



# 高能与低能核物理交叉学术研讨会

轻核区原子核团簇的多探针研究及交叉理论研究

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肖志刚团队@清华大学

孟杰团队@PKU

J. B. Natowitz团队@TAMU

上海·普陀

2026年5月17日



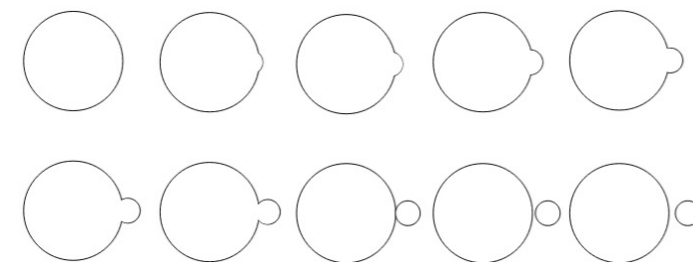
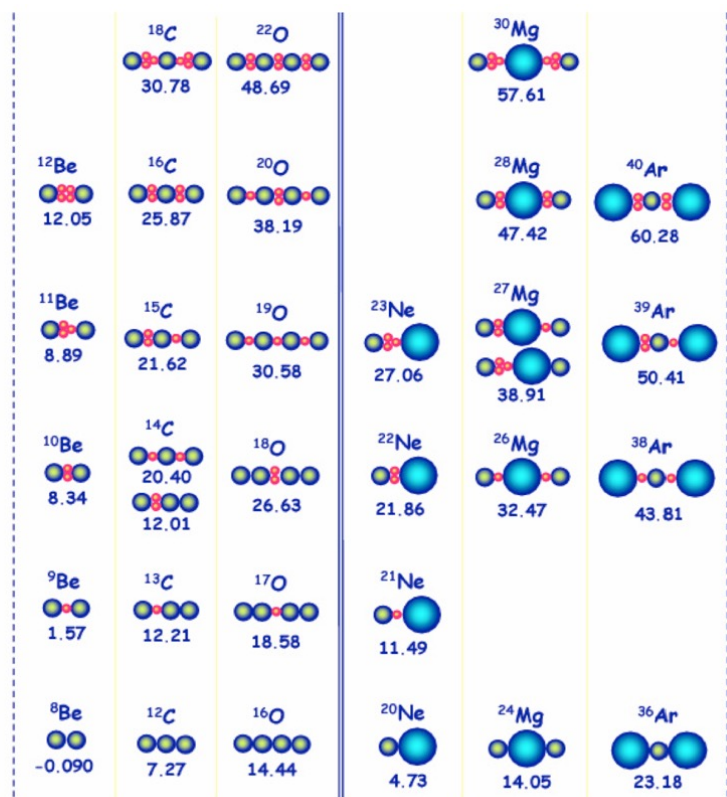
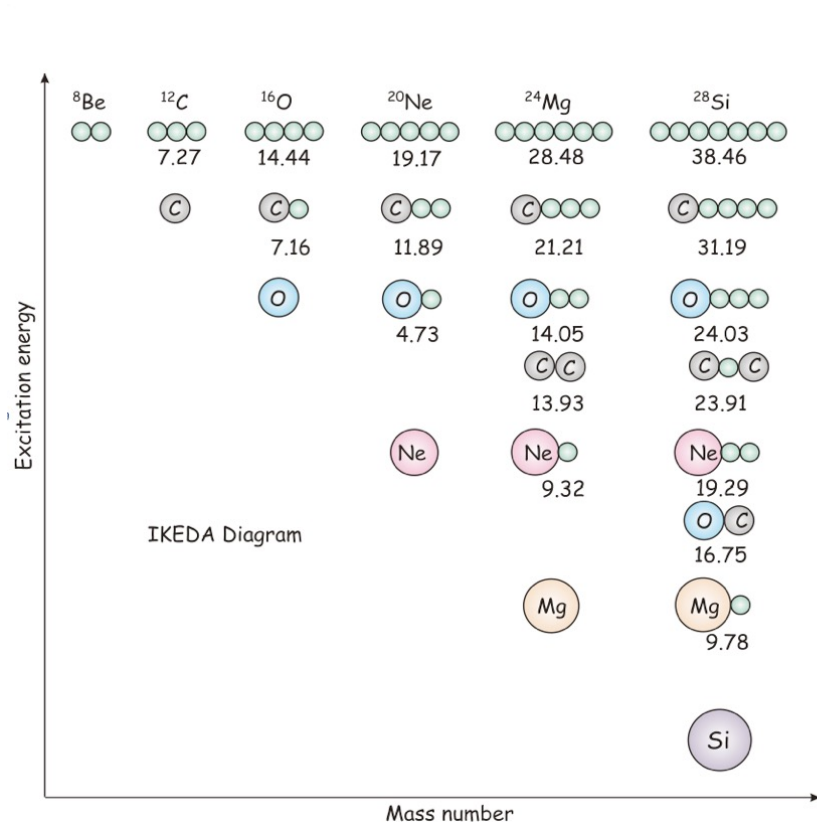
# Outline

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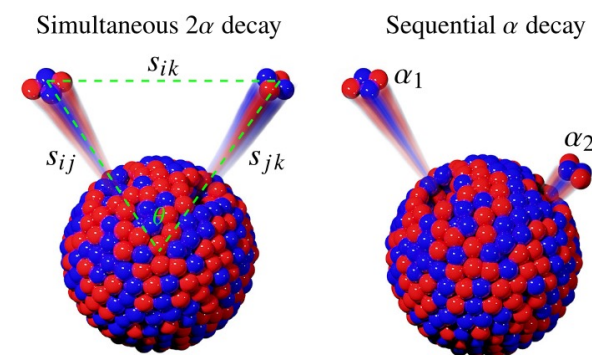
- I. Background
- II.  $N\alpha$  decay as toroidal high spin isomer probe
- III. Photodisintegration as cluster probe
- IV. Scattering/entanglement as two-body cluster probes
- V. New breathing modes as cluster/bubble probe
- VI. Ultra-brilliant, ultra-fast  $\gamma/e^+$  probes
- VII. Ultra-brilliant, ultra-fast heavy ion beam
- VIII. Summary

# I Background

## ➤ The universality of cluster d.o.f. in nuclei



A. Astier et al., PRL PRL 104, 042701 (2010)



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

Von Oertzen W, Freer M, Kanada-En'yo Y., Nuclear clusters and nuclear molecules, Phys Rep, 2006, 432: 43–113

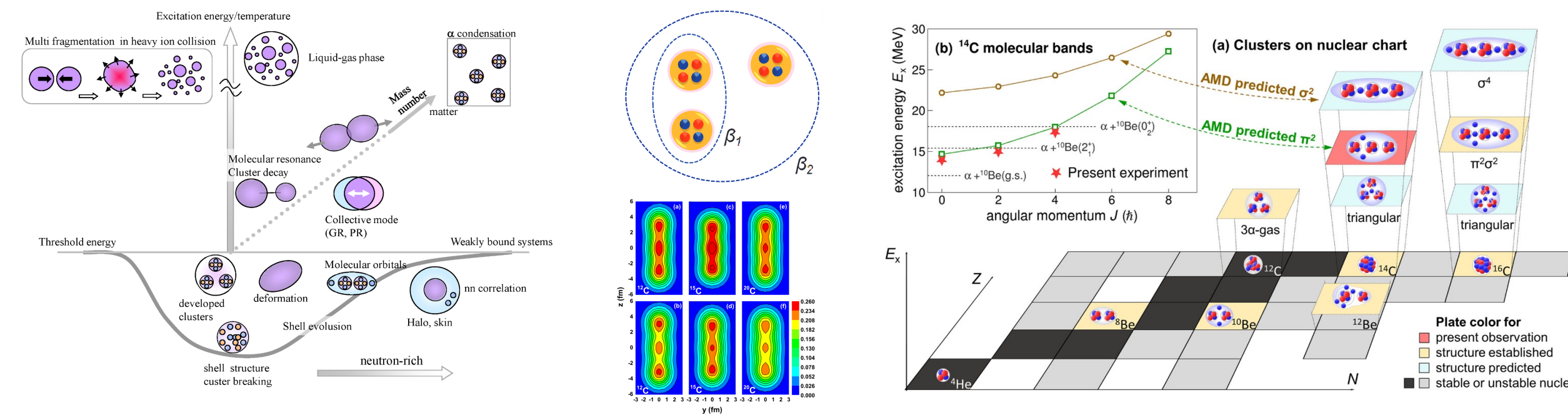
Predicted 2  $\alpha$ s in heavier nuclei,  $^{108}\text{Xe}$ ,  $^{218}\text{Ra}$  etc. Shulin Tang, PRL, 136, 172503 (2026)

➤ The complexity of cluster d.o.f. in nuclei

Different cluster type:  $\alpha$ ,  $^{12}\text{C}$ ,  $^{16}\text{O}$ ,  $^{10}\text{Be}$  etc.

Different cluster picture: BEC, container picture, linear chain, triangle, ...

Dependence on excitation energy and angular momentum



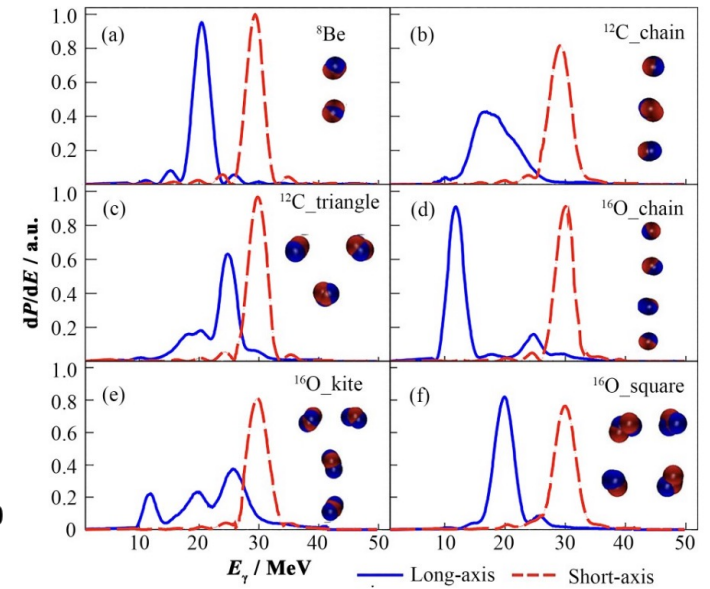
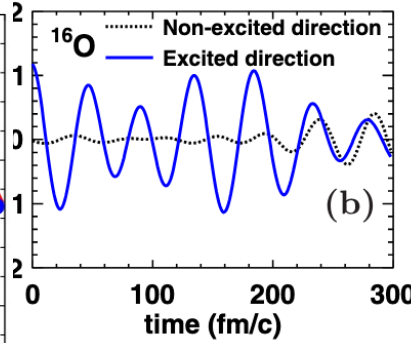
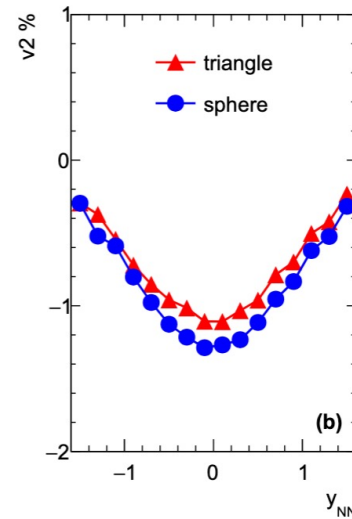
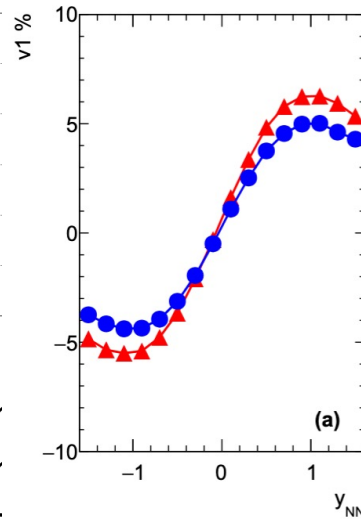
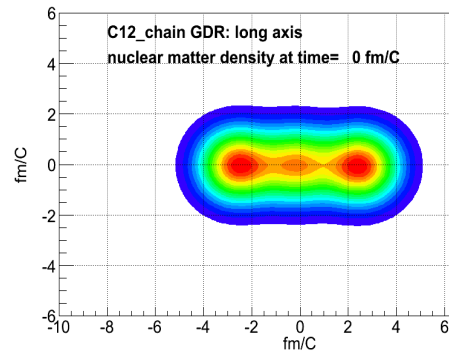
THSR, PRL 87, 192501 (2001)  
M. Chernykh et al., PRL 98, 032501 (2007)  
Y. Kanada-En'yo et al., PTEP 2012, 01A202 (2012)

B. Zhou et al., PRL 110, 262501 (2013)  
P. W. Zhao et al., PRL 115, 022501 (2015)

M. Freer et al., PRL 96, 042501 (2006)  
Z. H. Yang et al., PRL 112, 162501 (2014)  
H. Yamaguchi et al. PLB 766, 11 (2017).  
Y. Liu et al., PRL 124, 192501 (2020)  
J. X. Han et al, Commun Phys 6, 220 (2023)

# ➤ The study of cluster probes in nuclei

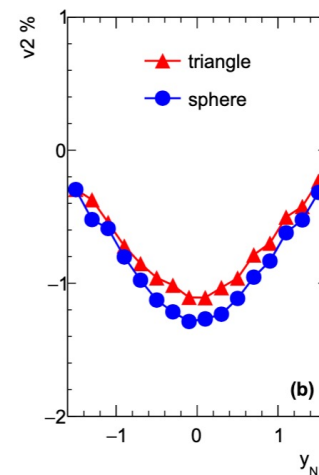
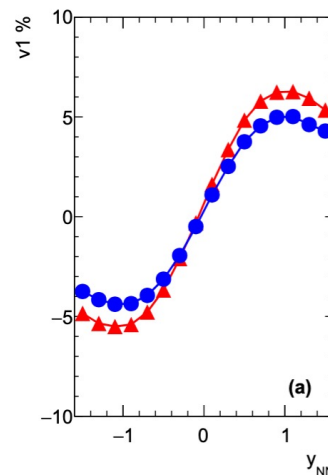
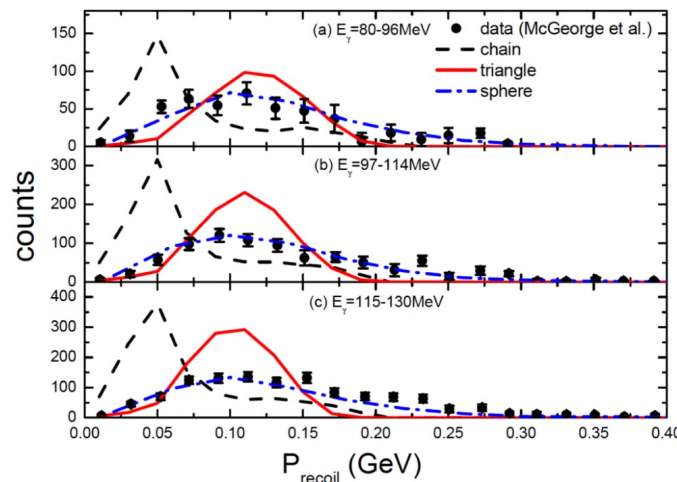
## ✓ The GDR probes and dynamics study



Wan-Bing He, Yu-Gang Ma, PRC 105, 034310 (2021)  
Wan-Bing He, Yu-Gang Ma, PRC 105, 034310 (2021)  
Bo-Song Huang, Yu-Gang Ma, PRC 105, 034310 (2021)

Guo-Qiang Zhang, PRL 113, 032506 (2014)  
Guo-Qiang Zhang, PRC 94, 014301 (2016)

## ✓ Quasi-deuteron reaction and direct photon flow probes



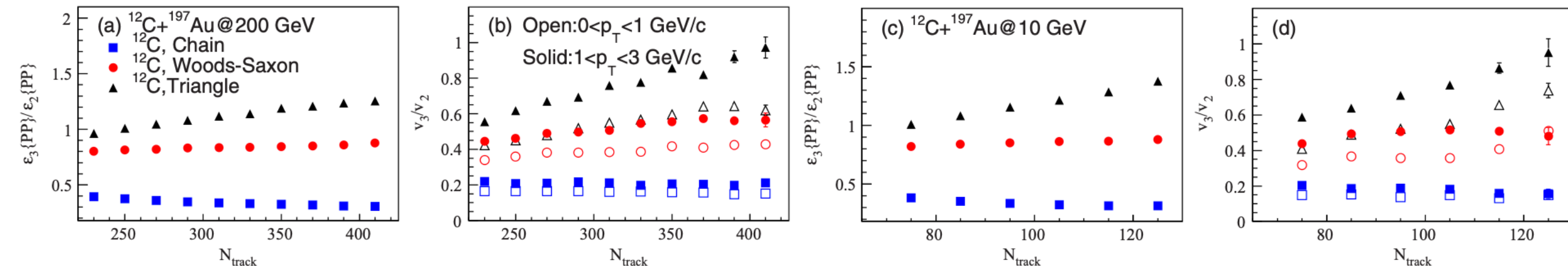
B. S. Huang, Y.G. Ma. W. B. He,  
Eur. Phys. J. A (2017) 53: 119  
B. S. Huang, Y.G. Ma. W. B. He,  
PRC 95, 034606 (2017)  
C. Z. Shi, Y. G. Ma, Nucl. Sci. Tech. 32, 66 (2021)

# ✓ Relativistic heavy-ion collisions

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

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

S. Zhang,<sup>1</sup> Y. G. Ma,<sup>1,2,3,\*</sup> J. H. Chen,<sup>1</sup> W. B. He,<sup>4</sup> and C. Zhong<sup>1</sup>



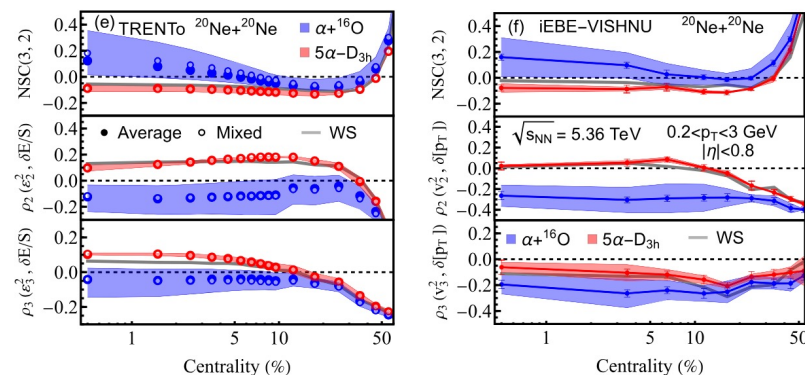
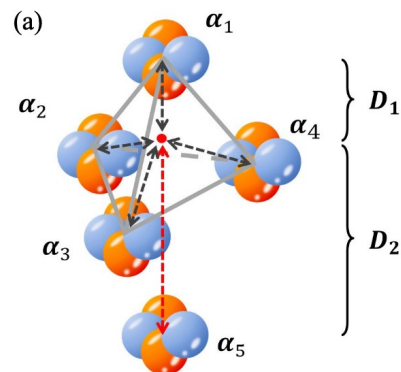
PHYSICAL REVIEW LETTERS **136**, 082302 (2026)

## Identifying $\alpha$ -Cluster Configurations in $^{20}\text{Ne}$ via Ultracentral Ne + Ne Collisions

Pei Li (李沛)<sup>①</sup>, Bo Zhou (周波)<sup>①,\*</sup>, and Guo-Liang Ma (马国亮)<sup>①†</sup>

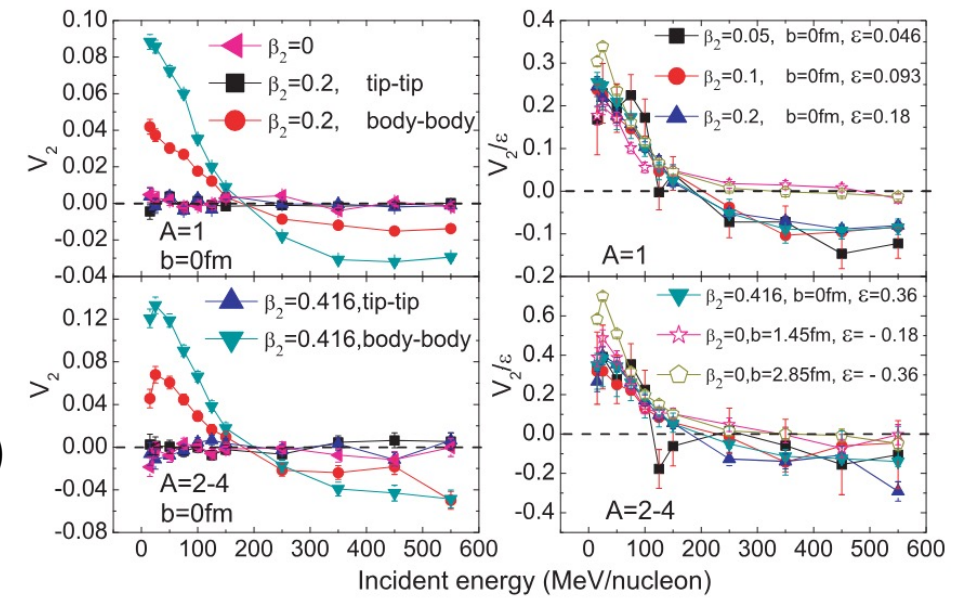
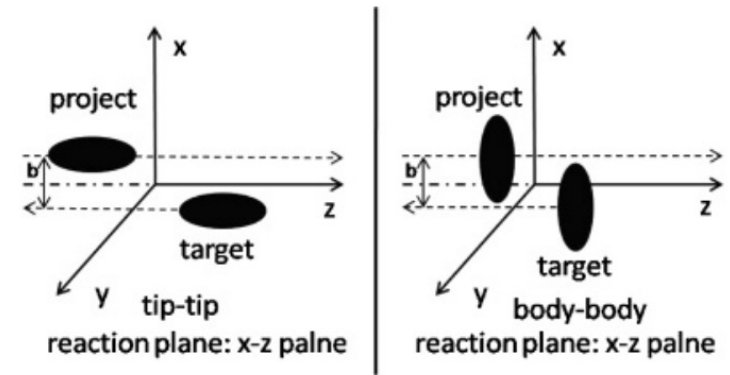
Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, *Fudan University*,  
Shanghai 200433, China

and Shanghai Research Center for Theoretical Nuclear Physics, NSFC and *Fudan University*, Shanghai 200438, China



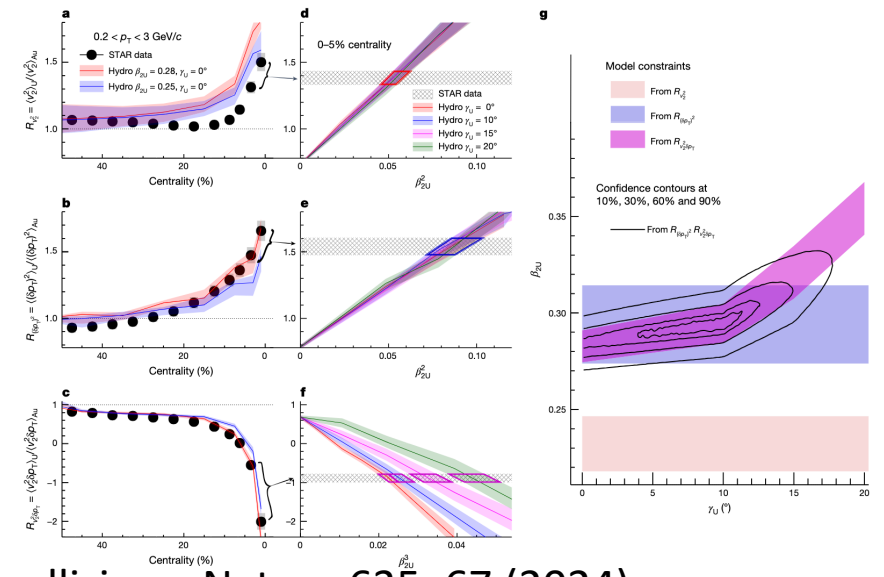
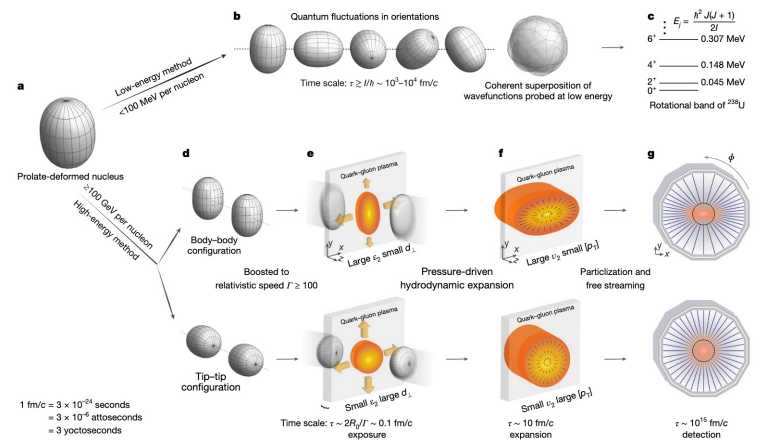
➤ Cross between nuclear structure and reactions

✓ Deformation



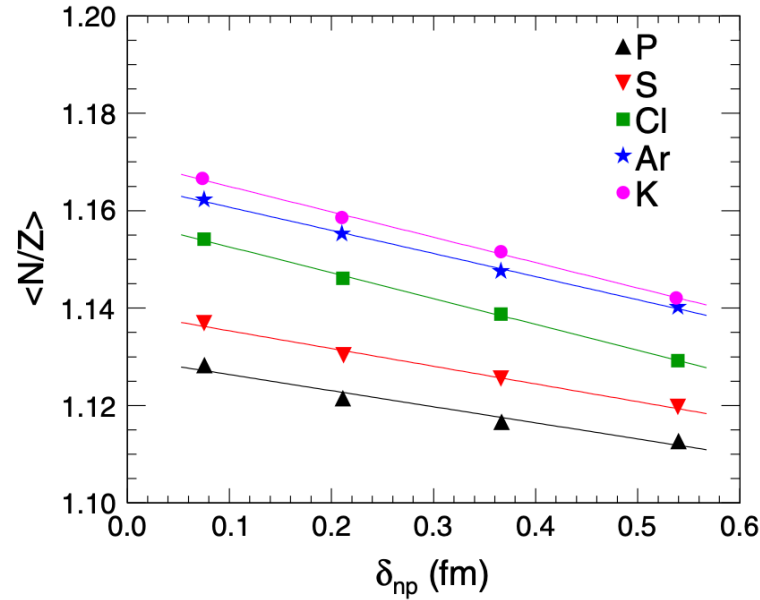
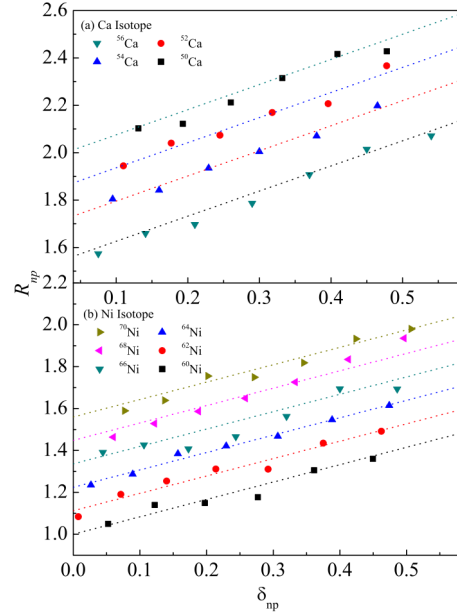
X. G. Cao, G. Q. Zhang, X. Z. Cai, Y. G. Ma et al., PRC 81, 061603(R) (2010)  
X. G. Cao, G. Q. Zhang, X. Z. Cai, Y. G. Ma et al., IJMPPE 19, 1794 (2010)

nature  
Imaging shapes of atomic nuclei in high-energy  
nuclear collisions



STAR Collaboration, Imaging shapes of atomic nuclei in high-energy nuclear collisions, Nature 635, 67 (2024)

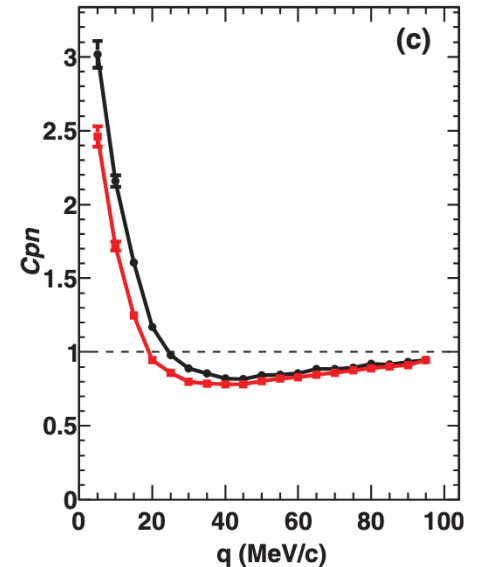
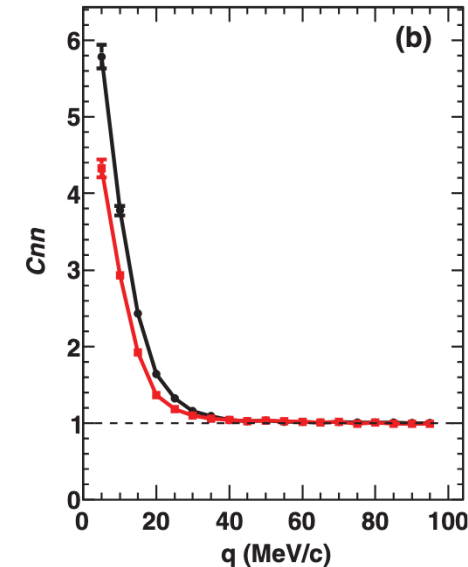
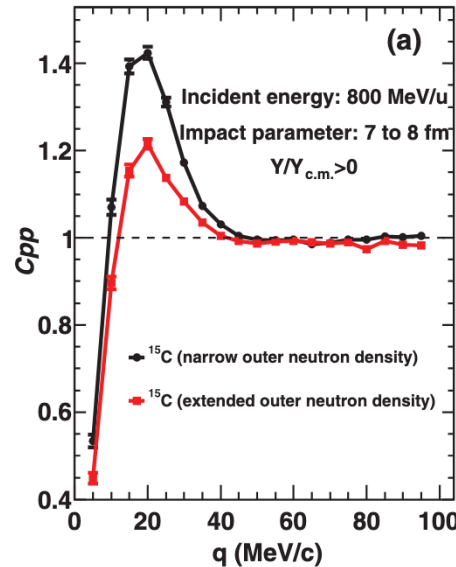
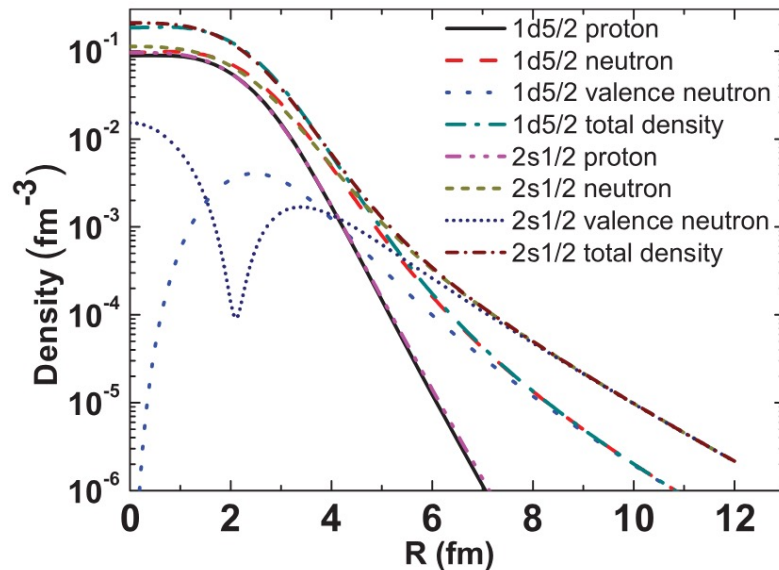
## ✓ Neutron skin incident channel effect



X. Y. Sun, D. Q. Fang, Y. G. Ma et al., PLB 682, 396 (2010)  
 Z. T. Dai, D. Q. Fang, Y. G. Ma et al., PRC 89, 014613 (2014)  
 Z. T. Dai, D. Q. Fang, Y. G. Ma et al., PRC 91, 034618 (2015)  
 ... ..

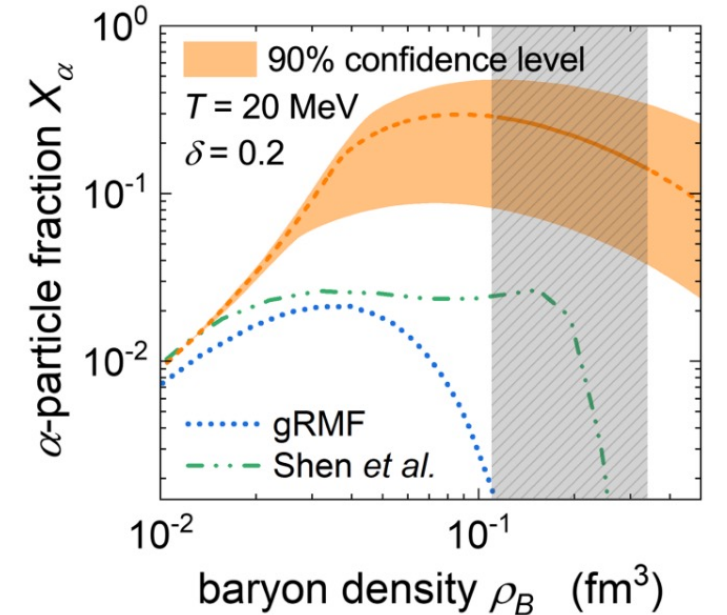
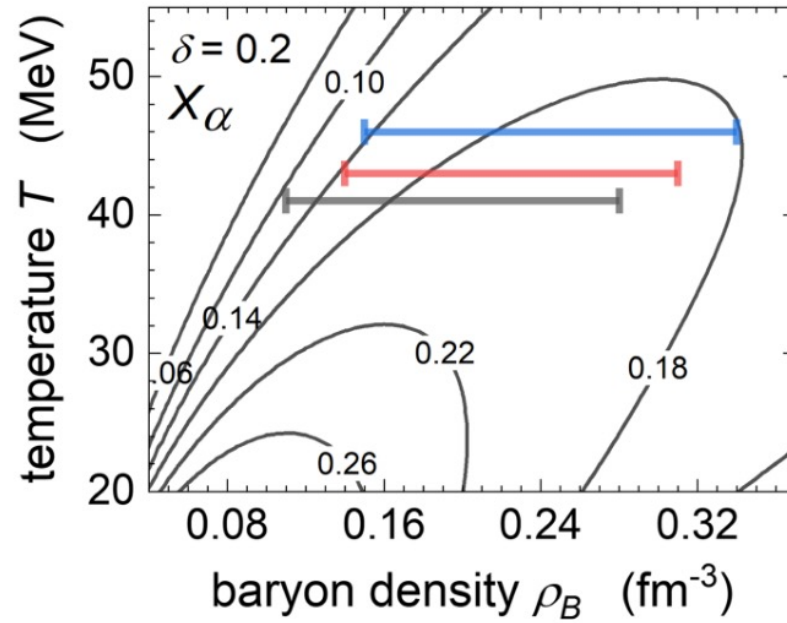
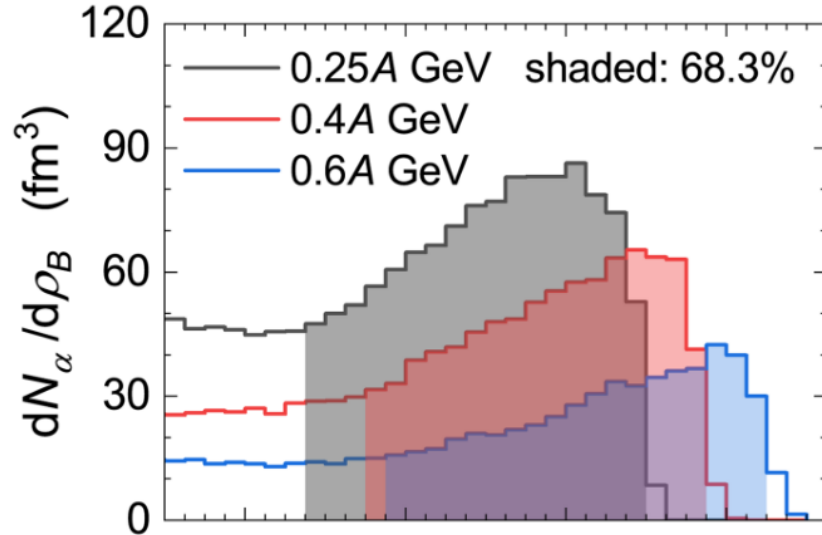
## ✓ Neutron halo incident channel effect

X. G. Cao, X. Z. Cai, Y. G. Ma et al., 86, 044620 (2012)  
 X. G. Cao, J. G. Chen, Y. G. Ma et al., CPC(HEP & NP), 2009, 33(Suppl. I): 49



**Clustered Nature of Hot and Dense Nuclear Matter: Signatures from Heavy-Ion Collisions**Rui Wang<sup>1,2,3,\*,\*\*</sup> Zhen Zhang<sup>4,†</sup> Yu-Gang Ma<sup>1,5,6,‡</sup> Lie-Wen Chen<sup>7,§</sup> Che Ming Ko,<sup>8,||</sup> and Kai-Jia Sun<sup>1,5,¶</sup>

Although light nuclear clusters are known to form abundantly in warm and dilute nuclear matter, their role in hot and dense nuclear matter remains unclear due to the lack of experimental indication for their modifications by the Mott effect under such conditions. To address this issue, we resort to intermediate-energy heavy-ion collisions, where light clusters are mainly produced in the transiently formed hot and dense matter. A kinetic approach, which includes dynamically the formation and dissociation of light clusters, is employed to deduce the strength of the Mott effect and the  $\alpha$ -particle fraction in hot and dense nuclear matter from the light-nuclei yields measured by the FOPI Collaboration in central Au + Au collisions at energies of  $0.25A$  to  $0.6A$  GeV. We find an unexpectedly abundant  $\alpha$  clustering in this environment, which will have profound implications for modeling the nuclear equation of state and describing supernovae and neutron star mergers.



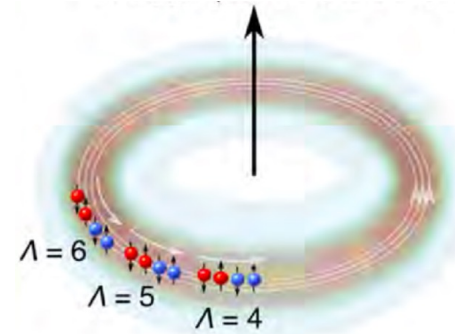
# II. $N\alpha$ decay as toroidal high spin isomer probe

- Besides the spherical and ellipsoidal shape, nuclei far from the  $\beta$  stability line can show various exotic shapes, such as pear-shape ( $^{224}\text{Ra}$ ,  $^{144}\text{Ba}$ ), hollow ( $^{34}\text{Si}$ ), and chain ( $^{14}\text{C}$ ,  $^{16}\text{C}$ ) etc.
- Various cluster configurations are predicted in excited light nuclei
- Wheeler suggested **toroidal** nuclear fluid with proper conditions in the 1950s

- ✓ excessive charges,
- ✓ excessive angular
- ✓ shell effects

Princeton University Graduate  
Course Physics 576 Take-Home  
Exam- ination Problem 2, May 22,  
1963 (unpublished).  
in a course taught by Wheeler

J. A. Wheeler, Nucleonics  
Notebook, 1950 (unpublished),  
see also p. 297 in G. Gamow,  
Biography of Physics, Harper &  
Brothers Publishers, N.Y. 1961



From C. Y. Wong talk

Princeton University  
Physics Department  
Physics 576 -- Nuclear Models  
Final "Take-Home" Examination for Those Taking Course for Credit  
22 May 1963

Please answer each question in a separate standard University examination book, and answer all five questions.

You are free to use any course notes or reference books or periodicals, but you are requested (1) not to consult with others, and (2) to list any reference which you use in any major way in answering the question.

Please put into an envelope and put into the box of J. A. Wheeler by 5 p.m., Saturday, June 1. (To be given back by him by 5 p.m., Monday, 3 June)

1. SUPERCONDUCTING MODEL  
Discuss in 3 pages, as quantitatively as possible, the relation between nuclear structure and superconductivity.

2. DOUGHNUT NUCLEI  
Gamow's recent book, *The Biography of Physics*, refers in a few passing sentences to unpublished Princeton work on the theory of doughnut shaped nuclei. (1) Develop this theory in the approximation in which the minor radius  $b$  of the torus is treated as very small in comparison with the major radius  $a$ , and in which the effect of the electrons is neglected.  
(Hint: The coulomb energy is the integral over the bent cylinder of the quantity  $\frac{1}{2} \rho V$ , where  $\rho$  is idealized as constant. The charge density per unit length of the ring is  $\lambda = \pi b^2 \rho$ . Outside the ring treat its electrical potential as if caused by a wire, thus (in c.s.u.),

$$V = \int_0^{2\pi} \frac{\lambda a d\theta}{(a^2 + x^2 - 2a x \cos \theta + z^2)^{1/2}}$$

where  $x$  and  $z$  are the coordinates of the point of observation. Reduce to a complete elliptic integral  $K(k)$  (see Peirce) and, with  $k^2 + k'^2 = 1$  and  $k' = 1$ , note

$$K \approx \ln(4/k') \quad (\text{Jahnke - Emde}).$$

Thus the potential outside the ring looks -- to an observer close up -- like that caused by an infinite cylinder of charge, of radius  $b$ . Inside the potential goes as a function of the distance  $r$  from the axis of the "cylinder" as

$$V = \text{constant} - \pi \rho r^2.$$

Find the constant by matching at the surfaces,  $r = b$ .

(2) Use the constants of Green's semi-empirical mass formula (see fission MS in library for references) to make your mass equation quantitative.

(3) Determine the equilibrium dimensions  $a$  and  $b$  of a nucleus of mass number  $A = 100,000$ , containing equal numbers of neutrons and protons.

➤ **Early work of C. Y. Wong predicted a region of toroidal ground state nuclei with  $40 \leq A \leq 70$  and  $A \leq 250$**

C.Y. Wong, Toroidal nuclei, Phys Lett B 41, 446 (1972)

C.Y. Wong, Toroidal and Spherical Bubble Nuclei, Ann.Phys.(N.Y.) {77}, 279 (1973)

➤ **Wong and collaborators later extended their investigations to light nuclear systems. They predicted that, given sufficient angular momentum, toroidal configurations were also possible for high spin light nuclei.**

C. Y. Wong, Phys. Rev. C 17, 331 (1978)

C. Y. Wong, Phys. Rev. Lett. 55, 1973 (1985)

➤ **Recently, various sophisticated microscopic methods address the problem of toroidal nuclei**

- ✓ Nuclear quadrupole moment ↑ , excitation energy ↑
- ✓ Spin zero toroid appears above threshold excitation energy
- ✓ Potential minima can exist for higher angular momenta due to the internal shell effect

Z. X. Ren, P.W. Zhao et al., Nucl. Phys. A 996 (2020)

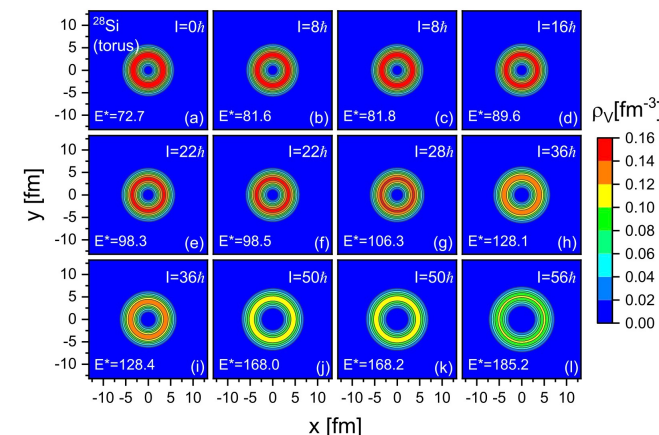
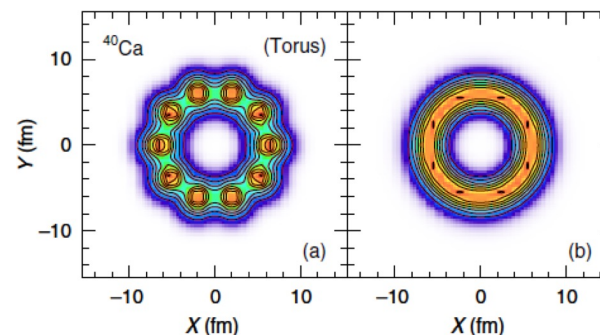
A. S. Umar et al., Phys. Rev. Lett. 104, 212503 (2010)

Zhang Wei et al. Chin. Phys. Lett. 27, 202103 (2010)

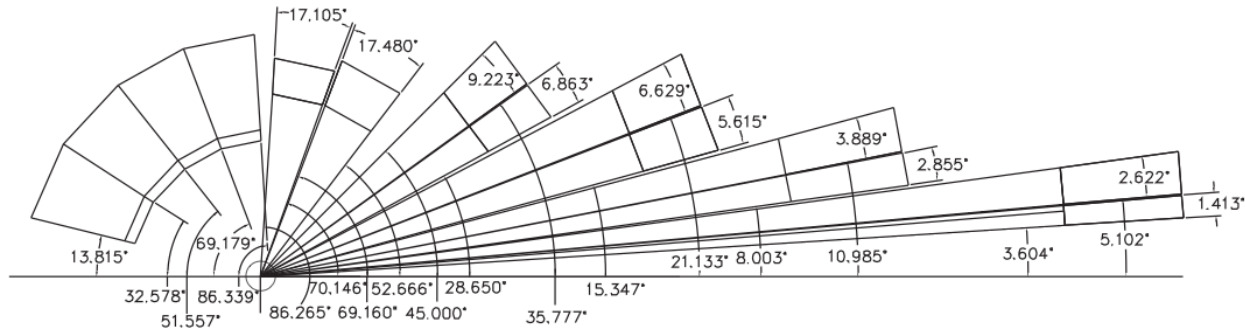
T. Ichikawa et al., Phys. Rev. Lett. 107, 112501 (2011)

T. Ichikawa et al., Phys. Rev. Lett. 109, 232503 (2012)

A. Staszczak, C.Y. Wong, Phys.Lett. B738, 401 (2014)



# NIMROD-ISiS, with TAMU

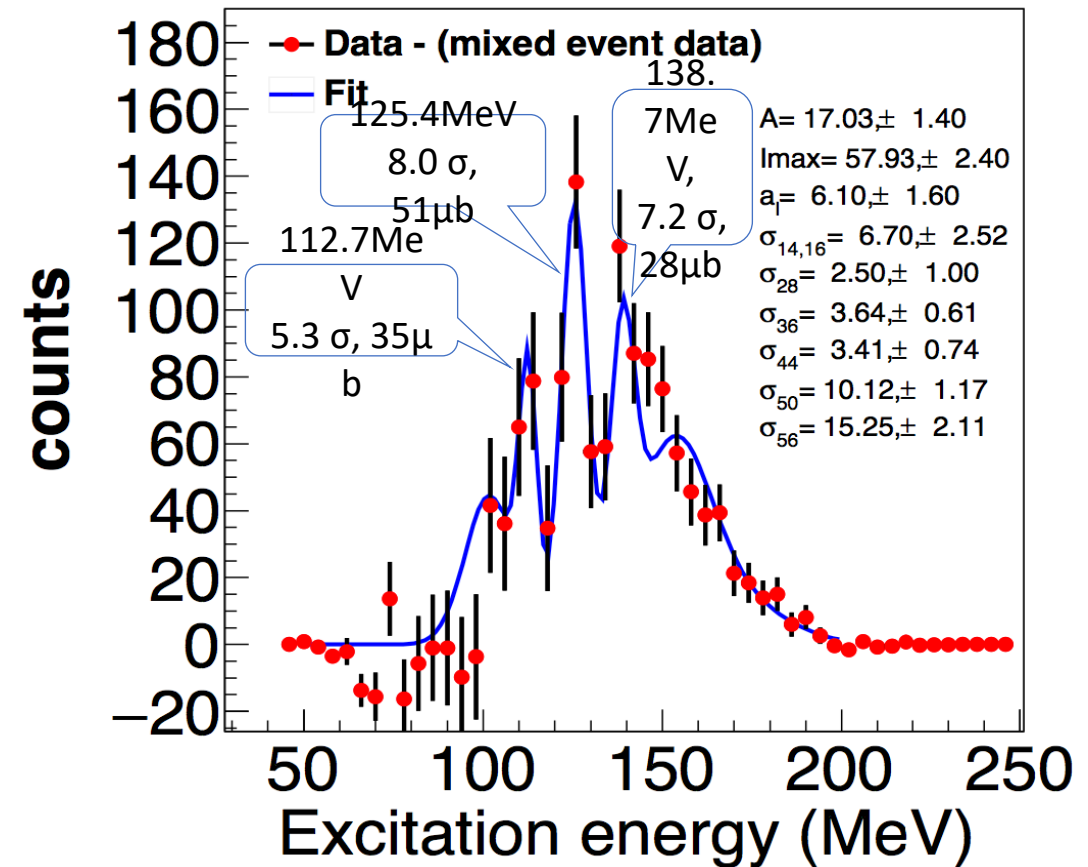


- To explore the peaks in excitation energy spectra of  $7\alpha$  events, several strategies are used:
- ✓ Uncorrelated spectra of data (mixing events)

- ✓ AMD-3.4+Gemini
- ✓ AMD-New(with cluster correlation) + Gemini
- ✓ HIPSE + Gemini

- ✓ A. Staszczak and C. Y. Wong's prediction
- ✓ CDFT calculation by J. Meng group from PKU

- Some excess is seen at 112.7 MeV. The peaks at 125.4 and 138.7 MeV are quite prominent and there is a tailing toward higher energies.
- Excitation energies centroids, CS, Angular momentum

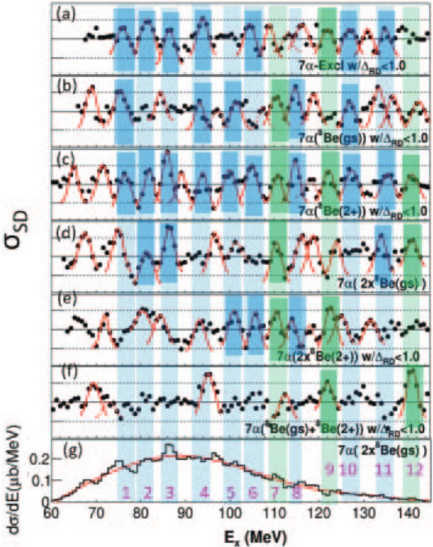


- [1] X. G. Cao, E. J. Kim, K. Schmidt et al., AIP Conf. Pro. 2038, 020021 (2018)
- [2] X. G. Cao, E. J. Kim, K. Schmidt et al., Phys Rev C 99, 014606 (2019)
- [3] X. G. Cao, E. J. Kim, K. Schmidt et al., JPS Conf. Proc. 32, 010038 (2020)
- [4] K. Schmidt, X. G. Cao et al., Phys. Rev. C 95, 054618 (2017)
- [5] K. Schmidt, X. G. Cao et al., Acta Phys. Polon. S13, 631 (2020)

Another experiment of TAMU using different detection array FAUST, comparisons of the two data sets

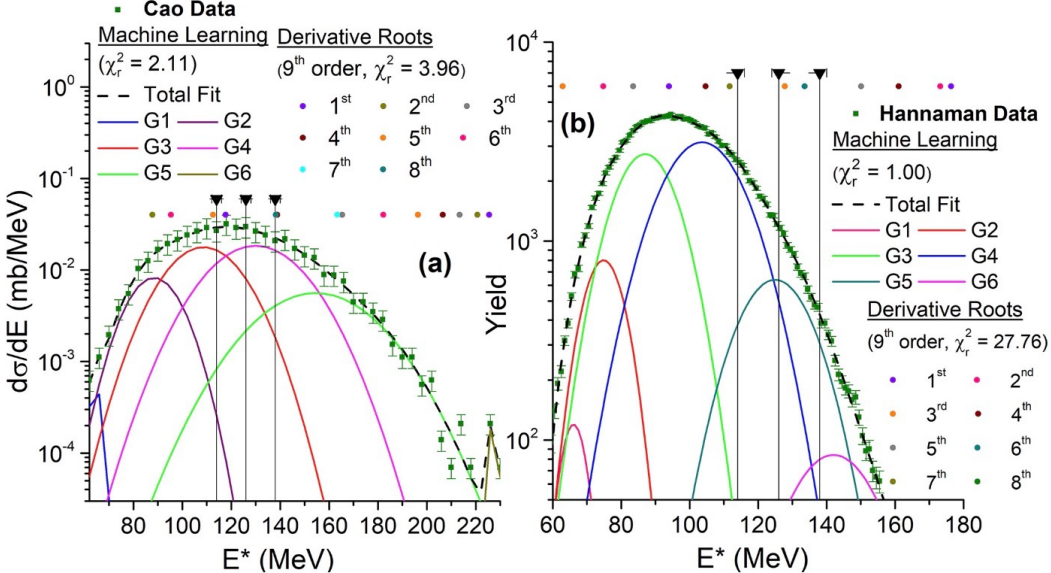
➤ <sup>8</sup>Be开窗方法

R. Wada, IL Nuovo Cimento 48 C (2025) 48



➤ AI assisted Gaussian Mixture Model

T. Depastas, A. Bonasera et al., PRC 112, 014614 (2025)



➤ Background free method, J. B. Natowitz, X. G. Cao, A. Bonasera and T. Depastas, Phys. Rev. C 113, 024325 (2026)

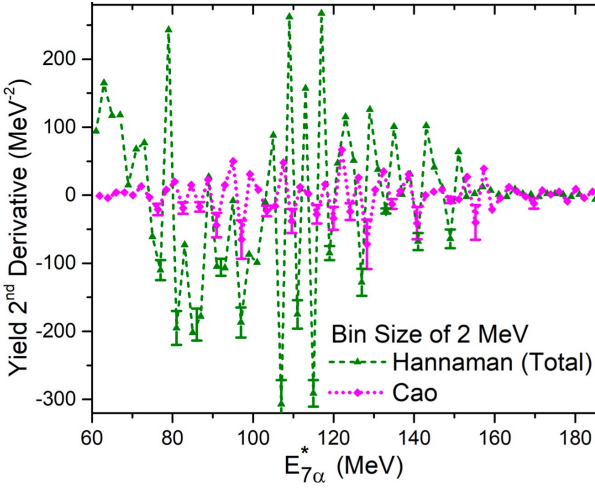
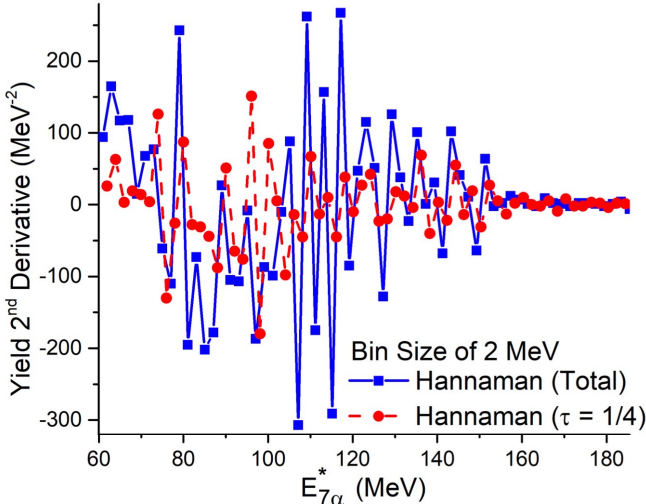


Table I. Identified 7α producing states in excited <sup>28</sup>Si. All energies are in MeV.

| Hannaman [28] | Cao [26]     | WADA [32]              | Ren Predictions [35] | Depastas AI Region Centroids [34] | Hannaman 95% Confidence level |
|---------------|--------------|------------------------|----------------------|-----------------------------------|-------------------------------|
|               |              | 69.5 ± 0.4             |                      | 63.8 ± 2.4                        | 67 ± 1                        |
| 77 ± 1.2      | 76 ± 1.2     | 76 ± 0.4               | 72.7                 | 73.1 ± 0.88                       | 75 ± 1                        |
| 81 ± 1.2      | 82.6 ± 1.2   | 81.5 ± 0.4             | 81.6, 81.8           |                                   | 83 ± 1                        |
| 86 ± 1.2      | 86.7 ± 1.2   | 86.5 ± 0.4             |                      | 85.1 ± 1.6                        |                               |
| 92 ± 1.2      | 90.9 ± 1.2   | 93.5 ± 0.4             | 89.6                 |                                   | 91 ± 1                        |
| 97 ± 1.2      | 97.1 ± 1.2   | 100.5 ± 0.4            | 98.3, 98.5           | 101 ± 2.5                         | 101 ± 1                       |
| 107 ± 1.2     | 103 ± 1.2    | 105.5 ± 0.4            | 106.3                |                                   |                               |
| 111 ± 1.2     | 110 ± 1.2    | 110.5 ± 0.4            |                      |                                   | 109 ± 1                       |
| 115 ± 1.2     | 116 ± 1.2    | 114.5 ± 0.4            |                      |                                   | 117 ± 1                       |
| 119 ± 1.2     | 120 ± 1.2    | 118.5 ± 0.4            |                      |                                   |                               |
|               | 124 ± 1.2    | 122.5 ± 0.4            |                      | 121 ± 4.11                        |                               |
| 127 ± 1.2     | 128 ± 1.2    | 127 ± 0.4              | 128, 128.1           |                                   | 127 ± 1                       |
| 133 ± 1.2     | 134 ± 1.2    | 134 ± 0.4              |                      |                                   |                               |
| 141 ± 1.2     | 141 ± 1.2    | 140.5 ± 0.4            |                      | 139 ± 4.5                         |                               |
| 149 ± 1.2     | 149 ± 1.2    |                        | 147.9                |                                   |                               |
|               | 155 ± 1.2    |                        |                      |                                   |                               |
|               | 170 ± 1.2    |                        | 168, 168.2           |                                   | 169 ± 1                       |
| Neg 2nd Der.  | Neg 2nd Der. | <sup>8</sup> Be filter |                      |                                   |                               |

- ✧ Resonance structures at very high excitation energies for  $7\alpha$  are first found, which coincides with the toroidal calculations
- ✧ More experiments with high resolution and high statics will push this study ahead

### Acknowledgement to the collaborators:

J. B. Natowitz, E. J. Kim, K. Schmidt, K. Hagel, M. Barbui, J. Gauthier, S. Wuenschel, G. Giuliani, M. R. D. Rodriguez, S. Kowalski, H. Zheng, M. Huang, A. Bonasera, R. Wada, N. Blando, C. Y. Wong, A. Staszczak, Z. X. Ren, P. W. Zhao, Y. K. Wang, S. Q. Zhang, J. Meng, Y. G. Ma

# $^{28}\text{Si} + ^{27}\text{Al}$ @ 35MeV/u experiment at RIBLL1



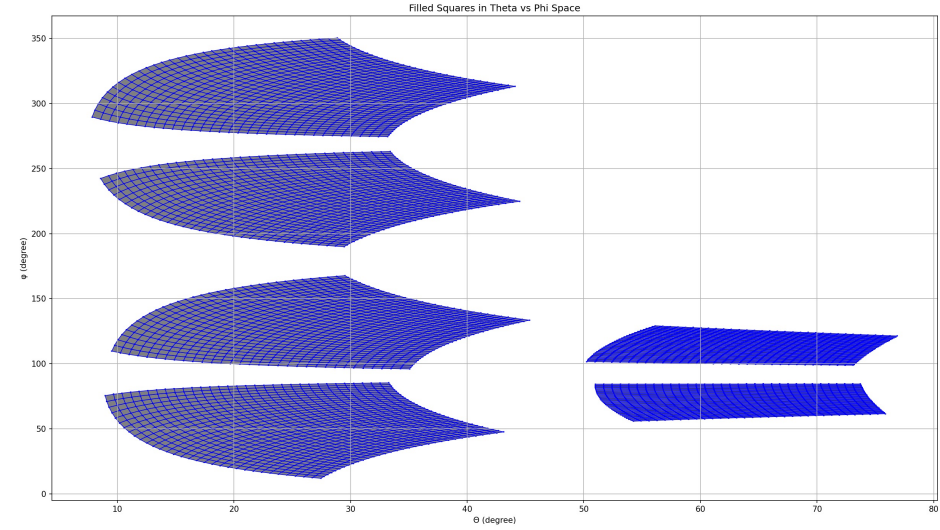
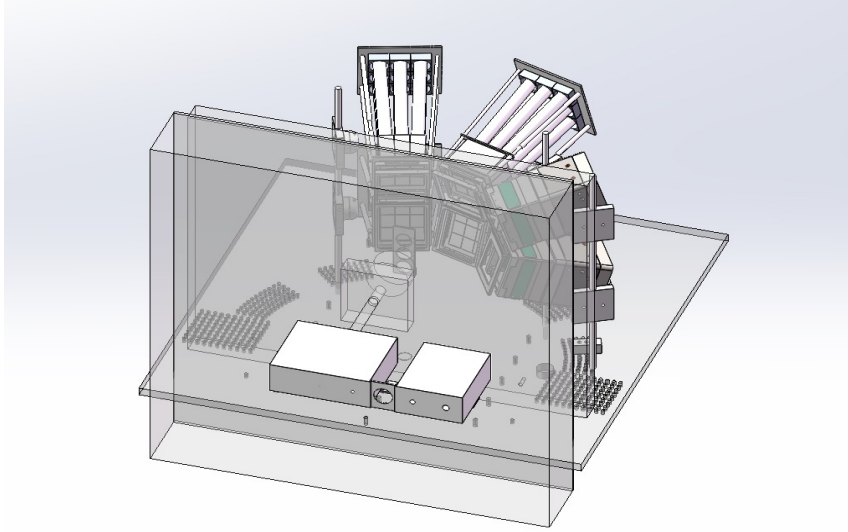
Collaborated with Fudan Uni., De-Qing Fang, Wan-Bing He, Yu-Gang Ma et al./Henan Normal Uni., Chun-Wang Ma et al. /Huzhou Uni., Jian-Song Wang et al./SUES: Qian-Min Su et al.

First very small forward angular measurement @RIBLL1 with main beam

Difficult points :

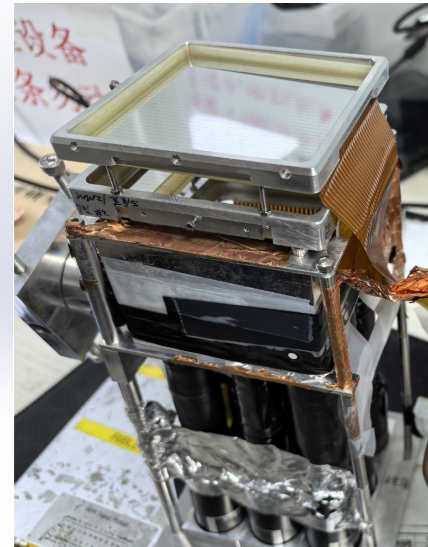
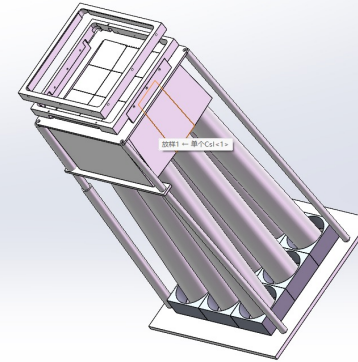
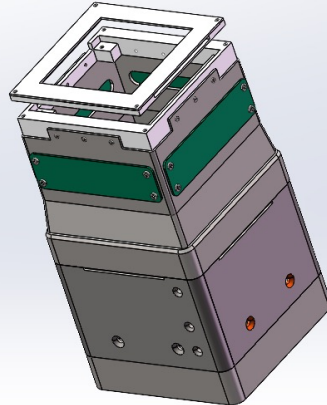
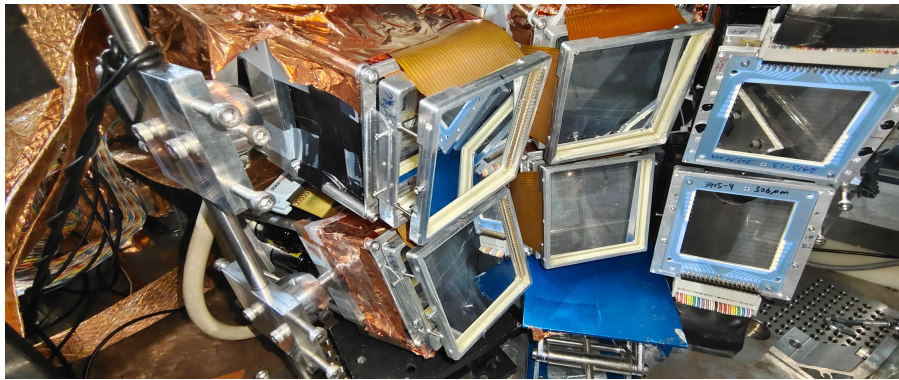
- 1) High risk of damaging DSSD in forward angle measurement
- 2) Large solid angle coverage required for  $7\alpha$  coincident measurement, as close to  $0^\circ$  as possible
- 3) How to avoid huge background induced by main beam incident on collimator
- 4) No detector can help to diagnose the beam besides the Faraday cup

- The granularity of the telescope and the accuracy of position reconstruction are crucial to extract the 7a excitation energy



Angular resolution  $< 1^\circ$

- R&D of high performance charged particle telescope



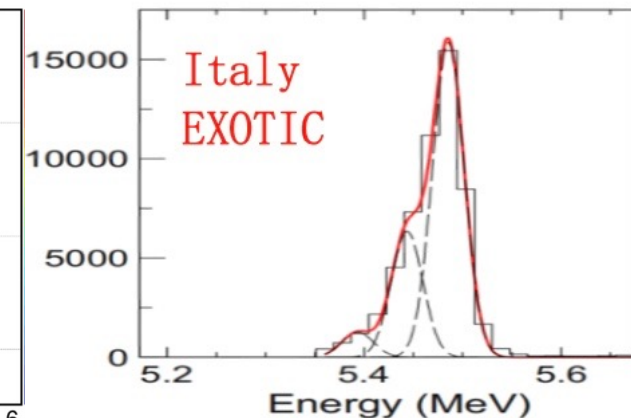
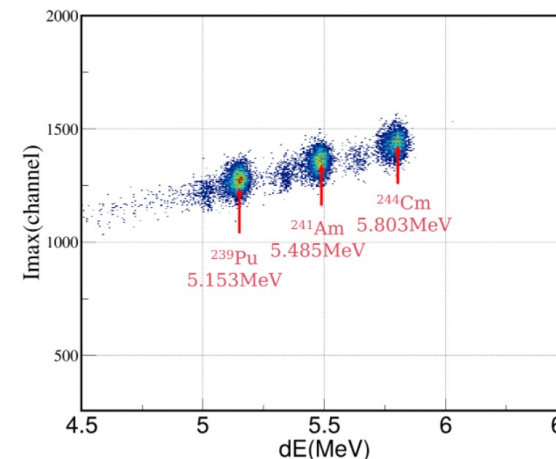
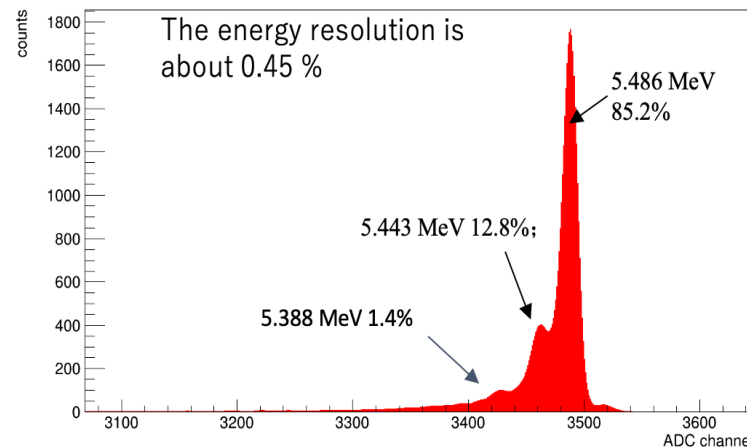
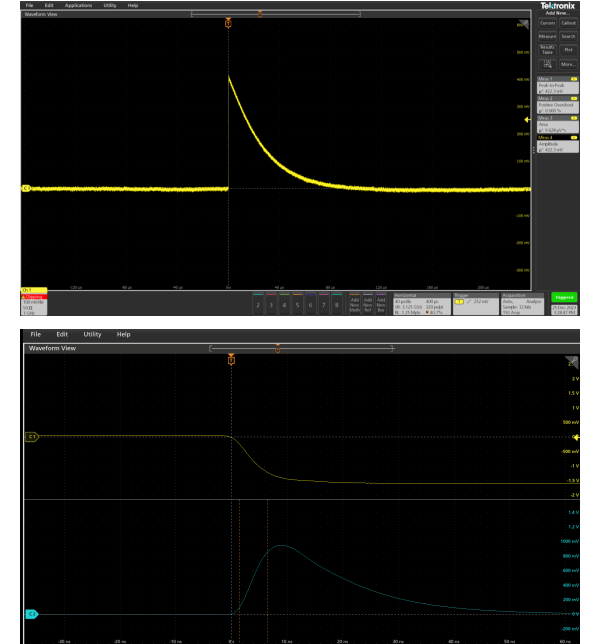
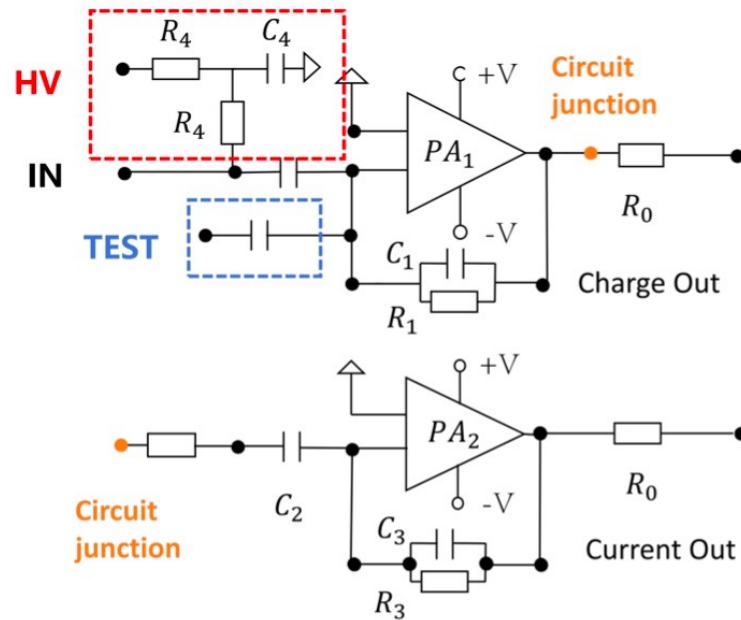
# 1) R&D of Charge-current dual readout preamplifier (CCPA) for SSSD

Charge Integration of DSSD:

$$V(t) = \int \frac{Idt}{C_1} \quad V(t) = -\frac{Q}{C_1} e^{-\frac{t}{C_1 R_1}}$$

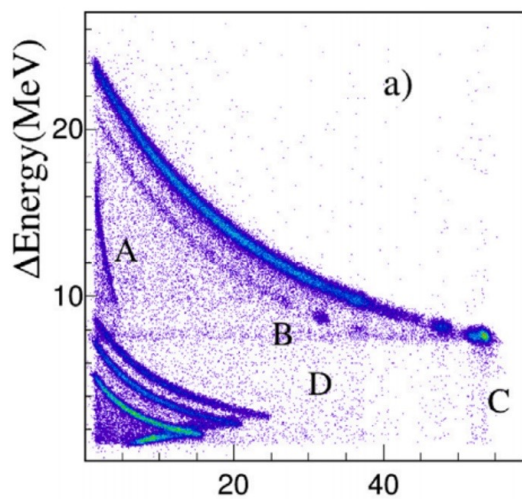
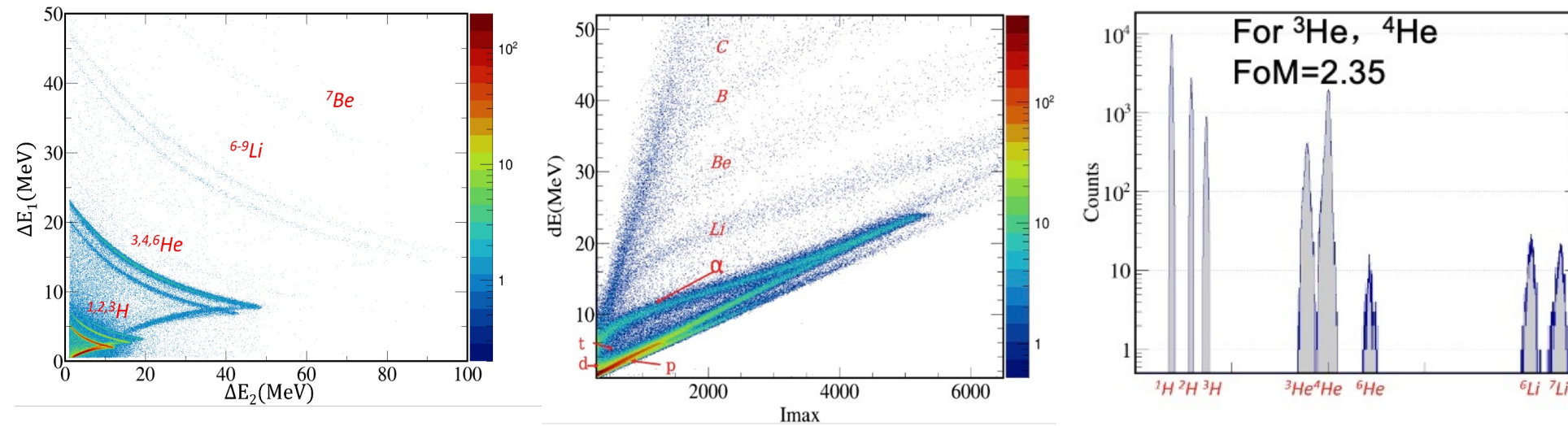
Current signal of DSSD:

$$V_I = -\frac{dV(t)}{dt} C_3 R_3 \quad V_I = \frac{I(t) C_3 R_3}{C_1}$$

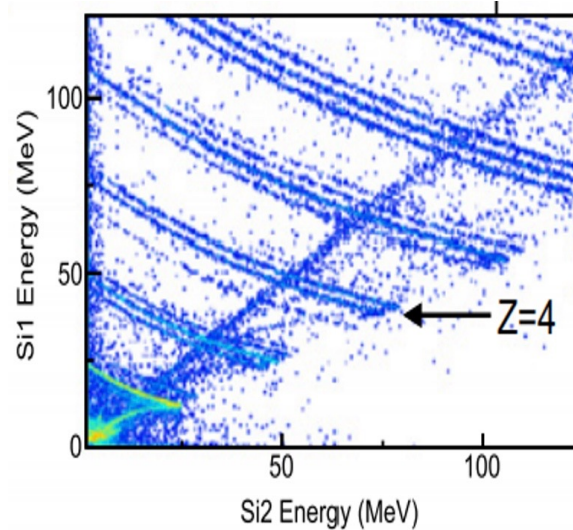


# PID performance with CCPA and comparisons with large array abroad

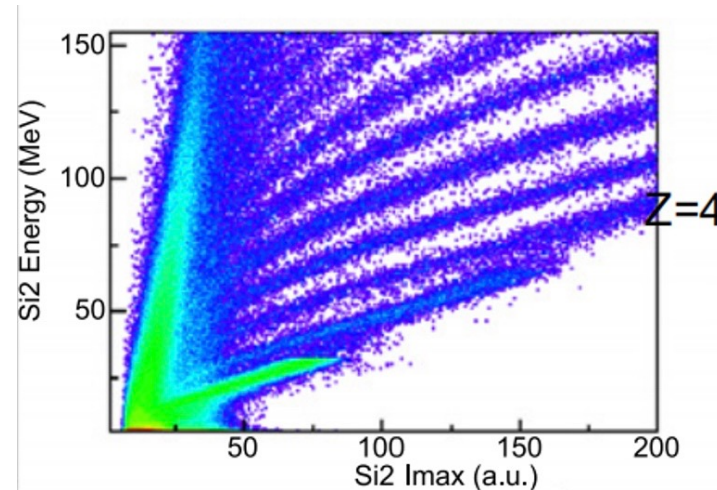
## The third one to realized the PID by PSD



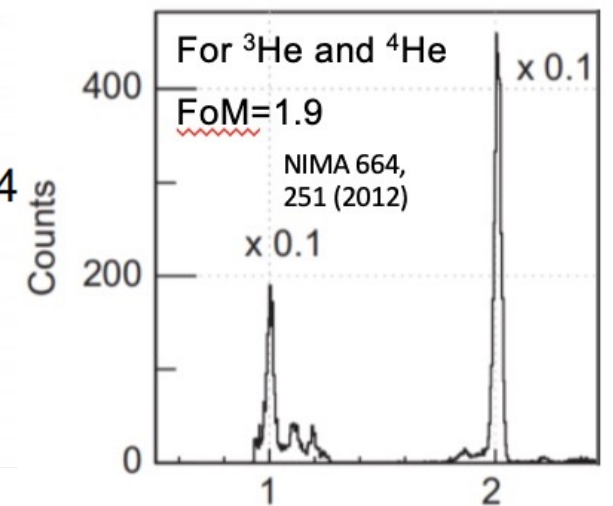
FARCOS



European FAZIA

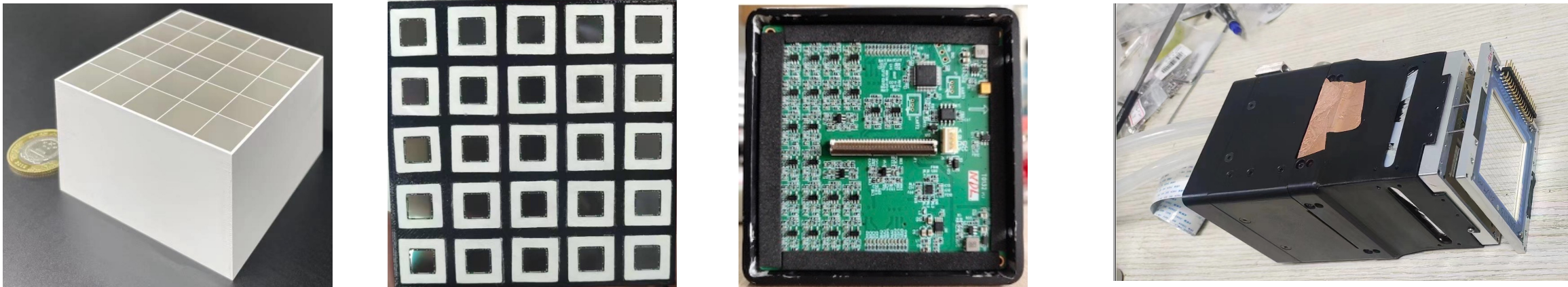


European FAZIA



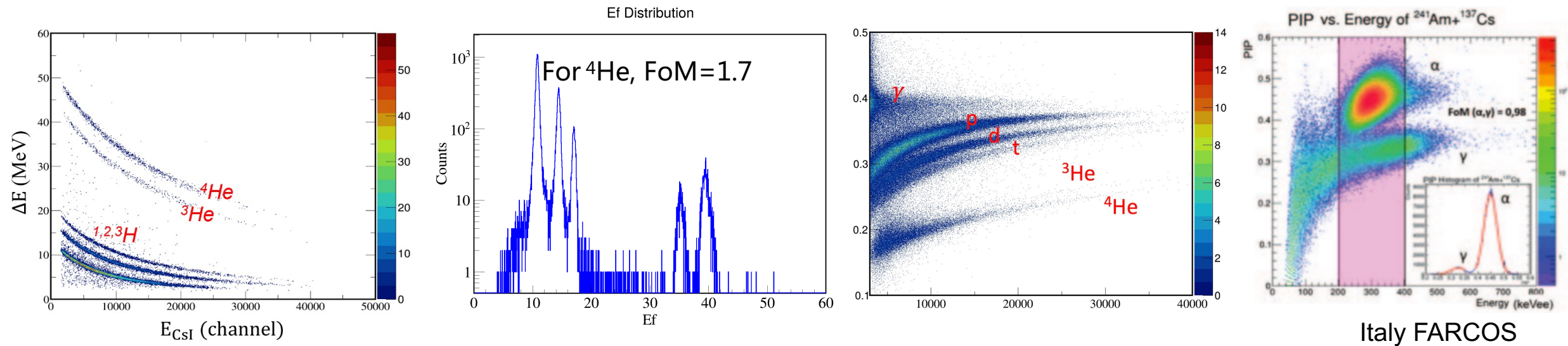
European FAZIA

## 2) R&D of high granularity CsI array by SiPM



Z. L. Liao, X. G. Cao\*, et al., Design and construction of charged-particle telescope array for study of exotic nuclear clustering structure, Nucl. Sci. Tech. 35, 134 (2024)

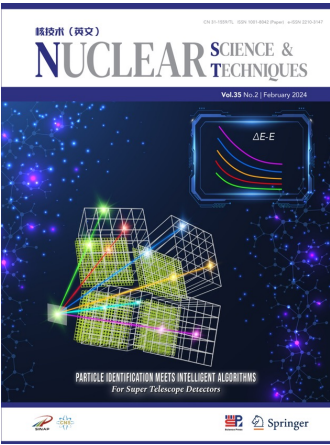
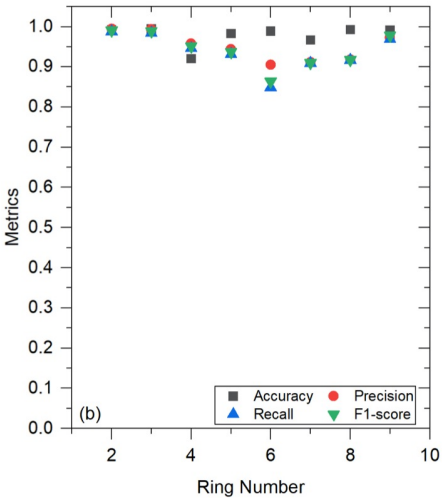
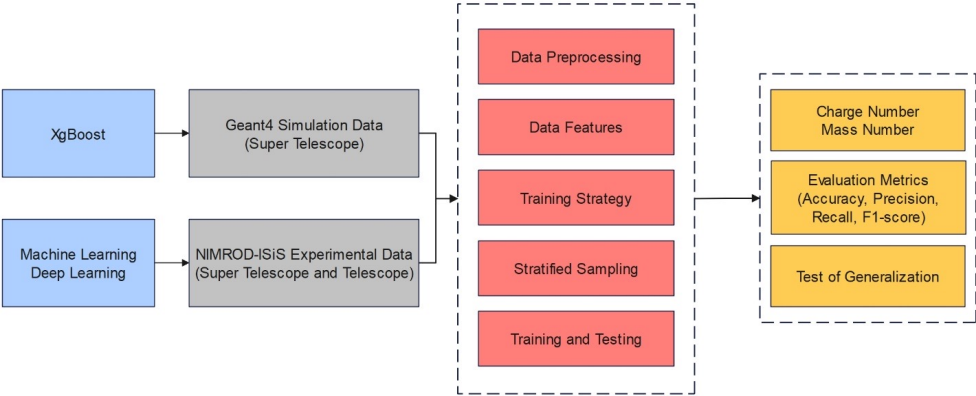
### Performance and comparison with other large array abroad



Ji-Shao Xu, Xi-Guang Cao\*, et al., Pulse shape discrimination with charge and current sensitive preamplifier, to be submitted to Nucl. Instrum. Methods Phys. Res. A

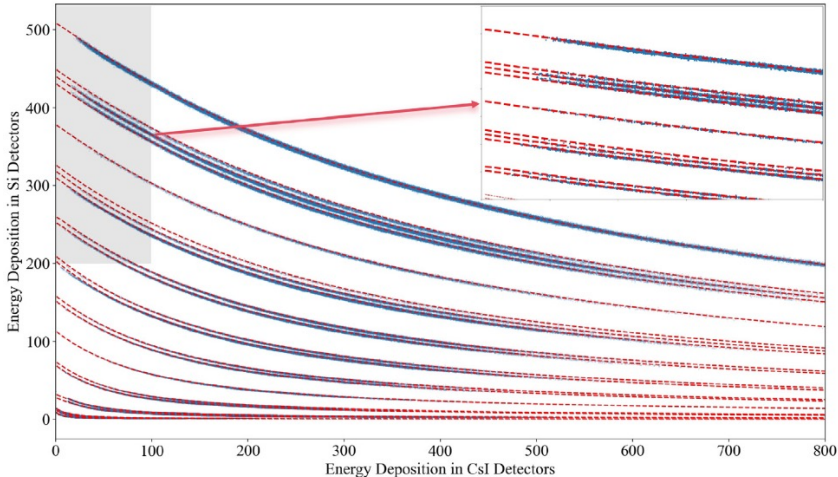
### 3) New data analysis method of PID

➤ Supervised learning algorithms exploration



Y. G. Cheng, Q. M. Su\*, X. G. Cao\* et al., The study of intelligent algorithm in particle identification of heavy-ion collisions at low and intermediate energies Nucl. Sci. Tech. Vol 35, 33 (2024)

➤ Proposed a particle identification method based on the optimal solution algorithm



$$\Delta E = [(gE)^{\mu+v+1} + (\lambda Z^{\alpha} A^{\beta})^{\mu+v+1} + \xi Z^2 A^{\mu} (gE)^v]^{1/(\mu+v+1)} - gE$$

$$X = [\alpha, \beta, \mu, v, g, \lambda, \xi, n_1, n_2, n_3, n_4, \dots, n_i]$$

$$y = \frac{1}{Nl} * \sum_{i=1}^{Nl} \frac{\sum_{j=1}^{Np_i} (\Delta E_j - f(E_j))^2}{Np_i}$$

G. Y. Cheng, X. G. Cao\*, Q. M. Su\* et al, Research on charged particle identification of telescope in heavy-ion collisions at low and intermediate energies based on optimization algorithms, Nucl. Instrum. Methods B 554, 165453 (2024)

# III. Photodisintegration as cluster probe

## Features of photonuclear reactions

- ✓ Reaction mechanism is clear and directly relates to nuclear structure

$$\sigma_{\text{exp}} \propto |\langle \psi_f | H_{EM} | \psi_i \rangle|^2$$

- ✓ Strict select rules

- Angular momentum rule :  $|J_i - L| \leq J_f \leq J_i + L$
- Parity rule :  
Electric multipole transition :  $\pi_f = \pi_i \cdot (-1)^L$   
Magnetic multipole transition :  $\pi_f = \pi_i \cdot (-1)^{L+1}$
- Isospin rule :  $\Delta T = 0, \pm 1$

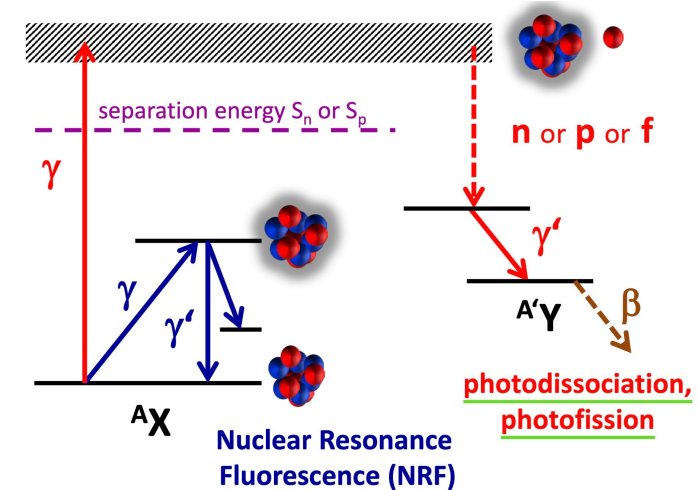
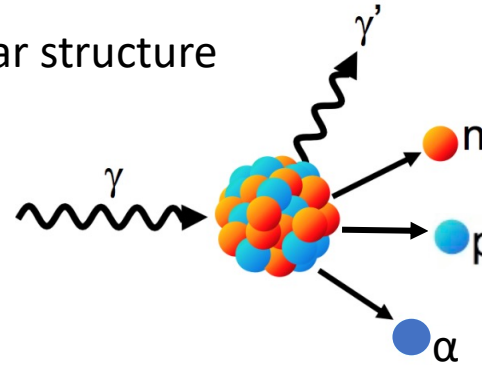
- ✓ Highly sensitive to cluster structure (e.g., E1)

$$\vec{D} \propto \sum q_i \vec{r}_i$$

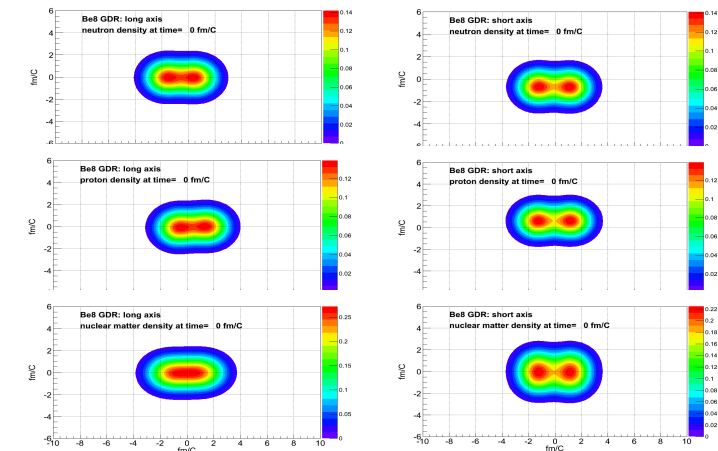
W. B. He, Y. G. Ma, X. G. Cao, X. Z. Cai, G. Q. Zhang, PRL 113,032506 (2014)

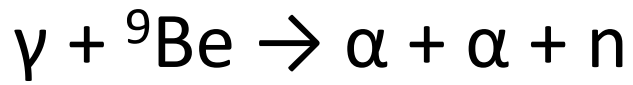
W. B. He, Y. G. Ma, X. G. Cao, X. Z. Cai, G. Q. Zhang, PRC 94, 014301 (2016)

- ✓ Directly corresponds to the reverse process of nuclear synthesis in astrophysics  
Suh as,  $\alpha + \alpha + n \rightarrow {}^9\text{Be} + \gamma$ , no model dependence

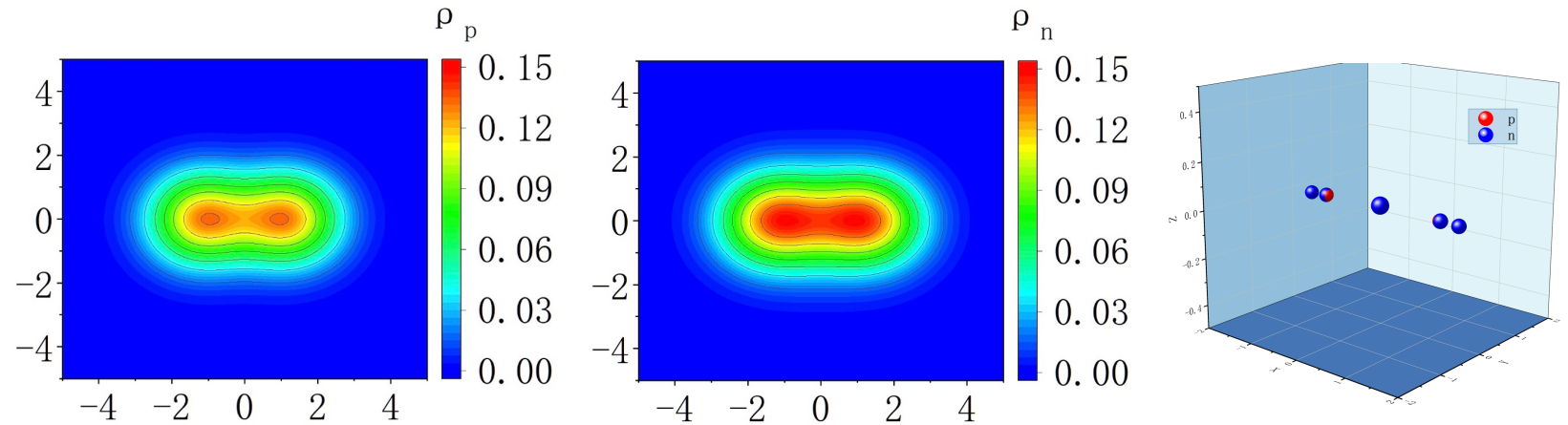


From T. Shizuma and A. Zilges

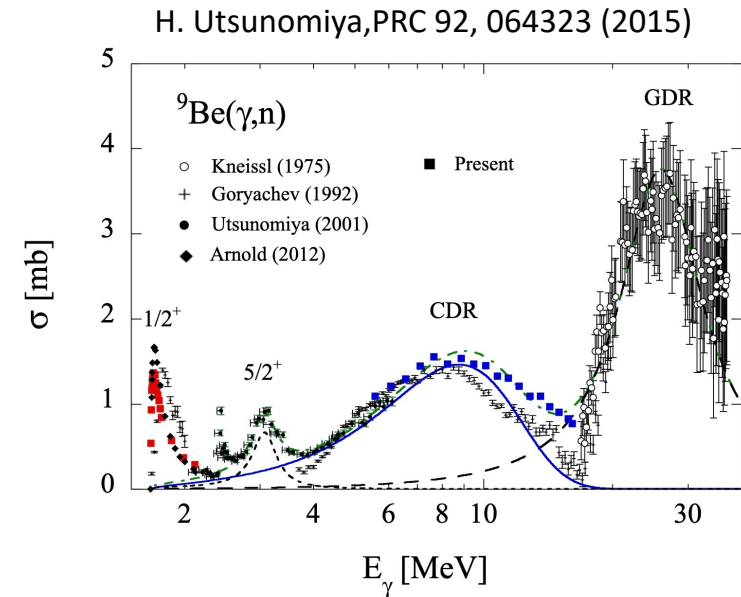
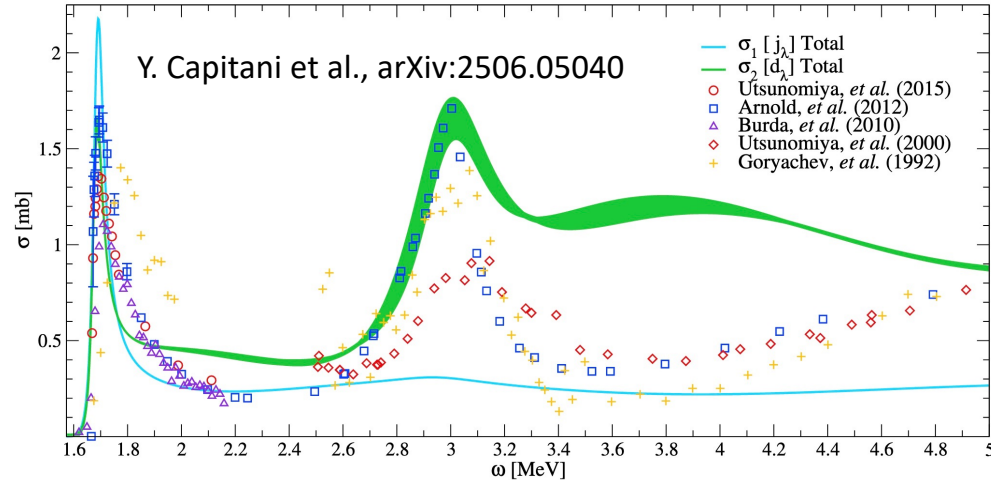




- Typical molecular configuration with  $2\alpha + n$



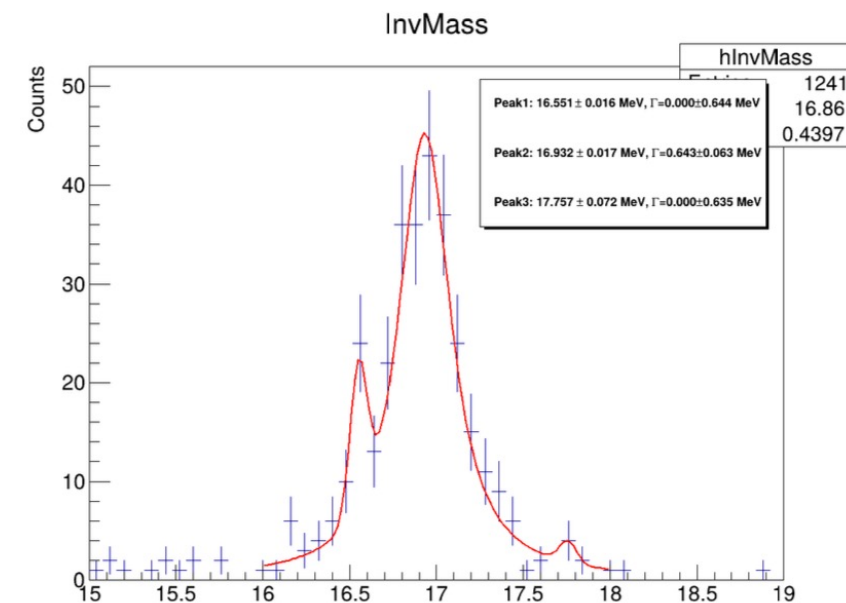
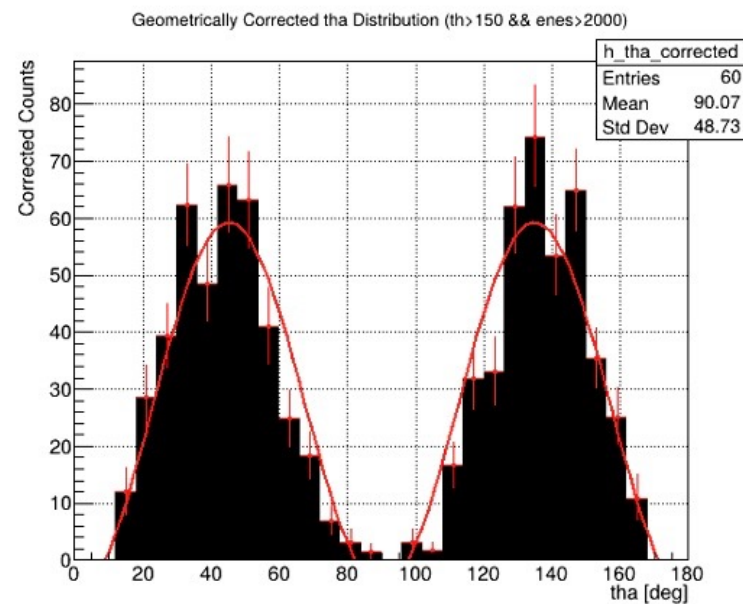
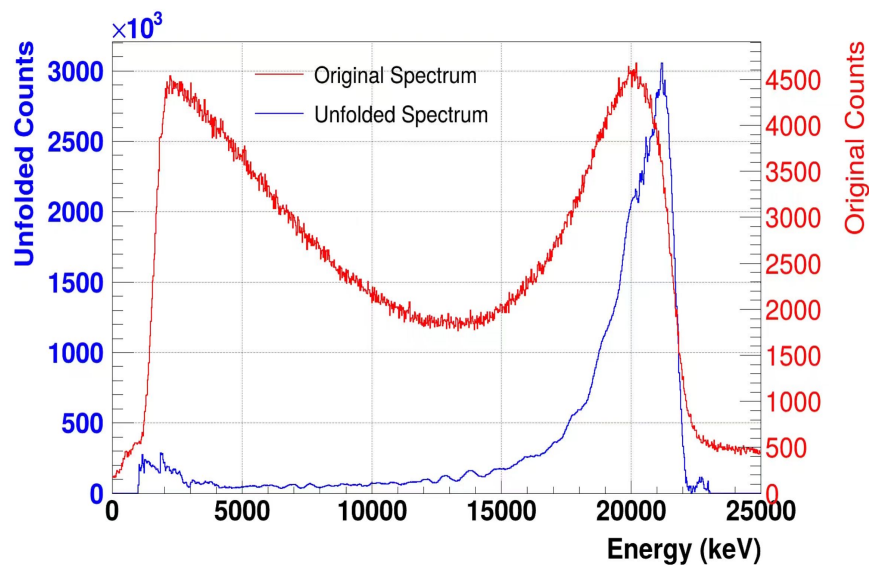
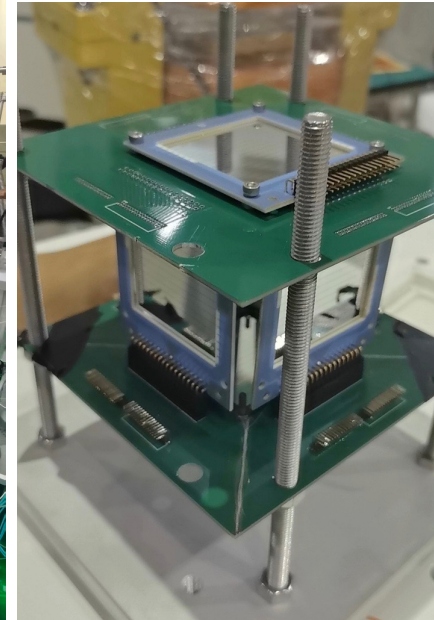
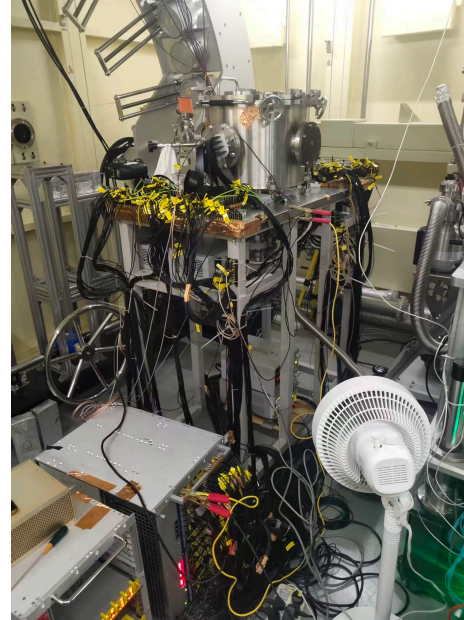
- For most all experiments till now, only n counts is measured for  $\gamma + {}^9\text{Be}$



- Coincident measurement  $2\alpha$  with high-precision energy and momentum will provide valuable information for decay paths, and cluster dynamics

# ➤ Challenge for low CS, low energy of charged particles for Photodisintegration

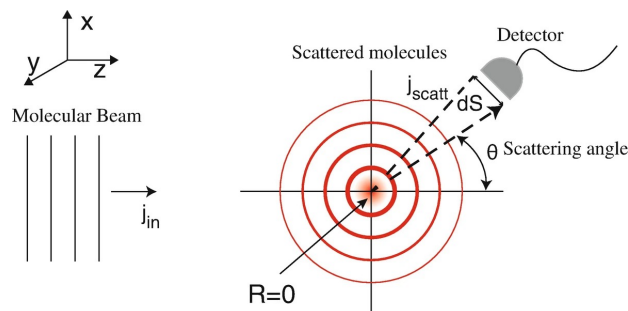
- ✓ Self-made CCPA amplifier preamplifier
- ✓ Silicon box detector array
- ✓ Ultra-thin reaction target
- ✓ Ultra-thin entrance window with special design
- ✓ Mesytec DAQ



Collaborated with Fudan Uni., De-Qing Fang, Ji-Shao Xu, Wan-Bing He, Yu-Gang Ma et al.

# IV. Scattering as two-body cluster probe

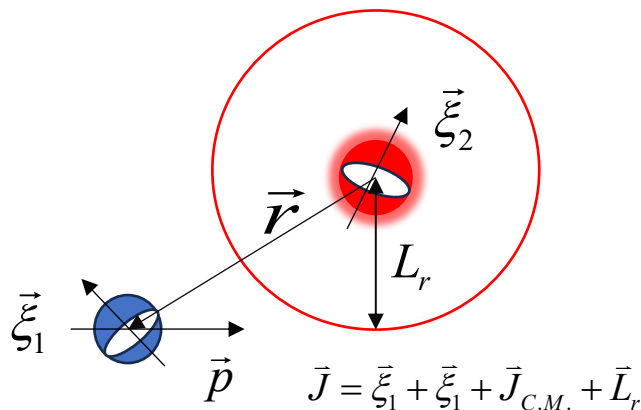
Our scheme: PFM+RGM to extract two body cluster structure



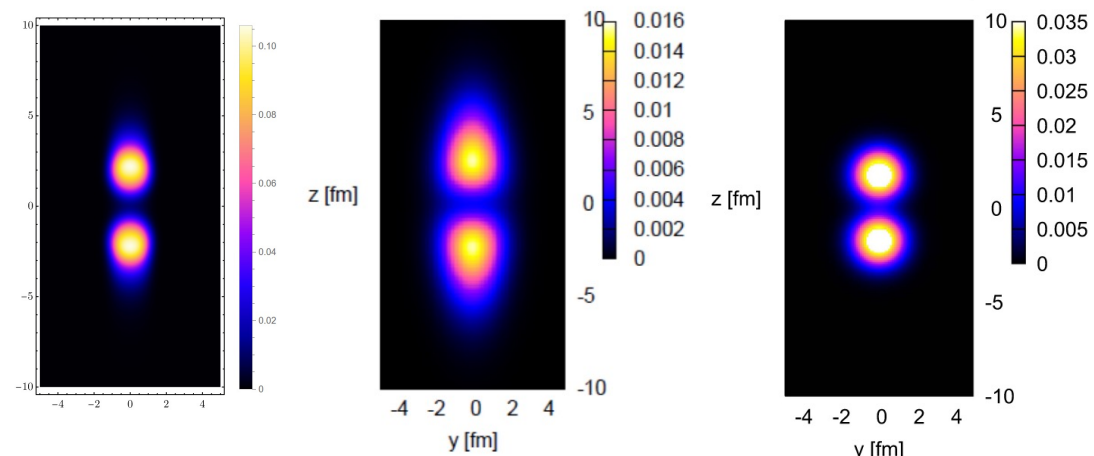
Phase Function Method (PFM)

$$\delta'_\ell(k, r) = -\frac{V(r)}{k(\hbar^2/2\mu)} \left[ \cos(\delta_\ell(k, r)) \hat{j}_\ell(kr) - \sin(\delta_\ell(k, r)) \hat{n}_\ell(kr) \right]^2$$

Ref: Babikov V V. Sov. Phys. Usp., 1967, 10(3): 271



- Encapsulation of internal degrees of freedom
- RGM antisymmetrization



PFM+RGM

THSR wave function

Brink wave function

B. Zhou et al., Phys. Rev. C  
89, 034319 (2014)

P. Schuck et al., Phys. Scr.  
91, 123001 (2016)

$$\Phi(C_1 + C_2) = \mathcal{A} \{ \chi(\mathbf{r}) \phi(C_1) \phi(C_2) \}$$

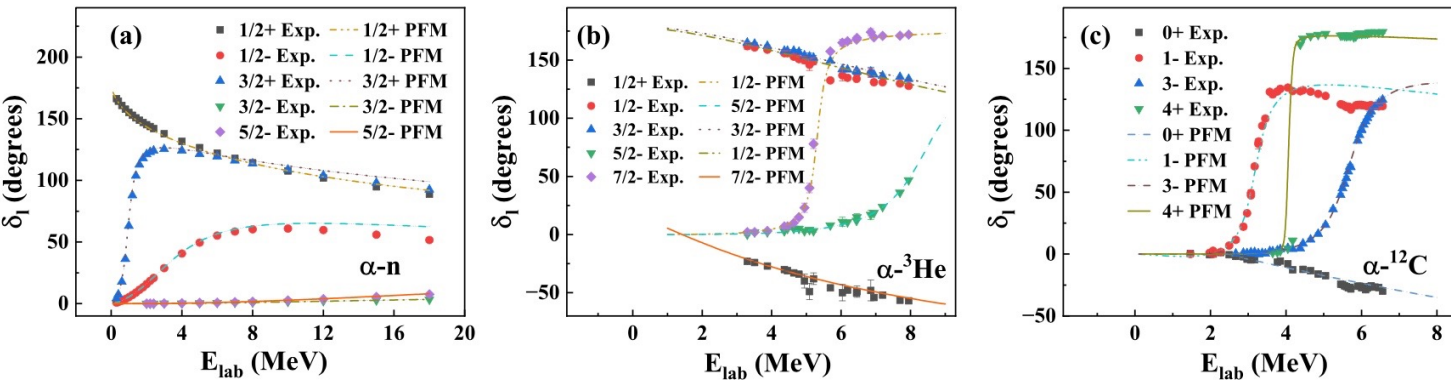
$$\left\{ \frac{-\hbar^2}{2\mu} \left( \frac{\partial}{\partial \mathbf{p}} \right)^2 + V_D(\rho) - E_r \right\} \chi(\mathbf{p}) + \int d\mathbf{p}' [H_{ex}(\mathbf{p}, \mathbf{p}') - EN_{ex}(\mathbf{p}, \mathbf{p}')] \chi(\mathbf{p}') = 0$$

$$H(\mathbf{p}, \mathbf{p}') \approx [T_p + V(\mathbf{p})] A(\mathbf{p}, \mathbf{p}') \quad \frac{\hbar^2}{2\mu} \left[ \frac{d^2}{dr^2} + \left( k^2 - \frac{\ell(\ell+1)}{r^2} \right) \right] \chi_l^{PFM}(r) = V_l(r) \chi_l^{PFM}(r)$$

$$\Phi(C_1 + C_2) = \mathcal{A} \{ \chi_l^{PFM}(\mathbf{r}) \phi(C_1) \phi(C_2) \}$$

- Construction of local potentials via phase shift functions
- Implementation of Pauli blocking

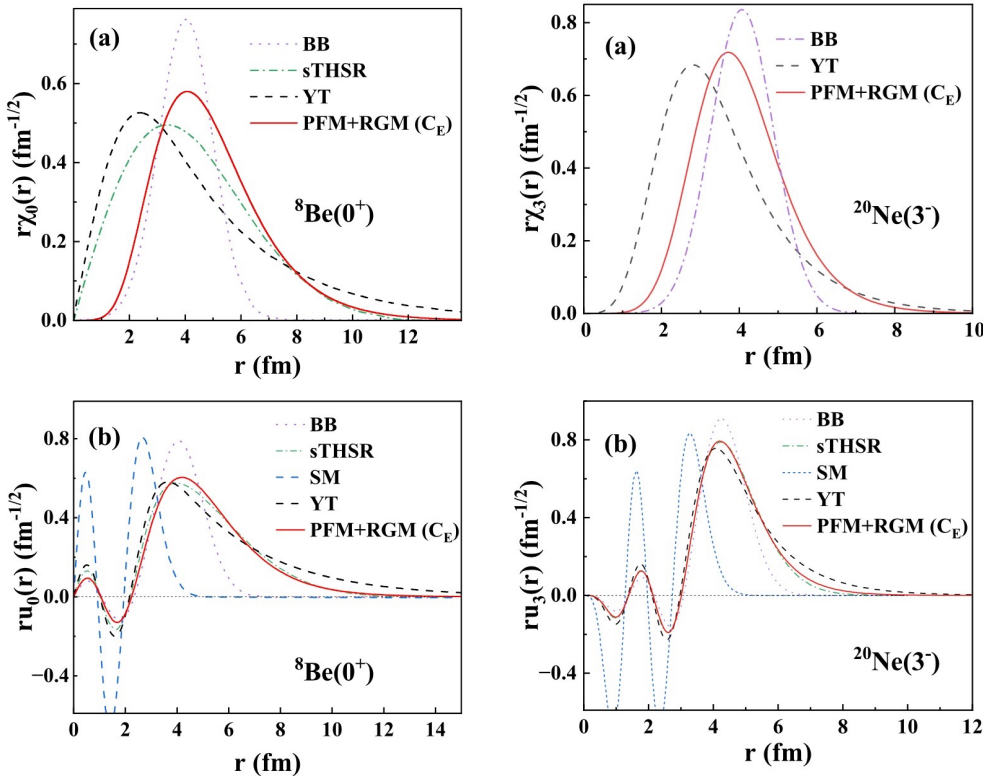
- Comparison between PFM-calculated scattering phase shift and experimental data



- Comparison of  $E_r$  values from experiment and various nuclear models

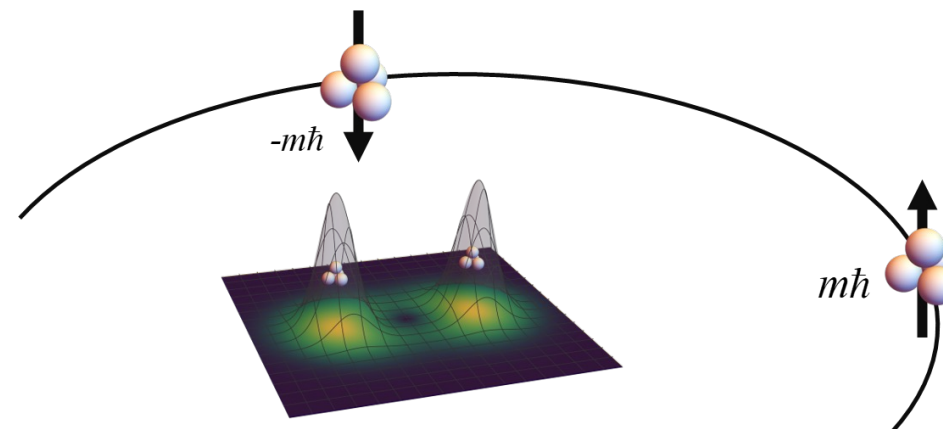
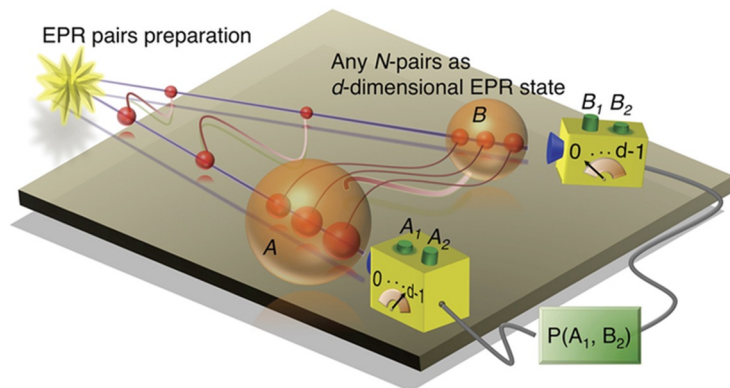
|                       | $E_r^{\text{expt}}$ | $E_r^{\text{YT/GCM}}$ | $E_r^{\text{PFM-RGM}}(C_E)$ | $E_r^{\text{NCSM}}$ | $E_r^{\text{NCSMC}}$ | $E_r(V_{\text{Morse}})$ | $E_r(V_{p4})$ | $E_r(V_{\text{WS}})$ |
|-----------------------|---------------------|-----------------------|-----------------------------|---------------------|----------------------|-------------------------|---------------|----------------------|
| $^8\text{Be}(0^+)$    | 0.092               | -0.02                 | 0.091                       |                     |                      | -1.25                   | 2.062         | -1.61                |
| $^{20}\text{Ne}(3^-)$ | 2.43                | 1.07                  | 2.43                        |                     |                      | 8.6                     | 0.847         | 1.85                 |
| $^7\text{Li}(3/2^-)$  | -2.467              |                       | -2.48                       | -1.79               | -2.43                | 2.919                   | 0.183         | -2.34                |

- Comparison of  $^8\text{Be}$  and  $^{20}\text{Ne}$  calculations by different models



Fei-Long Xu, Xi-Guang Cao\*, and Yu-Gang Ma\*, Extracting two-body nuclear cluster structure by combining the phase function method and the resonating group method, Phys. Rev. C 112, 064327 (2025)

# IV. Entanglement as cluster probe



$$|\psi\rangle_{AB} = \sum_{i,j} c_{ij} |i\rangle_A \otimes |j\rangle_B$$

In quantum information, entanglement is quantified within the tensor product space  $H_1 \otimes H_2$

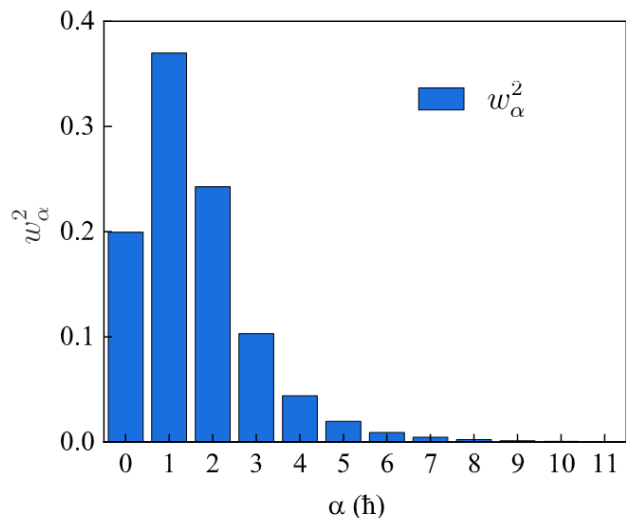
$$\Phi(C_1 + C_2) = \phi_{cm}(\mathbf{R}_{cm}) \mathcal{A}\{\chi(\mathbf{r})\phi_1(C_1)\phi_2(C_2)\}$$

For nuclear system,  $H_{R_{cm}} \otimes H_r$  representation is preferred

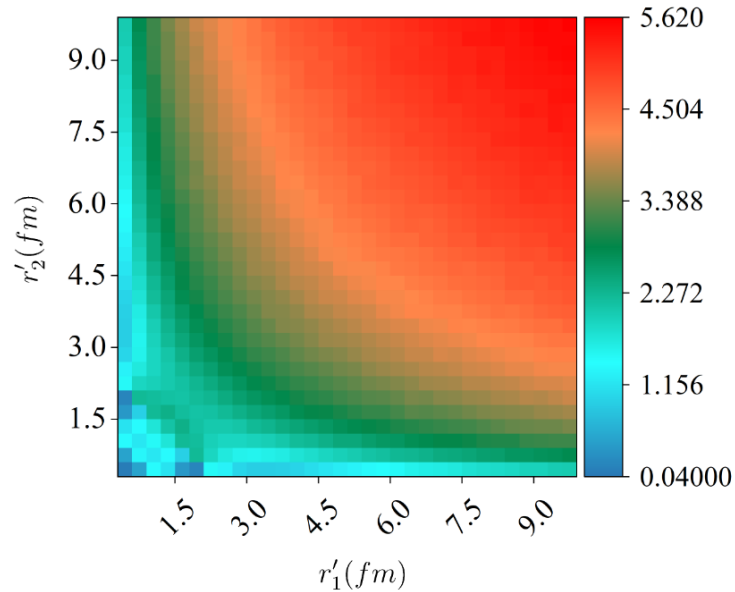
Thus, it is necessary to transform the basis from  $H_{R_{cm}} \otimes H_r$  to  $H_1 \otimes H_2$

$$\psi = \phi_{cm}(R_{cm})u(r)Y_{00} = \sum_{\alpha} \Phi_{\alpha}(r_1, r_2) [Y_{\alpha, -m}(\hat{r}_1) \otimes Y_{\alpha, m}(\hat{r}_2)]_{\{\alpha, 00\}}$$

Fei-Long Xu, Xi-Guang Cao\*, and Yu-Gang Ma\*, Two-body cluster entangled structure in the  $H_1 \otimes H_2$  Hilbert space, Phys. Rev. C113, 014313 (2026)



The proportion of the  $0^+$  coupled channels in  $^8\text{Be}$



Spatially resolved entropy on different spatial radii

$$\psi = \sum_i \lambda_i u_i \otimes v_i = \sum_\alpha \sum_{m=-\alpha}^\alpha w_\alpha \frac{(-1)^{\alpha-m}}{\sqrt{2\alpha+1}} Y_{\alpha,-m} \otimes Y_{\alpha,m}$$

Using a coupled-channel description where  $w$  quantifies the coupling, Left figure demonstrates the strong entanglement of the  $^8\text{Be}$   $0^+$  state.

Spatially resolved entropy visualizes the entanglement within the nucleus.

$$S(\rho_A) = -\text{Tr}_A(\rho_A \ln \rho_A) = -\sum_i \lambda_i^2 \ln(\lambda_i^2)$$

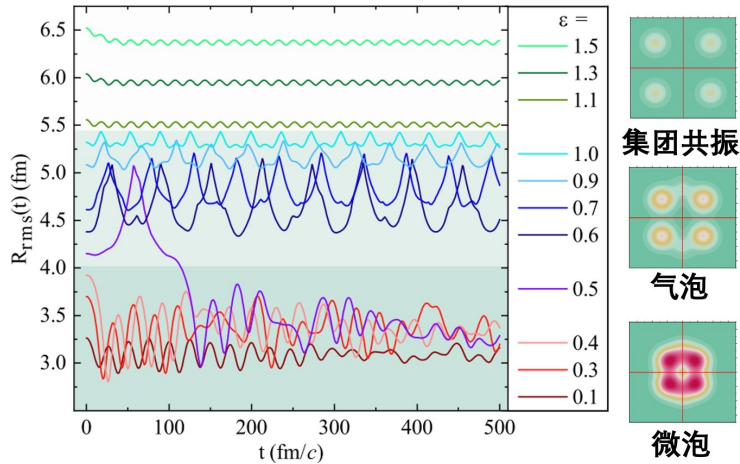
$$\lim_{r'_1 \rightarrow 0, r'_2 \rightarrow 0} \mathcal{W}_0(r'_1, r'_2) = \lim_{r'_1 \rightarrow 0, r'_2 \rightarrow 0} \iint dV_1 dV_2 \frac{\left(\frac{8\gamma_0}{\pi}\right)^{3/4} \exp\{-4\gamma_0 \mathbf{R}_{\text{CM}}^2\}}{F(r'_1, r'_2) r_1^2 r_2^2} \times \sum_n a_n \sqrt{\mu_{n,l_r}} R_{n,l_r}(b_r; r) [Y_{00} \otimes Y_{00}]_{\{0,00\}} \delta(r_1 - r'_1) \delta(r_2 - r'_2) = 1.$$

This suggests that the generation and evolution of spatially resolved entropy are driven by the S-wave channel from a dynamical perspective.

# V. New Breathing modes as cluster/bubble probe

The bubble structure lacks effective experimental probes. How collectively excited for bubble nuclei?

- Find three distinct breathing modes



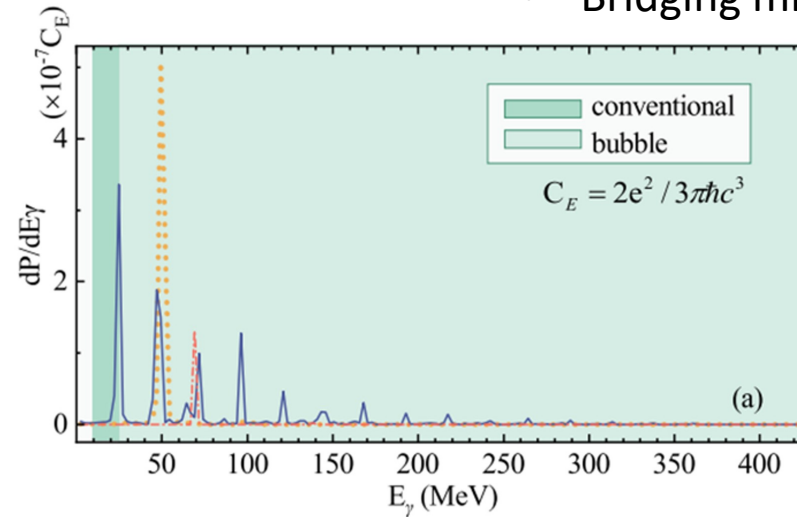
$$R''_{rms}(\omega) = \int_{t_0}^{t_{max}} R''_{rms}(t) e^{i\omega t} dt$$

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma} |R''_{rms}(\omega)|^2$$

G. Ren, C. W. Ma\*, X. G. Cao\*, Y. G. Ma\*, Bubble  $^{36}\text{Ar}$  and its new breathing modes, Phys. Lett. B 857, 138990 (2024)

G. Ren, C. W. Ma\*, X. G. Cao\* et al., accepted by Nucl. Sci. Tech., in press

- Bridging micro & macro physics



For nuclear bubble

$$R = R_0 + G_n Y_n \sin(\omega t + \epsilon)$$

$$f_n = \frac{1}{2\pi G(n)} \sqrt{\frac{\sigma}{\rho R_0^3}} (n-1)n(n+2)$$

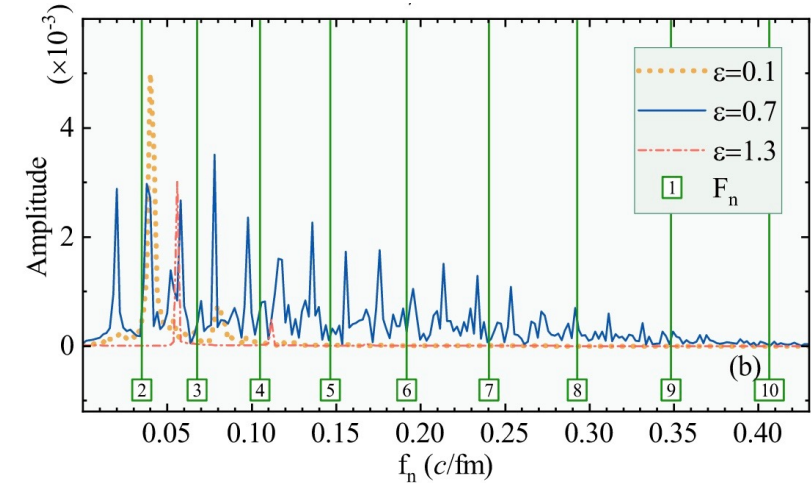
$$G(n) = A n^{\frac{1}{2}} + B n^{-\frac{1}{2}} + C \text{ as a function of mode } n$$



For macroscopic bubble

$$R = R_0 + Y_n \sin(\omega t + \epsilon)$$

$$f_n = \frac{1}{2\pi} \sqrt{\frac{\sigma}{\rho R_0^3}} (n-1)n(n+2)$$



Nuclear Science and Techniques (2024) 35:187  
https://doi.org/10.1007/s41365-024-01581-4

NST Research highlight

RESEARCH HIGHLIGHT

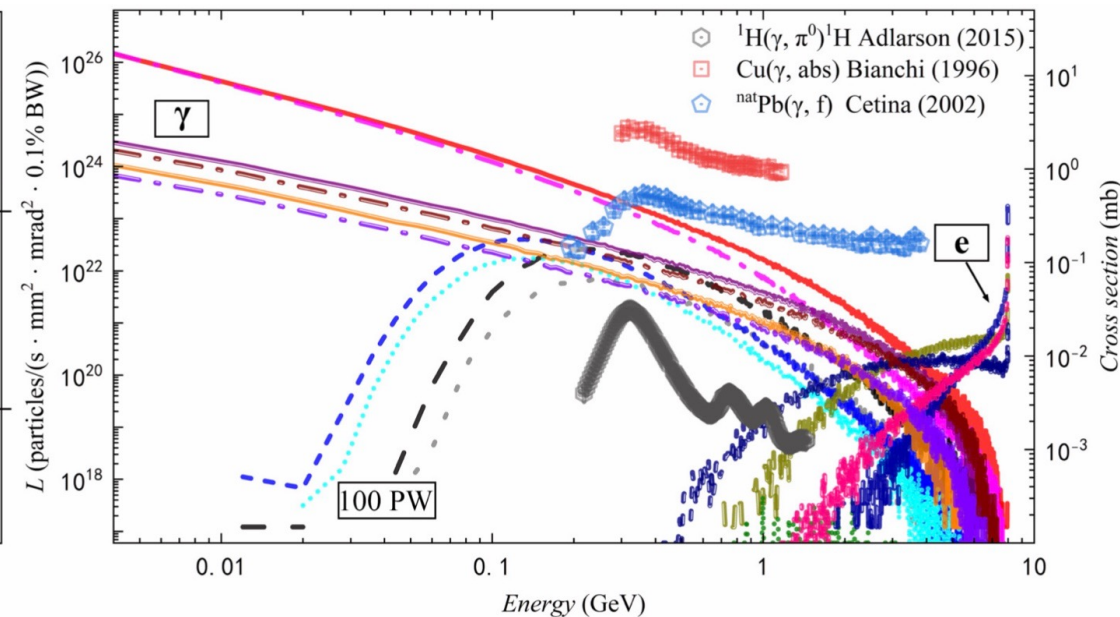
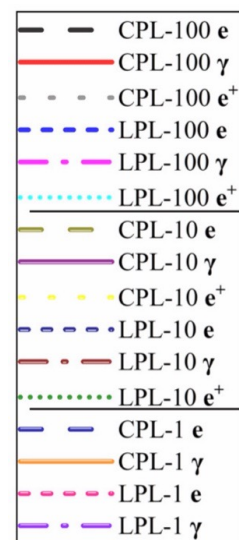
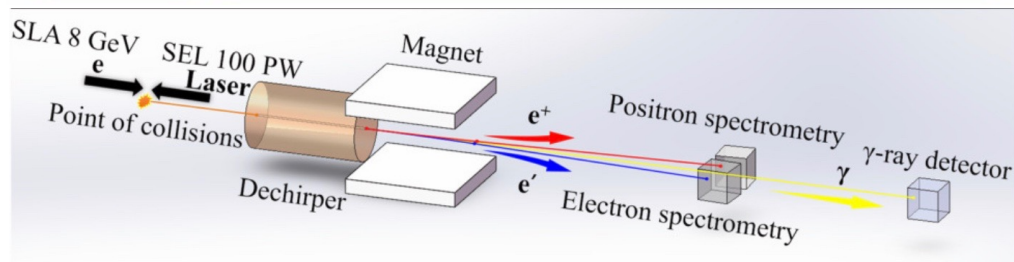
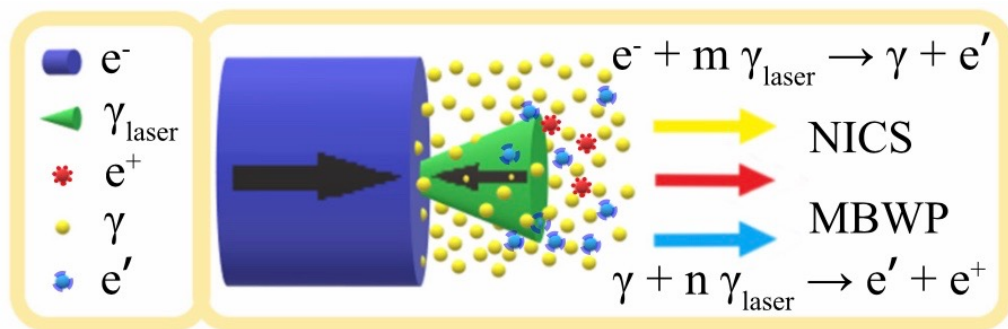
J. Natowitz, Extended quantum molecular dynamics model predicts new breathing modes in  $^{36}\text{Ar}$  bubble nuclei

# VI. Ultra-brilliant, ultra-fast $\gamma/e^+$ probes

Opportunity to study the real multi-photon nuclear absorption/reaction

SHINE (8GeV) + SEL(100 PW), multi-photon Breit-Wheeler process

- Ultra-brilliant:  $\gamma$ :  $10^{27}$  photons/(s·mm<sup>2</sup>·mrad<sup>2</sup>);  $e^+$ :  $10^{24}$  photons/(s·mm<sup>2</sup>·mrad<sup>2</sup>)
- Ultra-fast:  $\sim$ fs
- Low emittance: 0.1 mm · mrad, several orders smaller than traditional  $e^+$  sources
- High energy:  $\gamma$ : up to 8 GeV;  $e^+$ : up to 7 GeV



Wan-Qing Su, Chun-Wang Ma\*, Xi-Guang Cao\*, Guo-Qiang Zhang, and Yu-Ting Wang, GeV-level  $\gamma$ -ray and positron beams produced by collisions of multi-PW laser on high-energy electron beam, accepted by Nucl. Sci. Tech., in press

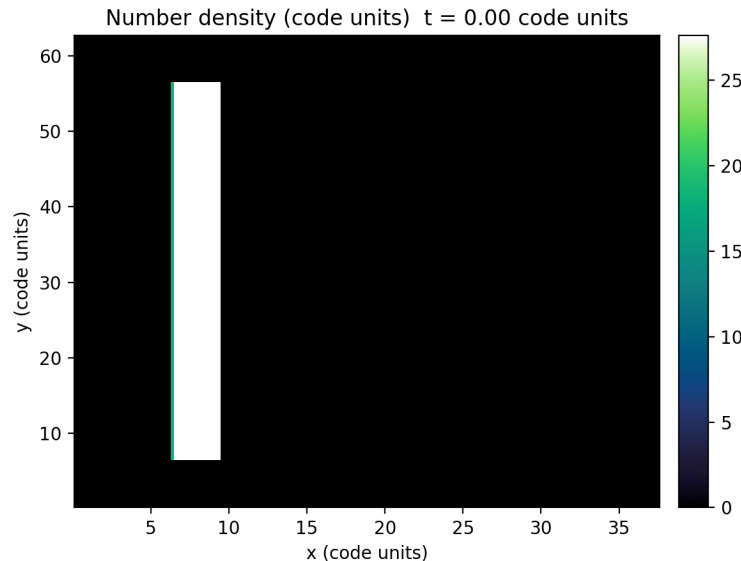
<https://doi.org/10.48550/arXiv.2504.13595>

# VII. Ultra-brilliant, ultra-fast heavy ion beam

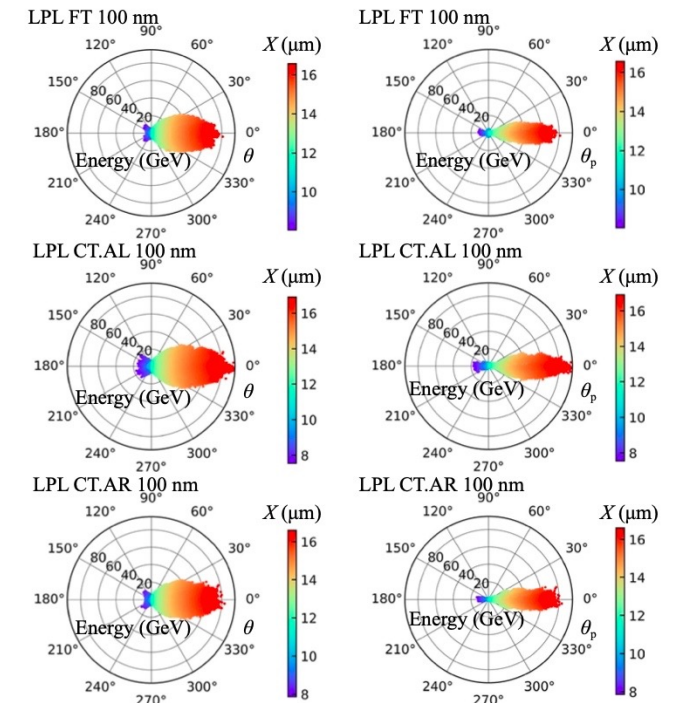
## Opportunity to explore SHN/SHE synthesis

SEL (100 PW) laser incident on thin metal target

- Ultra-brilliant:  $10^{23}$  pps, several orders higher than traditional accelerator,  $\Delta t \sim 40$  as
- Ultra-fast: fs-ps level
- To explore SHN/SHE under extreme plasma environment



| Ion | $D$ (nm) | $L$ (MA) | $\varepsilon$ (mm $\times$ mrad) | $\eta$ (%) |
|-----|----------|----------|----------------------------------|------------|
| Al  | 200      | 2.35     | 0.094                            | 4.66       |
| Ca  | 200      | 2.76     | 0.082                            | 6.36       |
| Cr  | 100      | 1.50     | 0.062                            | 2.40       |
| Fe  | 100      | 1.45     | 0.054                            | 2.33       |
| Ag  | 100      | 1.18     | 0.042                            | 2.22       |
| Ta  | 100      | 0.69     | 0.041                            | 2.05       |
| Au  | 100      | 0.52     | 0.059                            | 2.08       |
| Pb  | 100      | 0.89     | 0.036                            | 1.94       |
| Th  | 100      | 0.80     | 0.036                            | 1.96       |
| U   | 100      | 0.60     | 0.037                            | 2.04       |



Wan-Qing Su, Xi-Guang Cao\*, Chun-Wang Ma\* et al., Improved ion bunch quality of conical target irradiated by ultra-intense and ultra-short laser, *Frontiers of Physics* 20, 062200 (2025)

Wan-Qing Su, Xi-Guang Cao\*, Chun-Wang Ma\*, Yu-Ting Wang, Guo-Qiang Zhang, Multi-layer phenomena in petawatt laserdriven acceleration of heavy ions, *Plasma Sci. Technol.* 26, 025202 (2024)



## VIII. Summary

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- Resonance structures at very high excitation energies for  $7\alpha$  are found  
New experiment with high resolution is critical to reveal the  $7\alpha$  resonances
- New probes(Exp/Theory) are explored to study cluster in light nuclei region
- Ultra-brilliant, ultra-fast H $\alpha$ / $\gamma$ /e $^+$  beam is proposed to explore new physics

*Thanks for your attention!*



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