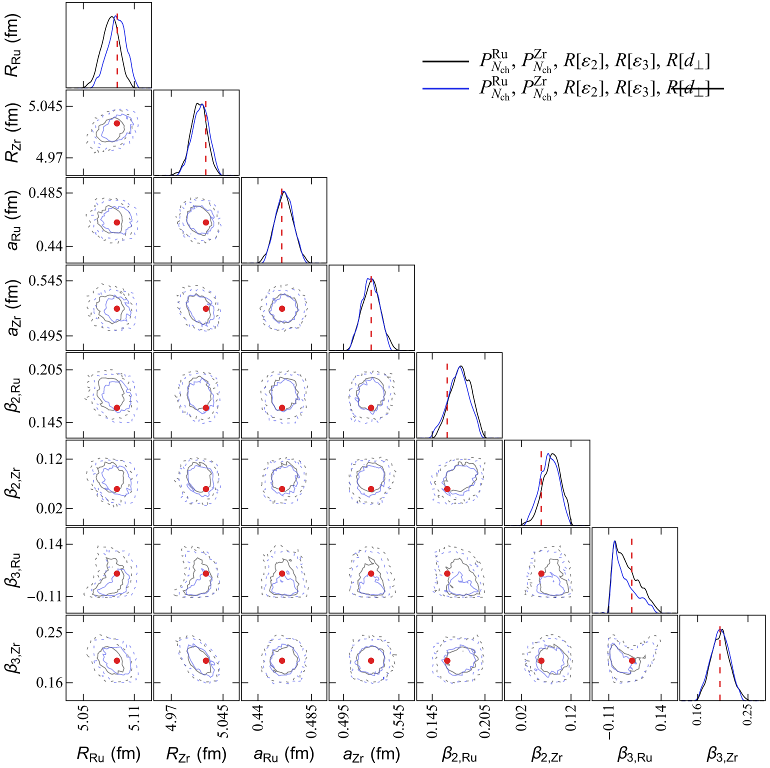
Yi-Lin Cheng[1,2,3,4] Shuzhe Shi[5,6,*] Yu-Gang Ma,[3] Horst Stöcker[1,7,8] and Kai Zhou[1,†]

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+\exp\left[r - R(\theta,\phi)\right]/a},$$

where

$$R(\theta,\phi) = R_0\left(1 + \beta_2 Y_2^0 + \beta_3 Y_3^0 + \beta_4 Y_4^0\right) \qquad (2)$$





- A Bayesian inference with employing the Monte Carlo Glauber model as an estimator of the mapping from nuclear structure to the final state observables and to provide the mock data for reconstruction.
- By varying combination of observables included in the mock data, we find it plausible to infer Woods-Saxon parameters from the observables.
- We also observe that the single-system multiplicity distribution for the isobar system, rather than its ratio, is crucial to simultaneously determine the nuclear structure for the isobar system.

Handbook of Nuclear Physics

Influence of Nuclear Structure in Relativistic Heavy-Ion Collisions

Yu-Gang Ma and Song Zhang

Contents

Abstract

Many probes are proposed to determine the quark-gluon plasma and explore its properties in ultra-relativistic heavy-ion collisions. Some of them are related to initial states of the collisions, such as collective flow, Hanbury-Brown-Twiss (HBT) correlation, chiral magnetic effects, and so on. The initial states can come from geometry overlap of the colliding nuclei, fluctuations, or nuclear structure with the intrinsic geometry asymmetry. The initial geometry asymmetry can transfer to the final momentum distribution in the aspect of hydrodynamics during the evolution of the fireball. Different from traditional methods for nuclear structure study, the ultra-relativistic heavy-ion collisions could provide a potential platform to investigate nuclear structures with the help of the final-state observables after the fireball expansion. This chapter first presents a

Y.-G. Ma (✉) · S. Zhang
Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai, China
Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai, China
e-mail: mayugang@fudan.edu.cn; song_zhang@fudan.edu.cn

I. Tanihata et al. (eds.), *Handbook of Nuclear Physics*,
https://doi.org/10.1007/978-981-15-8818-1_5-1

核 技 术 NUCLEAR TECHNIQUES
www.hjs.sinap.ac.cn

原子核中的α团簇对核反应与相对论重离子碰撞的影响

马余刚
（复旦大学 核科学与技术系/现代物理研究所 国家自然科学基金委理论物理专款-上海核物理理论研究中心 上海 200433）

摘要 团簇结构可以稳定存在于原子核的内部。研究原子核的α团簇结构及其影响在核物理与天体物理中是一个十分重要的课题。在过去几十年里，原子核的团簇结构效应在重离子核反应中有了较多的研究。本文主要总结了在核反应与相对论重离子碰撞中对原子核的α团簇结构效应的研究。例如，通过原子核的巨共振来研究原子核的团簇结构。通过核反应中的粒子（包括中子、质子以及光子）的发射与关联、集体流等研究原子核的团簇结构。进一步，我们把原子核的团簇效应延伸推广到相对论重离子碰撞中，比如，对集体流及其涨落、HBT（Hanbury Brown and Twiss）关联、多重性关联、双强子方位角关联、电磁场等的研究。

关键词 原子核内α团簇，巨共振，核子-核子关联，集体流，双强子关联
中图分类号 O41，O56

第 62 卷 第 3 期 复 旦 学 报（自然科学版） Vol. 62 No. 3
2023 年 6 月 Journal of Fudan University (Natural Science) Jun. 2023

文章编号：0427-7104(2023)03-0273-20 DOI： 10.15943/j.cnki.fdxb-jns.20230525.001

集体流——从核子自由度到夸克自由度

马余刚
（复旦大学 核科学与技术系/现代物理研究所）

摘 要：集体流是从中低能重离子物理到高能核物理之间一些共性的问题。集体流大小可以利用傅里叶级数展开的各阶系数来表示，其对应于直接流、椭圆流、三角流等。集体流在能量的依赖性上存在丰富的结构，反映了碰撞过程中的不同的作用机制和物质状态。同时，粒子的集体流在核子层次和夸克层次都存在标度率行为。本文简要评述了从低能到极端相对论重离子碰撞大跨度范围的集体流现象，分别讨论了核子层次、夸克层次的集体流现象，特别是简述了作者近 30 年来在集体流方向的系统工作，包括提出的一些理论预言得到了大型实验组的验证。

关键词：重离子碰撞；集体流；直接流；椭圆流；组分标度率
中图分类号：O571.6 **文献标志码**：A

Nuclear Science and Techniques (2023) 34:88
https://doi.org/10.1007/s41365-023-01233-z

REVIEW ARTICLE

High-energy nuclear physics meets machine learning

Wan-Bing He[1,2] · Yu-Gang Ma[1,2] · Long-Gang Pang[3] · Hui-Chao Song[4] · Kai Zhou[5]

Received: 10 March 2023 / Revised: 13 April 2023 / Accepted: 18 April 2023

Abstract

Although seemingly disparate, high-energy nuclear physics (HENP) and machine learning (ML) have begun to merge in the last few years, yielding interesting results. It is worthy to raise the profile of utilizing this novel mindset from ML in HENP, to help interested readers see the breadth of activities around this intersection. The aim of this mini-review is to inform the community of the current status and present an overview of the application of ML to HENP. From different aspects and using examples, we examine how scientific questions involving HENP can be answered using ML.

SCIENCE CHINA
Physics, Mechanics & Astronomy

• Invited Review •

August 2023 Vol. 66 No. 8: 28
https://doi.org/10.1007/s11433-023-21

Machine learning in nuclear physics at low and intermediate energies

Wanbing He[1,2*], Qingfeng Li[3,4*], Yugang Ma[1,2*], Zhongming Niu[5*], Junchen Pei[6,7*], and Yingxun Zhang[8,9*]

[1] *Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China;*
[2] *Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China;*
[3] *School of Science, Huzhou University, Huzhou 313000, China;*
[4] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China;*
[5] *School of Physics and Optoelectronic Engineering, Anhui University, Hefei 230601, China;*
[6] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China;*
[7] *Southern Center for Nuclear-Science Theory (SCNT), Institute of Modern Physics, Chinese Academy of Sciences, Huizhou 516000, China;*
[8] *Department of Nuclear Physics, China Institute of Atomic Energy, Beijing 102413, China;*
[9] *Guangxi Key Laboratory of Nuclear Physics and Technology, Guangxi Normal University, Guilin 541004, China*

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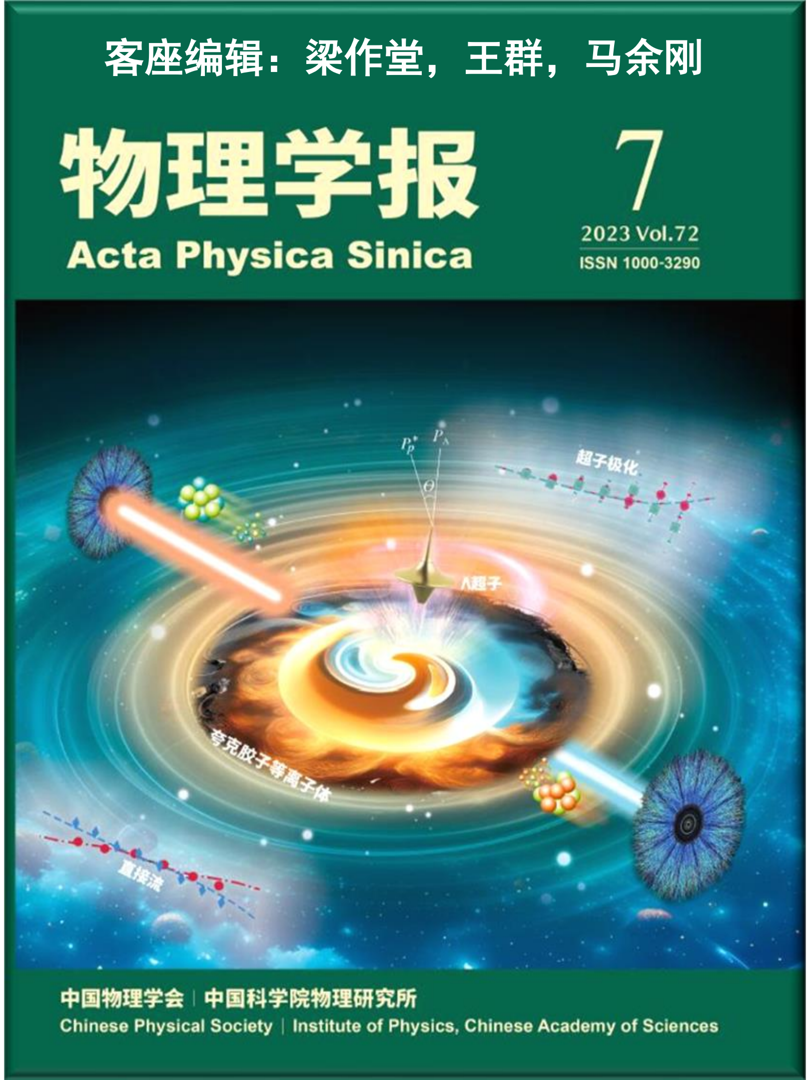
Machine learning (ML) is becoming a new paradigm for scientific research in various research fields due to its exciting and powerful capability of modeling tools used for big-data processing tasks. In this review, we first briefly introduce the different methodologies used in ML algorithms and techniques. As a snapshot of many applications by ML, some selected applications are presented, especially for low- and intermediate-energy nuclear physics, which include topics on theoretical applications in nuclear structure, nuclear reactions, properties of nuclear matter, and experimental applications in event identification/reconstruction, complex system control, and firmware performance. Finally, we present a summary and outlook on the possible directions of ML use in low-intermediate energy nuclear physics and possible improvements in ML algorithms.

machine learning, nuclear physics, low and intermediate energies

QCD相图和临界点专刊



1篇观点与展望，9篇综述，3篇研究论文

观点与展望

夸克物质中的超子整体极化与矢量介子自旋排列

阮丽娟，许长补，杨驰

物理学报.2023, 72 (11): 112401.

2023年7月27日

《中国科学》专辑考虑

相对论重离子碰撞中核结构效应

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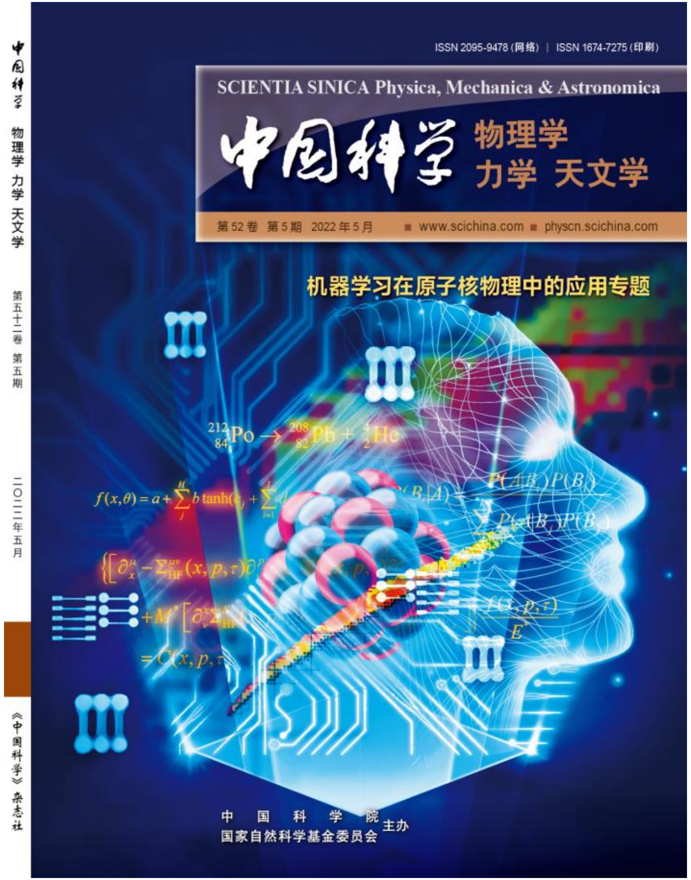


Conclusion

- Heavy ion collisions provide a wide range to learn nucleon dynamics to partonic dynamics.

- Many common observables and features emerge in nucleonic degree of freedom as well as in partonic degree of freedom.

- In this talk, I show some examples for collective flows and alpha-clustering effects. In fact, much more can be explored. eg. viscosity, phase transition, fluctuations…

- Heavy ion collisions provide a rich mine for understanding initial-state nuclear structure, nucleonic matter, quark matter, even for astrophysics process and neutron star etc.

FUDAN UNIVERSITY 1905

原子核的放射性

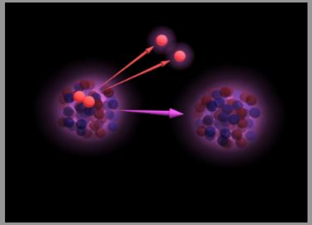
奇特放射性

- $1p$: many candidates since 1970, ^{51}Lu, ^{147}Tm, ^{53}Co^m(Isomer) etc.
- $2p$: only few nuclei found ^{45}Fe, ^{48}Ni, ^{54}Zn(ground st.), ^{14}O, ^{17,18}Ne, ^{22}Mg, ^{94}Ag(exc. St.)

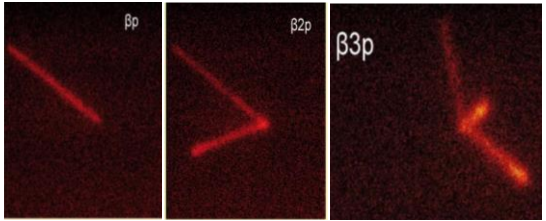
V. Goldanskii, Nucl. Phys. 19 (1960) 482

Two-proton radioactivity

nucleus → two protons + nucleus – 2p

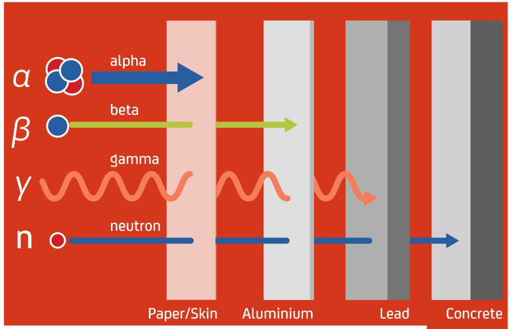


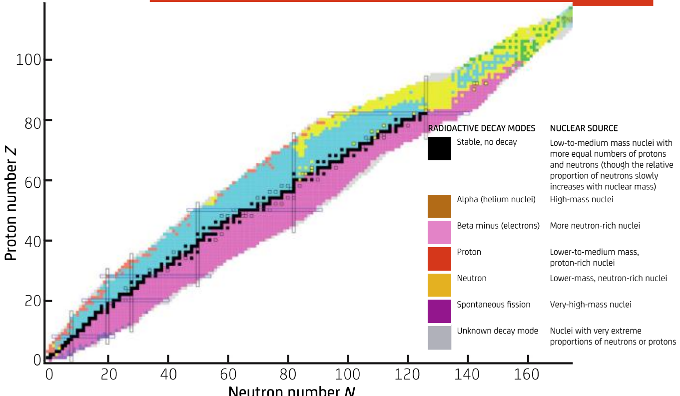
1960年理论预言基态双质子发射现象，直到2000年初才实验发现。对研究核力、核子结构及核子关联具有重要意义。



经典放射性

- Natural radioactivity (H. Becquerel, 1896)
- α, β decay(P. Curie, M. Curie, E. Rutherford, 1899)
- γ decay(P. Villard, 1900)
- Fission(O. Hahn, F. Strassmann, 1938)

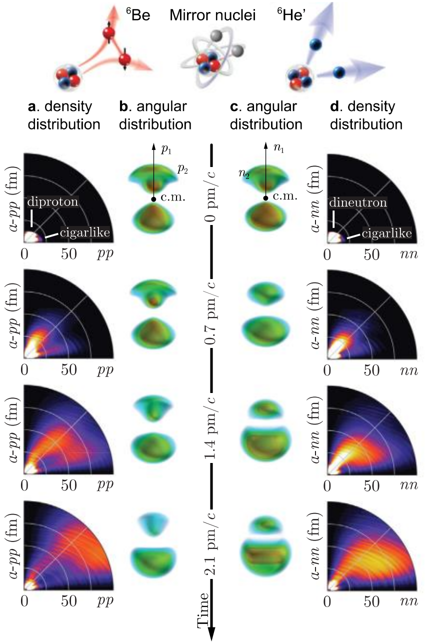


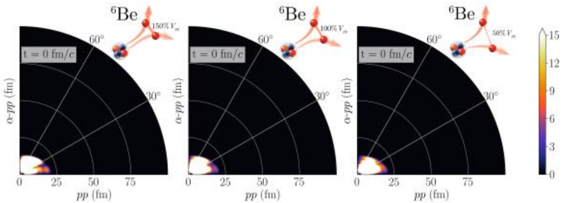


PHYSICAL REVIEW LETTERS 126, 142501 (2021)

Fermion Pair Dynamics in Open Quantum Systems

S. M. Wang (王思敏)[1,2] and W. Nazarewicz[3]





四质子、四中子发射?

Featured in Physics | Editors' Suggestion

First Observation of the Four-Proton Unbound Nucleus ^{18}Mg

Y. Jin *et al.*

Phys. Rev. Lett. **127**, 262502 – Published 22 December 2021

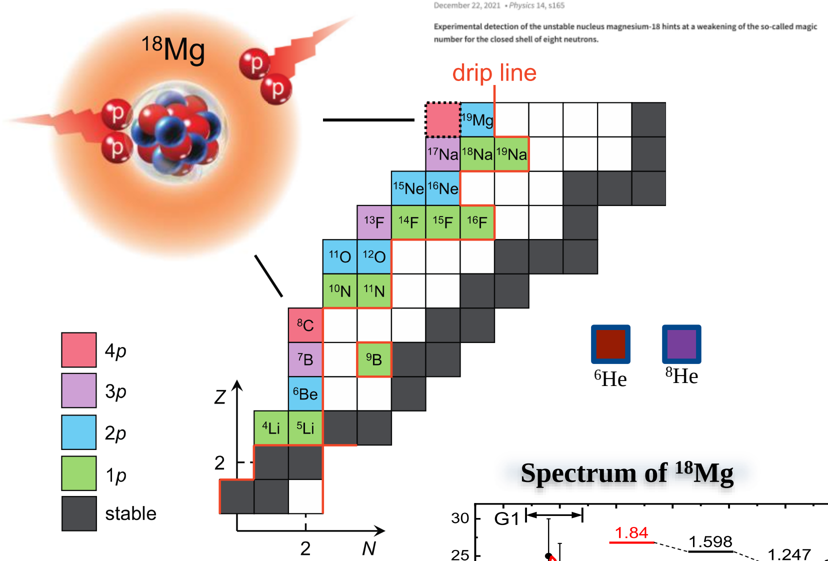
Physics See synopsis: New Unstable Nucleus Detected

SYNOPSIS

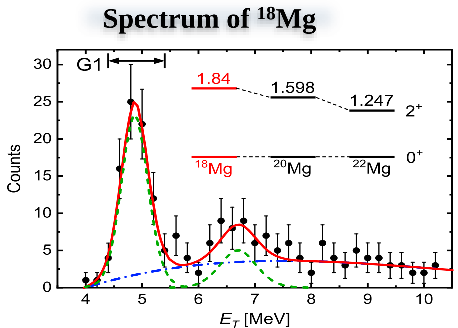
New Unstable Nucleus Detected

December 22, 2021 • *Physics* 14, s165

Experimental detection of the unstable nucleus magnesium-18 hints at a weakening of the so-called magic number for the closed shell of eight neutrons.



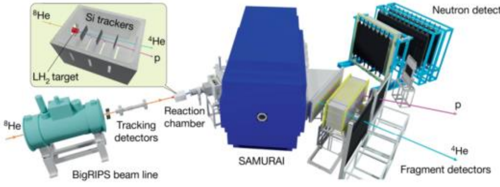
Y. Jin *et al.*, PRL 127, 262502 (2021)



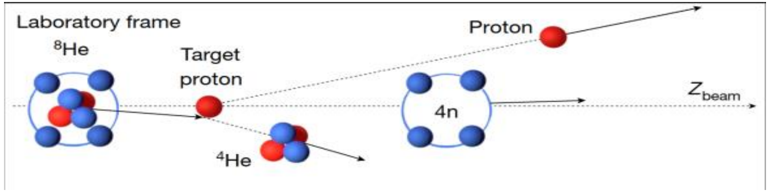
678 | Nature | Vol 606 | 23 June 2022

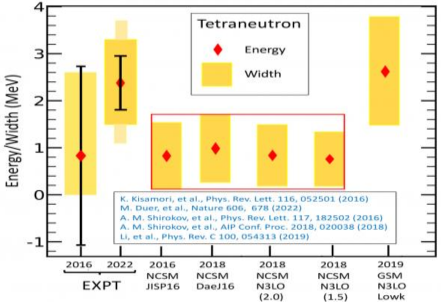
Article

Observation of a correlated free four-neutron system



M. Duer[1]✉, T. Aumann[1,2,3], R. Gernhäuser[4], V. Panin[2,5], S. Paschalis[1,6], D. M. Rossi[1], N. L. Achouri[7], D. Ahn[5,16], H. Baba[5], C. A. Bertulani[8], M. Böhmer[4], K. Boretzky[2], C. Caesar[1,2,5], N. Chiga[5], A. Corsi[9], D. Cortina-Gil[10], C. A. Douma[11], F. Dufter[4], Z. Elekes[12], J. Feng[13], B. Fernández-Domínguez[10], U. Forsberg[6], N. Fukuda[5], I. Gasparic[1,5,14], Z. Ge[5], J. M. Gheller[9], J. Gibelin[7], A. Gillibert[9], K. I. Hahn[15,16], Z. Halász[12], M. N. Harakeh[11], A. Hirayama[17], M. Holl[1], N. Inabe[5], T. Isobe[5], J. Kahlbow[1], N. Kalantar-Nayestanaki[11], D. Kim[16], S. Kim[1,16], T. Kobayashi[18], Y. Kondo[17], D. Körper[2], P. Koseoglou[1], Y. Kubota[5], I. Kuti[12], P. J. Li[19], C. Lehr[1], S. Lindberg[20], Y. Liu[13], F. M. Marqués[7], S. Masuoka[21], M. Matsumoto[17], J. Mayer[22], K. Miki[1,18], B. Monteagudo[7], T. Nakamura[17], T. Nilsson[20], A. Obertelli[1,9], N. A. Orr[7], H. Otsu[5], S. Y. Park[15,16], M. Parlog[7], P. M. Potlog[23], S. Reichert[4], A. Revel[7,9,24], A. T. Saito[17], M. Sasano[5], H. Scheit[1], F. Schindler[1], S. Shimoura[21], H. Simon[2], L. Stuhl[16,21], H. Suzuki[5], D. Symochko[1], H. Takeda[5], J. Tanaka[1,5], Y. Togano[17], T. Tomai[17], H. T. Törnqvist[1,2], J. Tscheuschner[1], T. Uesaka[5], V. Wagner[1], H. Yamada[17], B. Yang[13], L. Yang[21], Z. H. Yang[5], M. Yasuda[17], K. Yoneda[5], L. Zanetti[1], J. Zenihiro[5,25] & M. V. Zhukov[20]





许甫荣团队2019年的理论预言与实验数据符号最好!

Recent mini-review

NUCL SCI TECH (2022) 33:105
https://doi.org/10.1007/s41365-022-01091-1

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Recent progress in two-proton radioactivity

Long Zhou[1,2] · Si-Min Wang[1,2] · De-Qing Fang[1,2] · Yu-Gang Ma[1,2]

科学通报 2020 年 第 65 卷 第 35 期: 4018 ~ 4026
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《中国科学》杂志社
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双质子发射实验研究进展

方德清*, 马余刚*
复旦大学现代物理研究所, 教育部核物理与离子束应用重点实验室, 上海 200433
* 联系人, E-mail: dqfang@fudan.edu.cn; mayugang@fudan.edu.cn

2020-04-17 收稿, 2020-05-06 修回, 2020-05-07 接受, 2020-05-08 网络版发表
国家重点研发计划(2018YFA0404404)、国家自然科学基金(11925502, 11935001, 11961141003, 11421505, 11475244, 11927901)、上海市自然科学基金(19ZR1403100)和中国科学院B类战略性先导科技专项(XDB34030100)资助

摘要 放射性是不稳定核的一个重要特性, 比较常见的模式有α、β、γ衰变及裂变. 双质子发射是质子滴线区原子核的一种奇异放射性, 对研究极端丰质子核的结构、质量、质子对关联等有重要意义, 是近年来放射性核束物理的重要前沿方向之一. 本文简要评述了双质子发射实验研究进展, 介绍了几种常用的实验探测方法及鉴别双质子发射机制的研究方法. 奇异放射性研究的困难在于滴线区不稳定核的产生. 中国在建的HIAF装置有强流的优势, 结合先进的探测技术与研究方法, 将来有望在滴线区原子核的奇异放射性实验研究方向开展最前沿的工作.

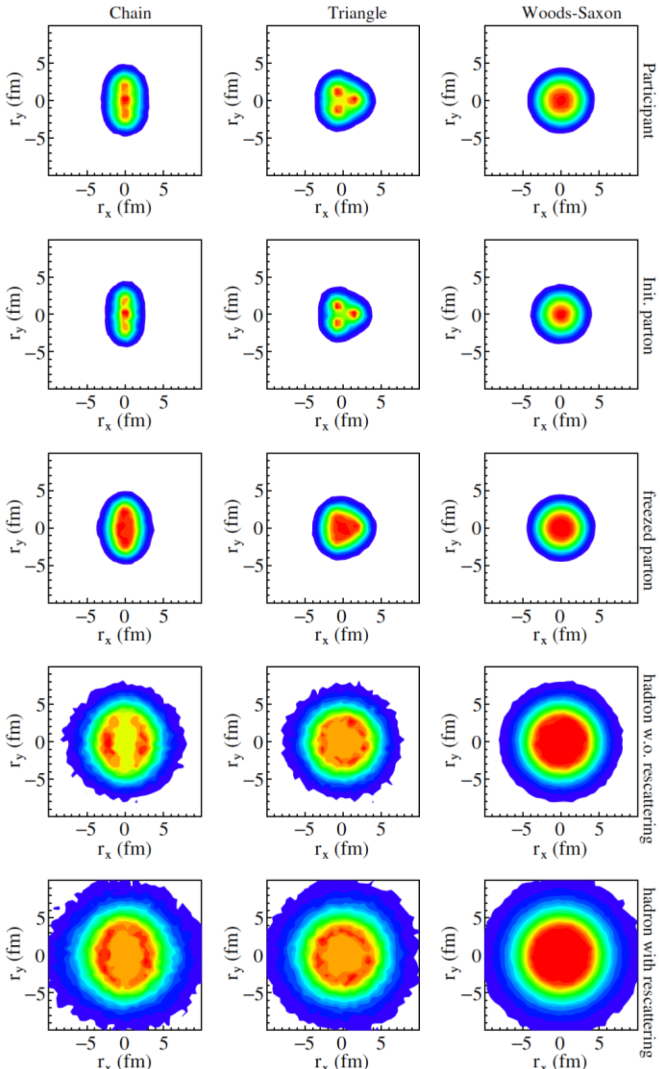
关键词 丰质子核, 双质子发射, 在束衰变方法, 注入衰变方法, 光学读出时间投影室成像方法

Nuclear Physics News feature article

Exploring the Edge of Nuclear Stability on the Proton-Rich Side

De-Qing Fang[1,2], Hui Hua[3], Yu-Gang Ma[1,2] and Si-Min Wang[1,2]
[1]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[2]Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China
[3]School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

Coordinate distribution



Participant

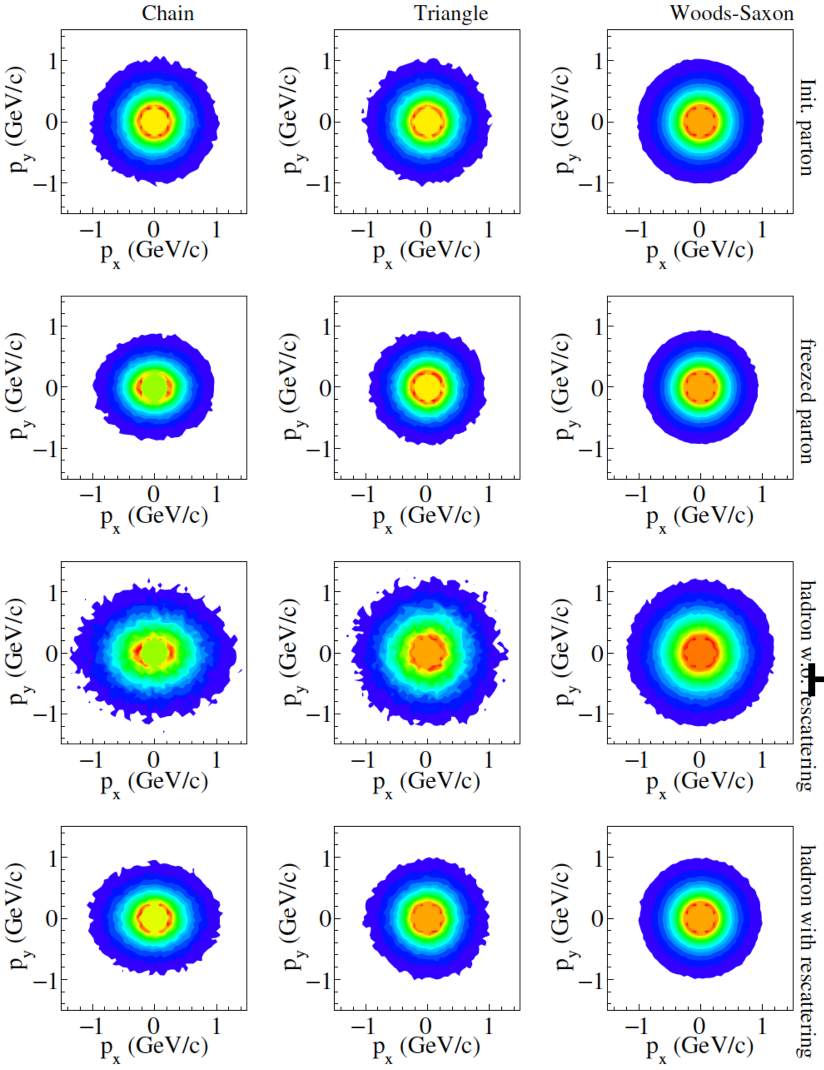
Initial parton

Freeze-out partons

Hadron w/o rescattering

Hadron w/ rescattering

Px-py distribution



Initial parton

Freeze-out partons

Hadron w/o rescattering

Hadron w/ rescatering

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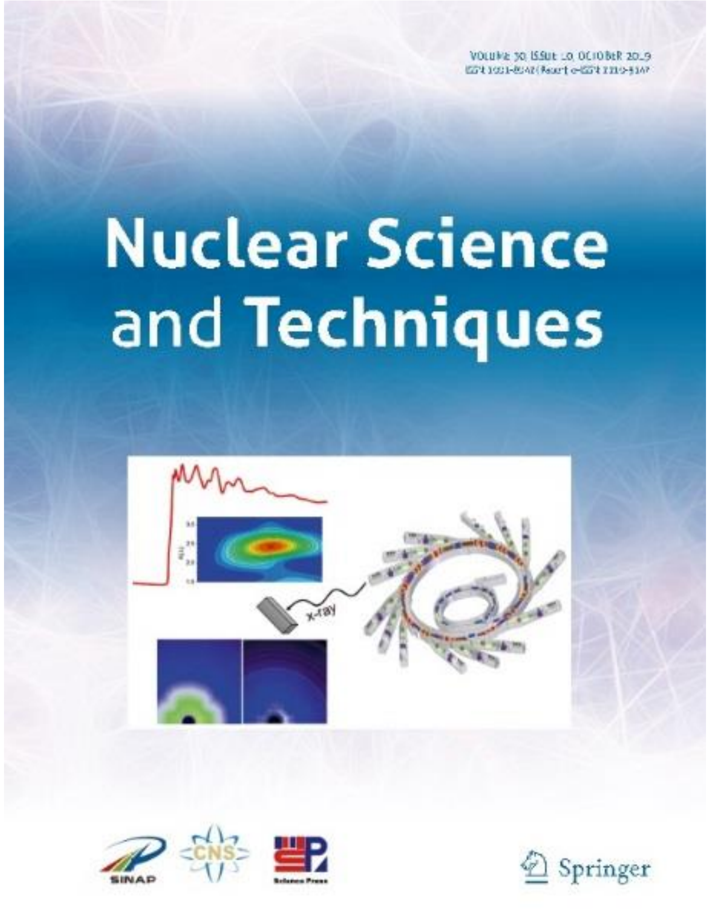
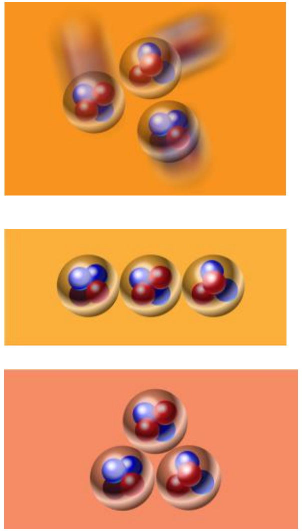
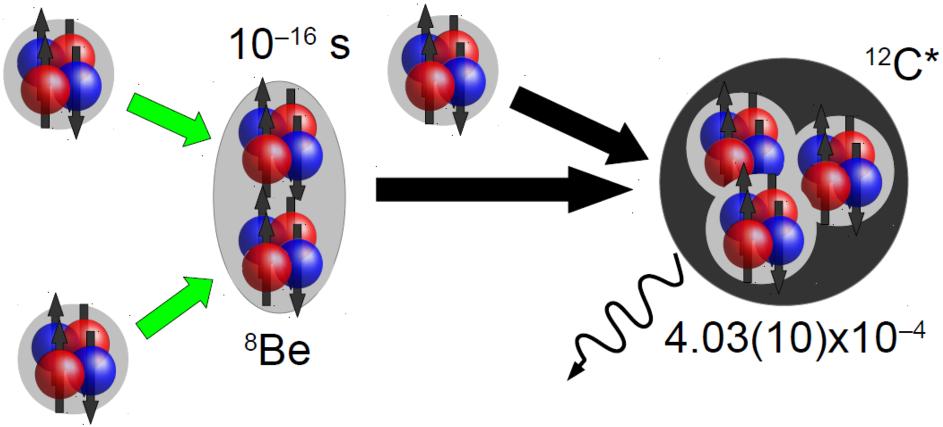


Triple-alpha process occuring in Red Giants => Origin of carbon !





Schematic of the triple alpha process at T~10^8 K.

Most important nuclear reaction during Helium burning !

$\alpha + \alpha$ → ^{8}Be – 0.092 MeV; ^{8}Be is unstable with $\tau_{1/2}$ ~ 10^{-16} s and decays quickly into two α-particles !

Carbon production is possible only via a resonance reaction

$$\alpha + \alpha + \alpha \rightarrow {}^{12}C^* \rightarrow {}^{12}C + 2\gamma + 7.37 \text{ MeV}$$

$J^{\pi}=0^+$, E_x=7.654 MeV

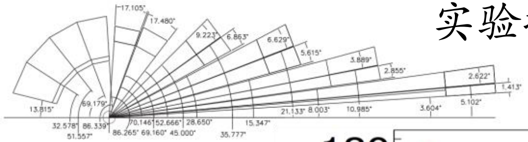
predicted by Fred Hoyle in 1953

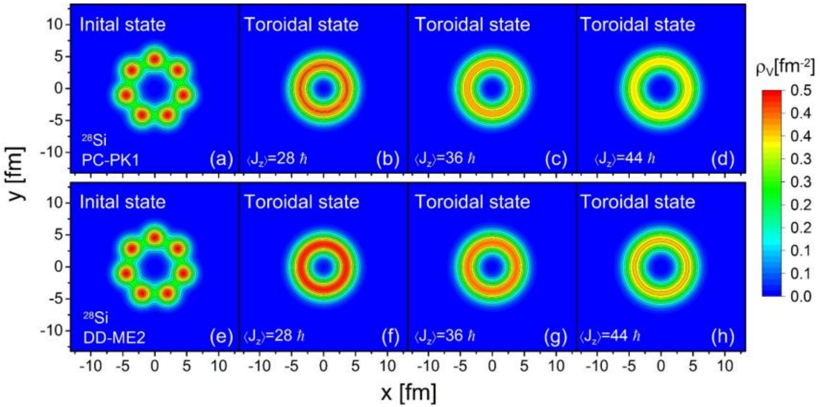
发现原子核极高激发能共振实验证据

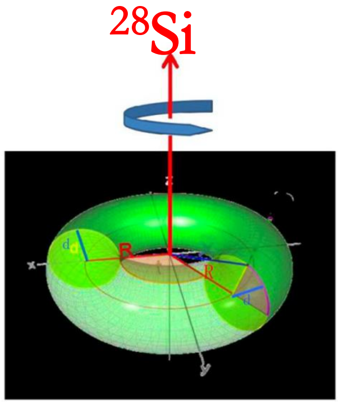
约翰·惠勒在20世纪五六十年代预言在一定的条件下原子核可能呈现准一维的环形结构

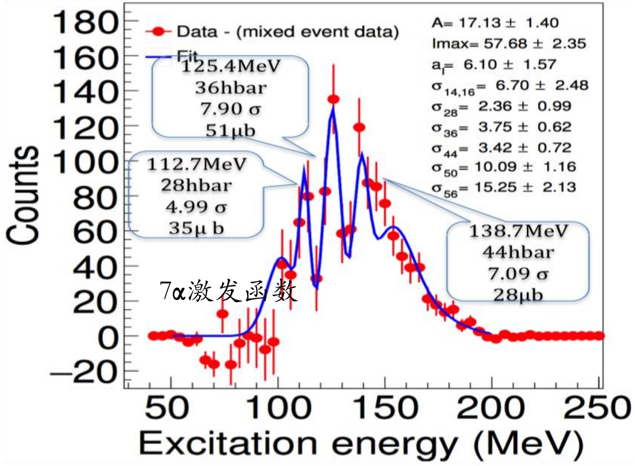
- J. A. Wheeler, Nucleonics Notebook, 1950 (unpublished), see also p. 297 in G. Gamow, Biography of Physics, Harper & Brothers Publishers, N.Y. 1961
- C. Y. Wong's predictions, Phys Lett B 41, 446 (1972), Phys Lett B 738, 401 (2014)

实验探测器布局









X. G. Cao et al., Phys Rev C 99, 014606 (2019)

✓ 首次测量到^{28}Si高激发态的7α发射道

✓ 观测到3个共振峰(置信度大于5个σ)，与理论预言的7α结构定量符合

✓ 7α发射来自低密度状态，核相图低密度区的α波色-爱因斯坦凝聚?

nature physics

LETTERS

https://doi.org/10.1038/s41567-020-01136-5

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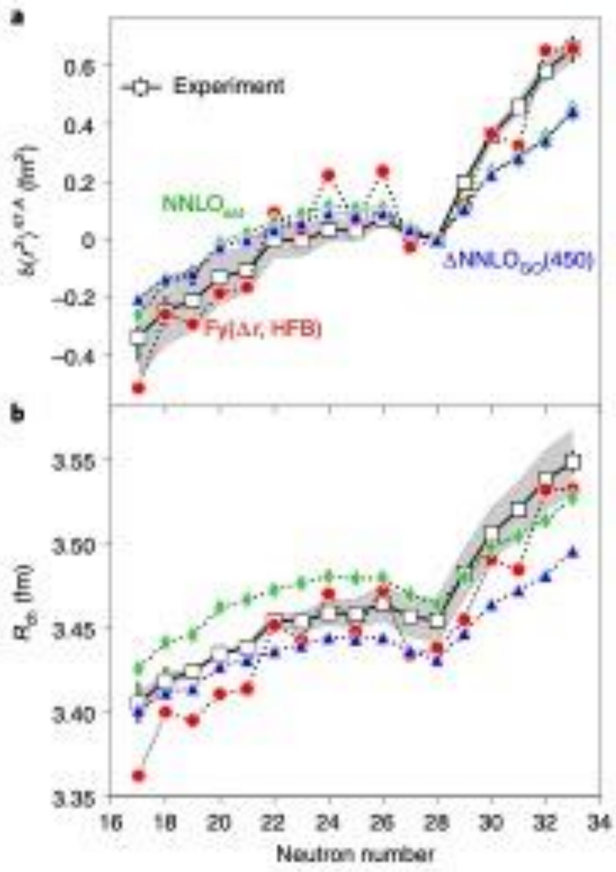
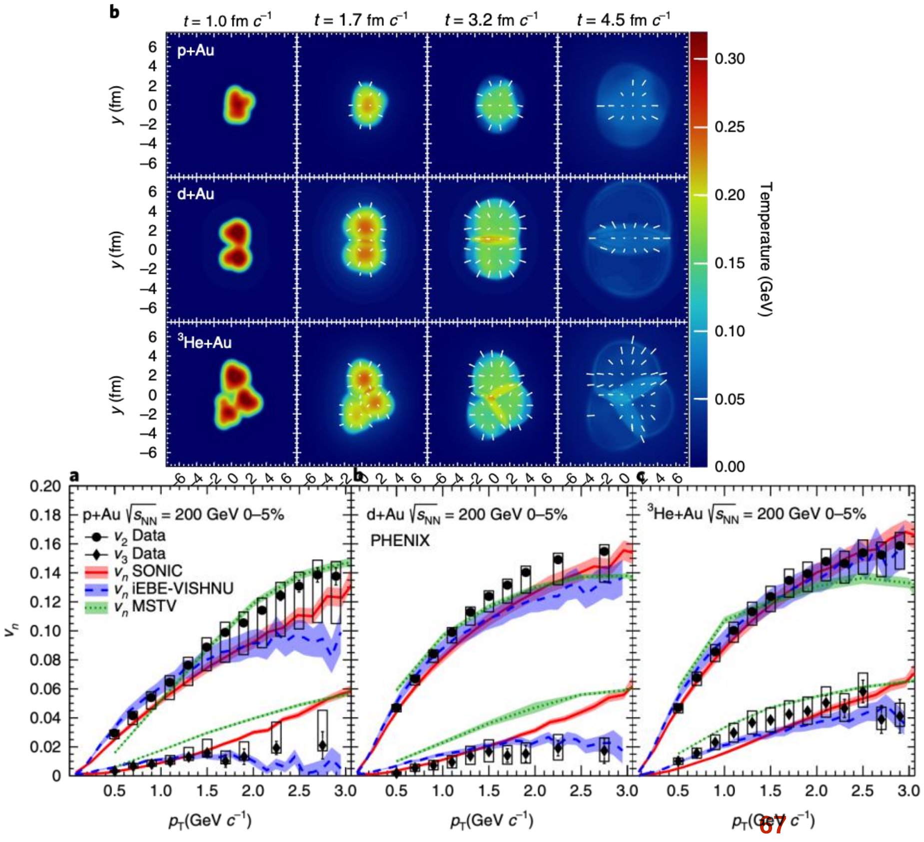
Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of $N=32$

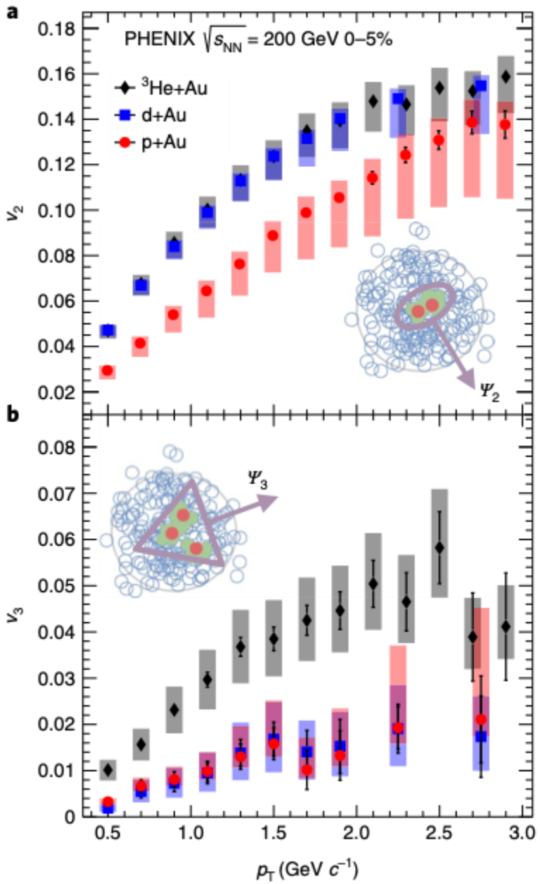
Á. Koszorús[1,17] ✉, X. F. Yang[1,2] ✉, W. G. Jiang[3,4,5], S. J. Novario[3,4], S. W. Bai[2], J. Billowes[6], C. L. Binnersley[6], M. L. Bissell[6], T. E. Cocolios[1], B. S. Cooper[6], R. P. de Groote[7,8], A. Ekström[5], K. T. Flanagan[6,9], C. Forssén[5], S. Franchoo[10], R. F. Garcia Ruiz[11,12], F. P. Gustafsson[1], G. Hagen[4], G. R. Jansen[4], A. Kanellakopoulos[1], M. Kortelainen[7,8], W. Nazarewicz[13], G. Neyens[1,12], T. Papenbrock[3,4], P.-G. Reinhard[14], C. M. Ricketts[6], B. K. Sahoo[15], A. R. Vernon[1,6] and S. G. Wilkins[16]



初始内秉几何结构对集体流的效应

PNENIX, Nat. Phys.15 (2019) 214; J. L. Nagle, et al., Phys. Rev. Lett. 113, 112301 (2014)





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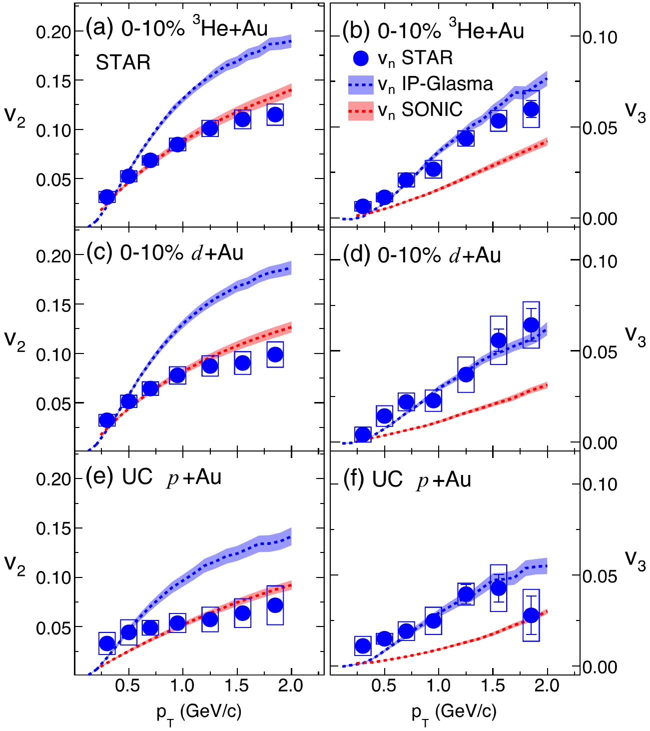
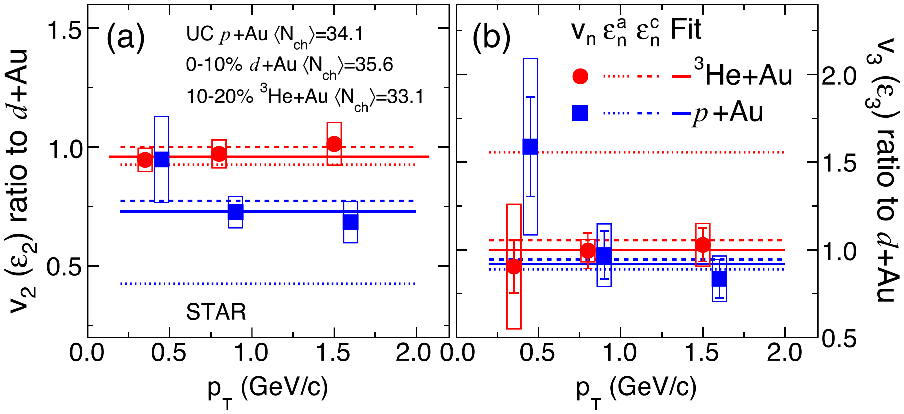
Measurements of the Elliptic and Triangular Azimuthal Anisotropies in Central ^{3}He + Au, d + Au and p + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV





- Figure 3 shows that both models fail to give a simulta- neous description of v2 and v3 vs pt, indicating that further studies are required to identify model parameters that regulate the influence of the subnucleonic fluctuations on ε2,3, and a possible influence from longitudinal flow decorrelation
- he v2 vs pt values depend on the colliding systems, the v3 vs pt values are system independent within the uncertainties, suggesting an influence on eccentricity from subnucleonic fluctuations in these small- sized systems.
- These results also provide stringent constraints for the hydrodynamic modeling of these systems.