10th international Symposium on Nuclear Symmetry Energy

Sep. 26 – 30, 2022, Catania, Italy

Observing the ping-pong modality of isospin degree of freedom in cluster emission from heavy ion reactions

Zhigang Xiao

Department of Physics， Tsinghua University

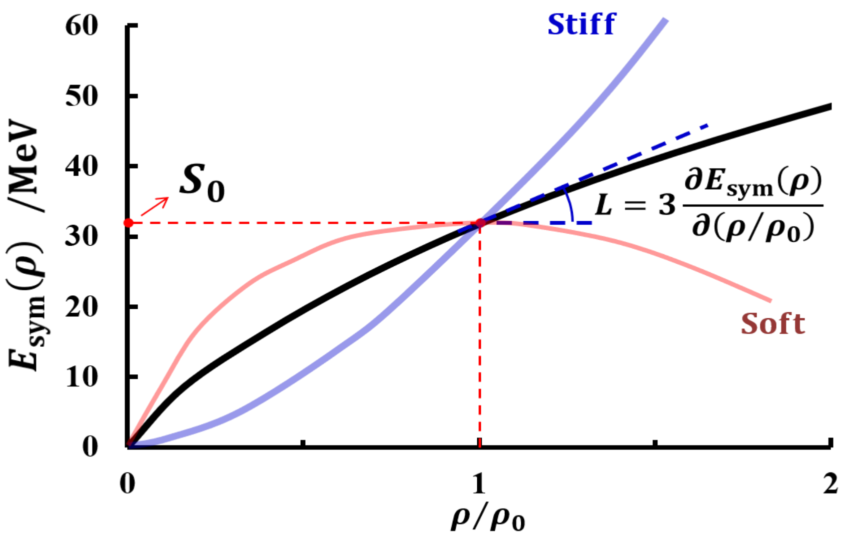
Outline

1. Introduction: Motivation
2. Experimental Setup
3. Results and Discussions
4. Summary

Nuclear EOS of asymmetric matter — $E_{\mathrm{sym}}(\rho)$

Nuclear matter EOS：

$$E(\rho,\delta) = \underbrace{E_0(\rho)}_{\text{Isoscale}} + \underbrace{\delta^2 E_{sym}(\rho)}_{\text{Isovector}} \quad \begin{cases} \delta = \dfrac{N-P}{N+P} \\ E_{sym}(\rho) = S_0 + L\dfrac{\rho-\rho_0}{3\rho_0} + \dfrac{K_{\mathrm{sym}}}{2}\left(\dfrac{\rho-\rho_0}{3\rho_0}\right)^2 + \dfrac{J_{\mathrm{sym}}}{6}\left(\dfrac{\rho-\rho_0}{3\rho_0}\right)^3 \end{cases}$$



Review articles in last 5 years

M. Colonna, **PPNP** 113,103775 (2020)

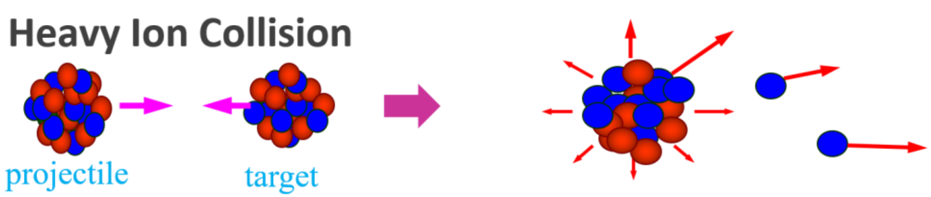
B. A. Li et al., **Universe**,7, 182 (2021)

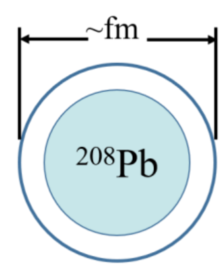
M. Oertel et al., **RMP.**, 89, 015007 (2017)

J. Xu, **PPNP** 106, 312 (2019)

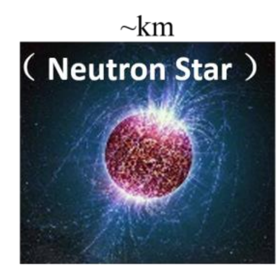
... ...

Heavy Ion Collision



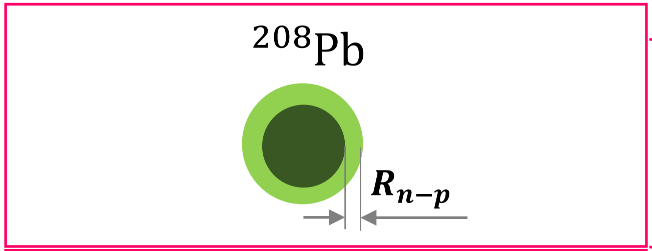


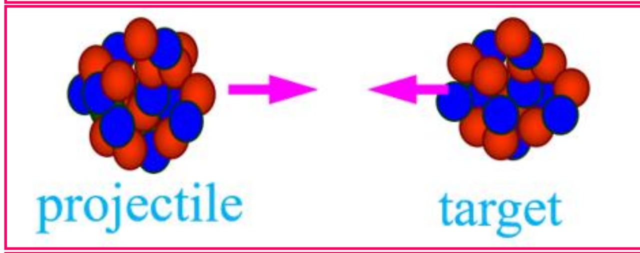
Neutron skin

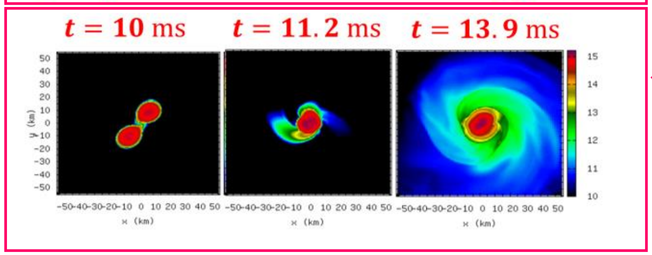


R-M Relation

Very Recent progress on constraining $E_{sym}(\rho)$







& Many talks on this symposium:

A. Levere T. Isobe

W. Trautmann S. Yennello

D. Cozma G. Colo

……

From R_{n-p} (^{208}Pb) and α_D

PREX collaboration., **PRL** 126, 172502 (2021)

B. T. Reed et al, **PRL** 126, 172503 (2021)

S. Bassauer et al, **PLB** 810, 135804 (2020)

From HIRs:

Y. Zhang,… ZGX et al., **PRC** 95, 041602(R) (2017)

Kaneko et al., **PLB** 822, 136681 (2022)

From n-H differential flow:

Y. J. Wang **Frontiers of Physics**, 15,1 (2020) and references therein

From π^-/π^+

G. Hang et al, **PLB** 813, 136016 (2021)

J. Estee et al., **PRL** 126, 162701 (2021)

From GW170817:

Z. Y. Zhu et al., **APJ** 862,98 (2018)

W. J. Xie et al., **APJ** 883,174 (2019)

Y. Zhou et al., **PRD** 99 121301(R) (2019)

Combine GW170817 and HIC:

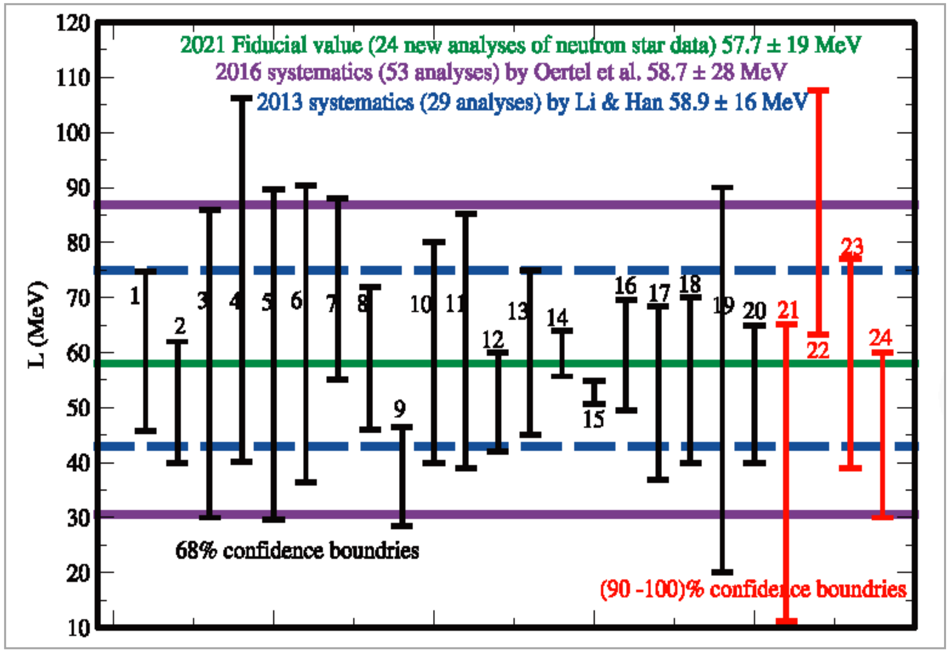
Y.Y. Liu et al., **PRC** 103, 014616 (2021)

S. Huth et al., **Nature**, 606, 276 (2022)

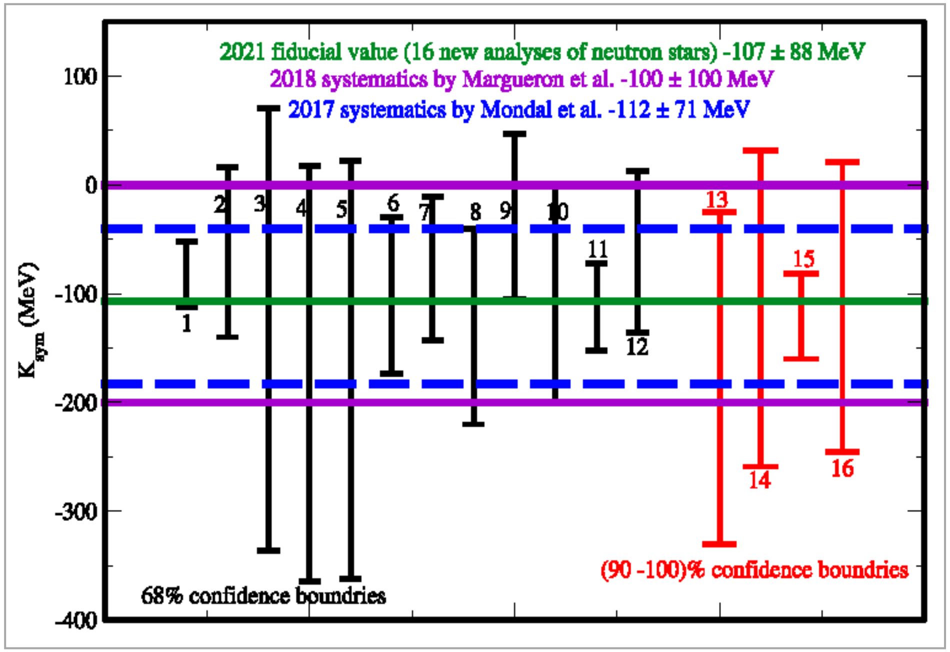
Review: B. A. Li et al., **Universe** 7, 182 (2021) ……

Fiducial Values of the $E_{\mathrm{sym}}(\rho)$

Recent results on L



Recent results on K_{sym}

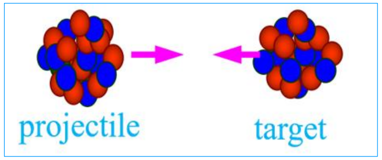


24 new analysis from the NS observables in comparison to 2013 and 2016 survey.
In some tension with the recent PREX II results.

$$\boldsymbol{L = 58 \pm 19\ \mathrm{MeV},\ K_{\mathrm{sym}} = -107 \pm 88\ \mathrm{MeV}}$$

Bao-An Li et al., **Universe 7**, 182 (2021)

Two fundamental questions in constraining $E_{\mathrm{sym}}(\rho)$ in HIRs



Usually isobaric ratio as a probe, since n(-like) and p(-like) particles transport differently!

$\mathrm{n/p}$, $^{3}\mathrm{H}/^{3}\mathrm{He}$, π^{-}/π^{+}, $\mathrm{K}^{0}/\mathrm{K}^{+}$, Σ^{-}/Σ^{+}, Ξ^{-}/Ξ^{0} **Beam energy**

C. M. Ko's talk

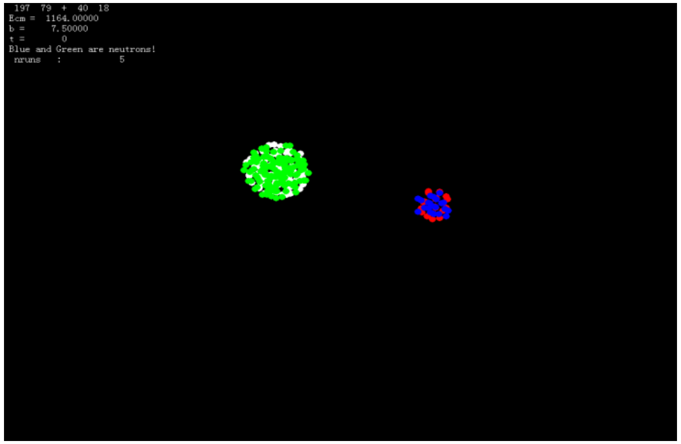
HIR is a non-equilibrium process in femtoscopic scale.

Q1: How does the isospin degree of freedom transport differently in HIRs?

Q2: What is the role of clustering in HIRs?

Both questions have to be understood before we obtain convincing and accurate $E_{\mathrm{sym}}(\rho)$.

M. Colonna, **PPNP**, 113 (2020) 103775.
S. Typel's talk

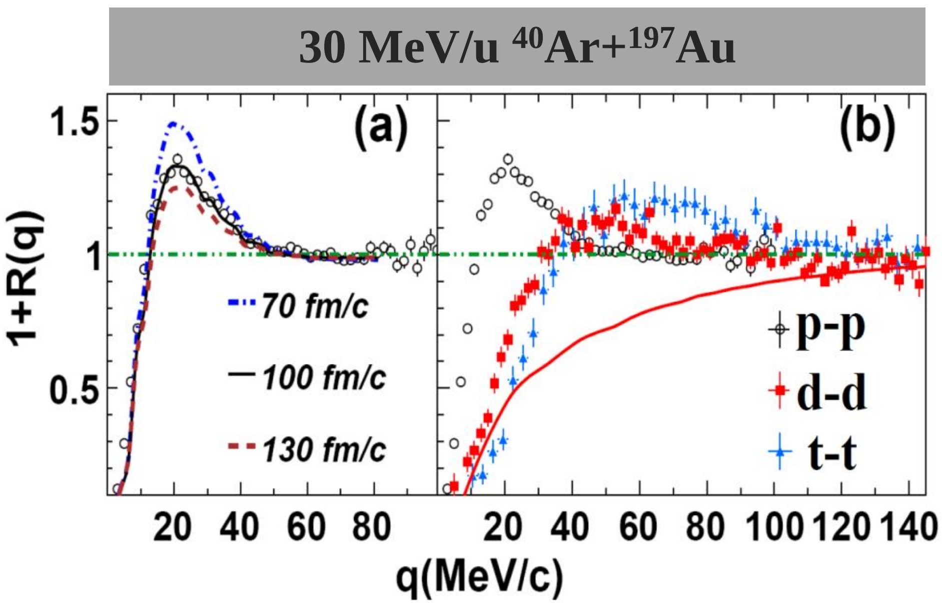


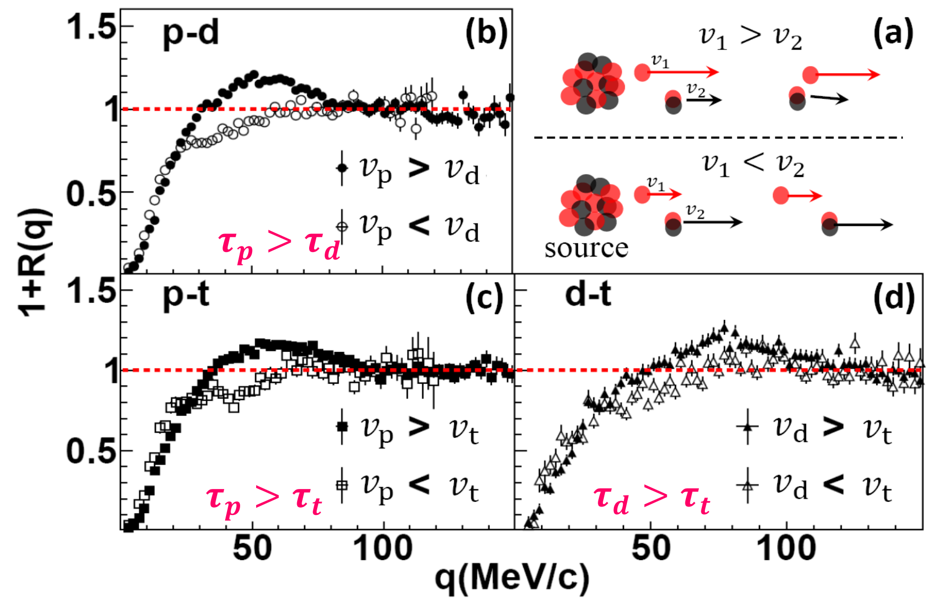
Theory: Modeling better the isospin dynamics and cluster formation;
Experiment: Need more data to test and develop the theory, to find more isospin observables to constrain $E_{\mathrm{sym}}(\rho)$

Isospin Chronology with CSHINE

Question 1 promotes lots of isospin chronology applications. For instance, using rotation angle as a clock, sub-zeptosecond chronology is implemented [A. Jedele et al, **PRL 118** (2017) 062501].

+ Recent results from HBT correlation function:





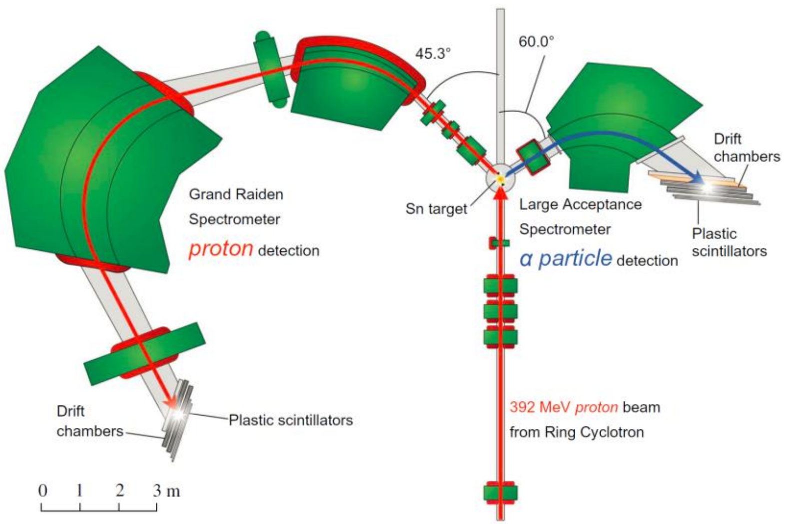
Velocity gated analysis can deduce the emission hierarchy of $Z = 1$ isotopes. Averagely, the neutron-rich tritons are emitted earlier than deuterons and protons: $\boldsymbol{\tau_p > \tau_d > \tau_t}$.

Consistent with previous studies, $\tau_p > \tau_d > \tau_n$ [R. Ghetti et al., PRL 91, 092701 (2003).]

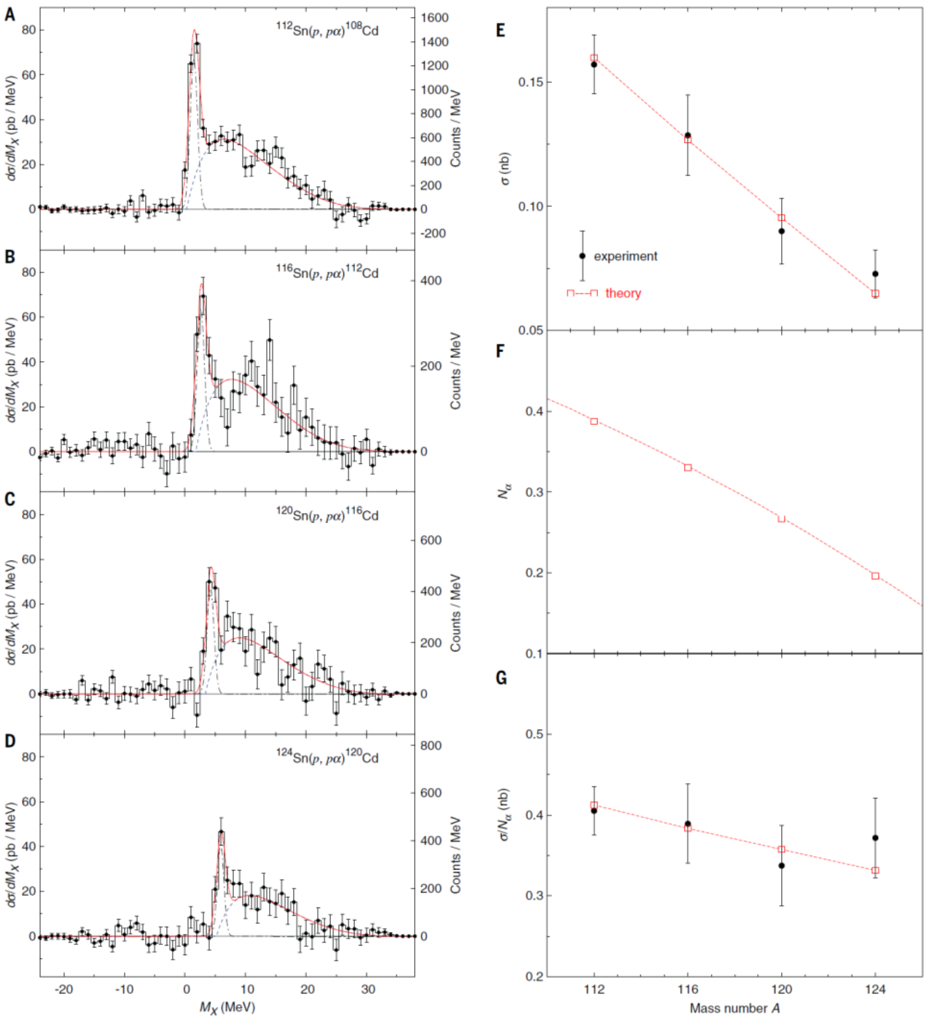
Y. J. Wang … ZGX, **PLB 825**, 136856 (2022)

Influence of Cluster formation

${}^{A}\mathrm{Sn}(\mathrm{p},\mathrm{p}\alpha)^{A-4}\mathrm{Cd}$ knock-out reactions, α cluster formation probability depends on the mass of the Sn isotopes, showing correlation to the neutron skin, and therefore to the symmetry energy.



Experimental Setup at RCNP



J. Tanaka et al., Science 371 (6526), 260-264, 2021

Typel's talk on Sep. 27

Our motivation

Aiming at the two questions, Clustering and transport of isospin DOF, we are motivated to

- identify a fine signal featuring the transport of IDOF related to the emission of clusters, and a new isospin observable sensitive to $E_{\mathrm{sym}}(\rho)$;
- illustrate how the IDOF evolves with the presence of cluster emission in heavy ion reactions.

Our intended observables:

$\underline{\mathbf{t/^3He}}$ in coincidence with isotope-resolved heavy clusters

[single isobaric ratio may loss the temporal information]

[Heavy cluster is temporally correlated with LCP]

Reaction system:

A heavy and neutron rich system: ^{86}Kr + ^{208}Pb at 25 MeV/u

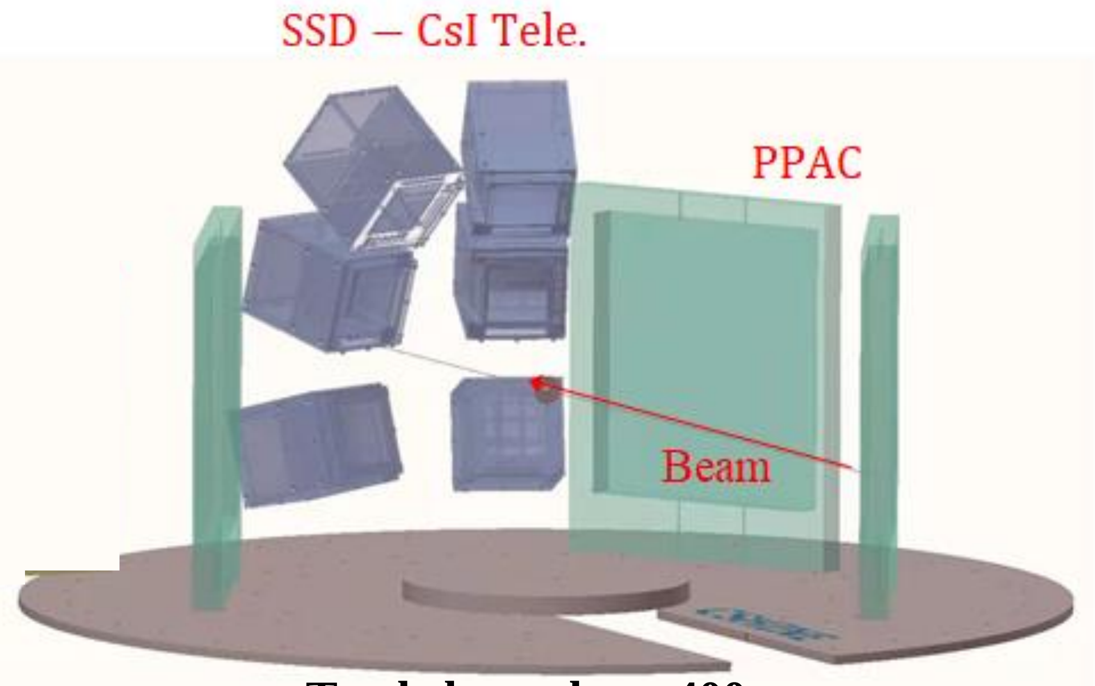
Outline

1. Introduction: Motivation
2. Experimental Setup
3. Results and Discussions
4. Summary

Detector setup of CSHINE

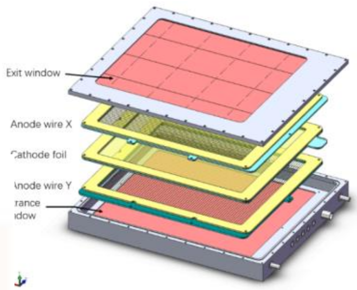
CSHINE

Compact Spectrometer for Heavy IoN Experiments

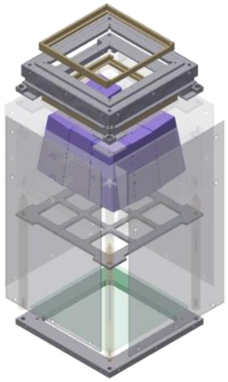


Total channels： ~400

PPAC



SSDT



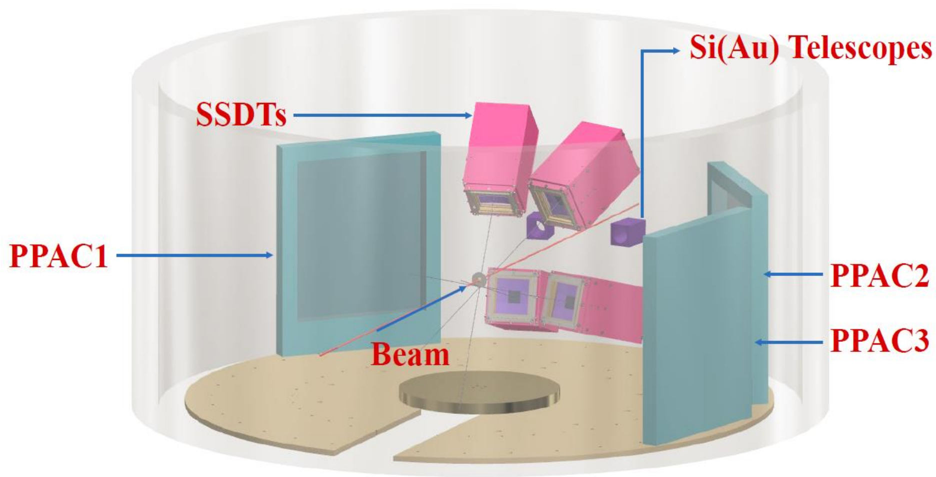
- Fission Fragments by PPAC：

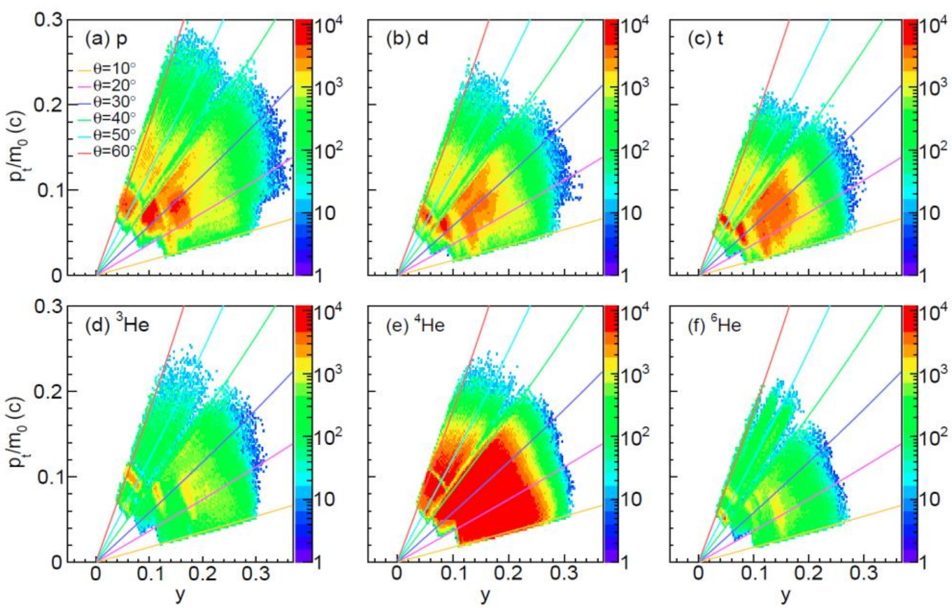
PPAC， $\boldsymbol{\sigma_{xy}}$~**1.3** mm， $\boldsymbol{\sigma_t}$~**300** ps

-LCP and IMFs by SSDT：

$\boldsymbol{\sigma_{xy}}$~**0.5** mm， $\boldsymbol{\sigma_E}$~**2**%

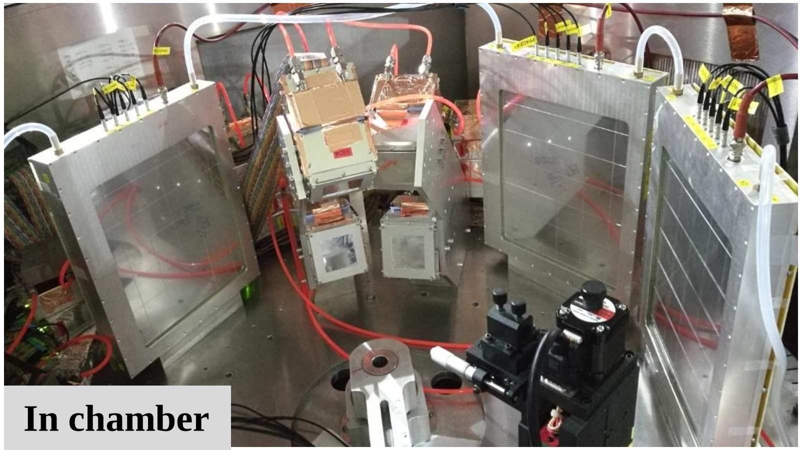
Experimental campaigns using CSHINE

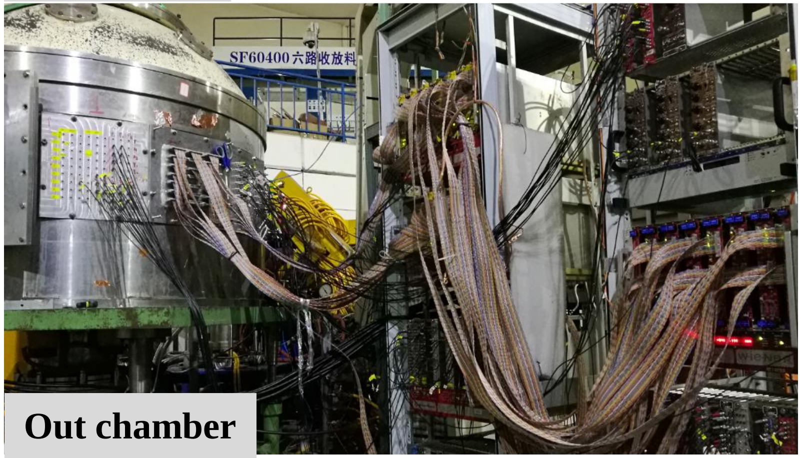




-Exp-III： 25 MeV/u ^{86}Kr+^{208}Pb

3 PPACs+ 4SSDTs + 2 Si(Au)

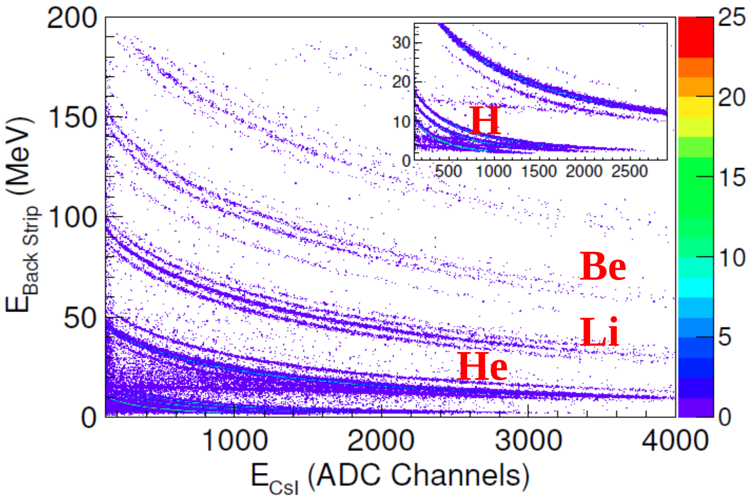


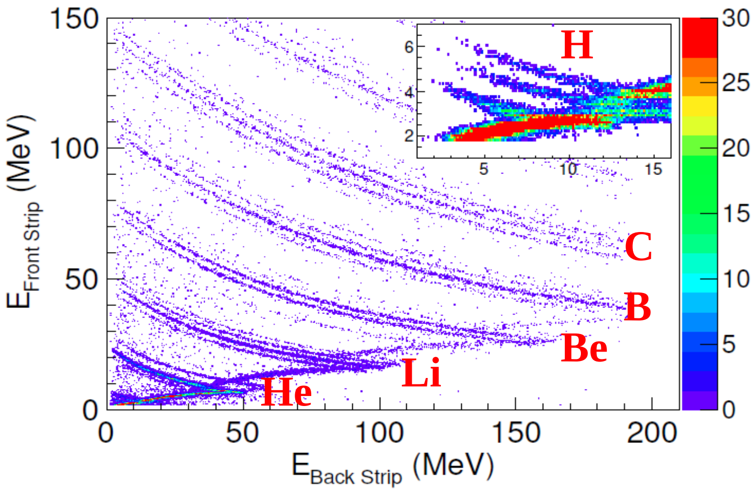


F. H. Guan … *ZGX*, et al. NIMA 1029, 166461(2022)

Performance of CSHINE detectors

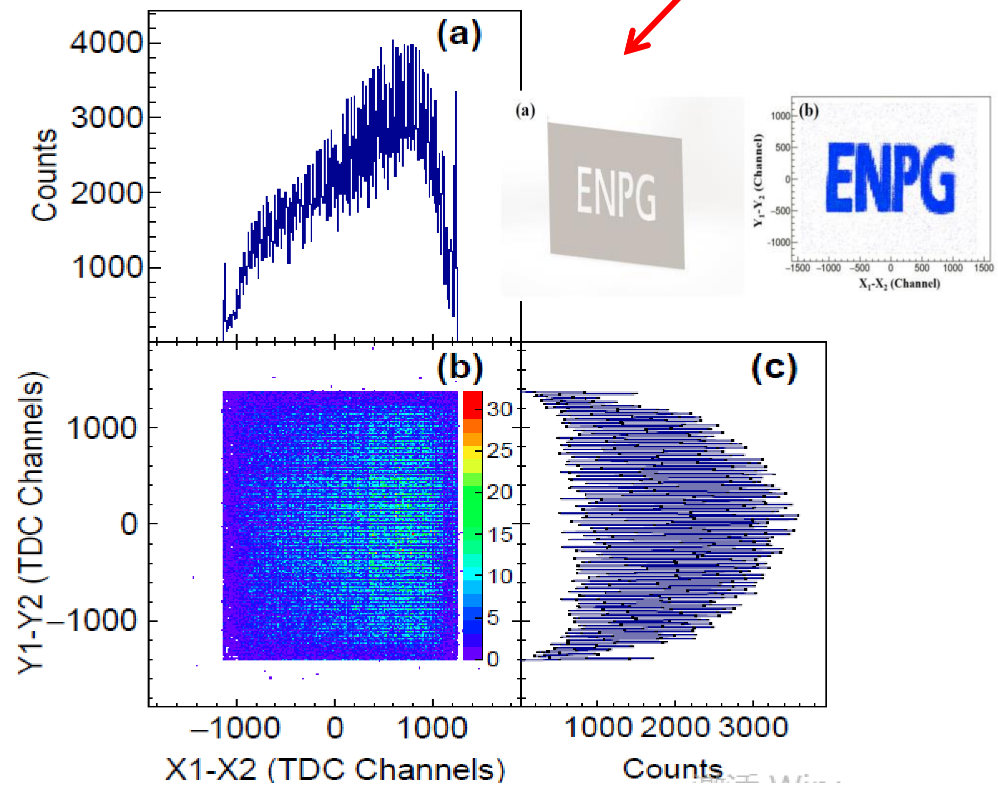
25 MeV/u ^{86}Kr+^{208}Pb





LCPs in SSD

FF in PPAC



F. H. Guan … ZGX, **Nucl. Inst. Meth. A** 1011 , 165592 (2021)

Analysis Scheme

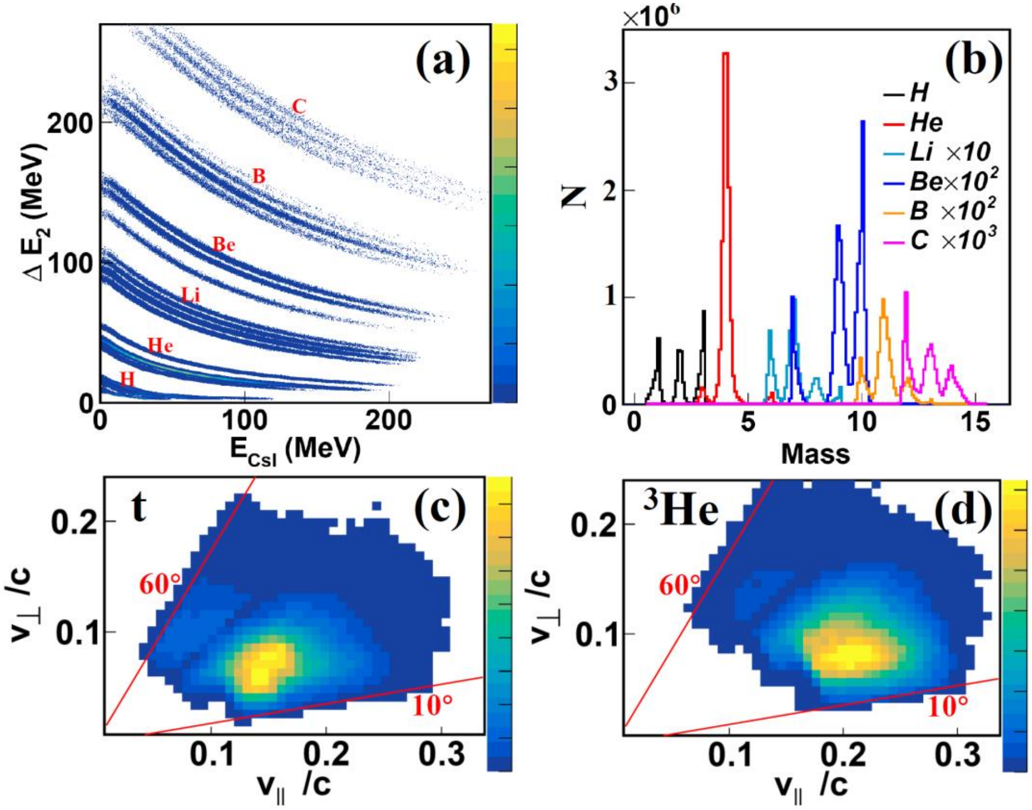
- Single isobaric ratio may loss temporal feature of the transport of isospin DOF;

- We analyze correlations of the light and the heavy clusters, both thermo-dynamically and chemically.

- Light cluster, F_L, $A = 3$ isobars;

- Heavy cluster, F_H, $7 \leq A \leq 14$

- Focus on the products stopped in CsI hodoscopes.



arXiv:2209.04079v1 [nucl-ex] 9 Sep 2022

Outline

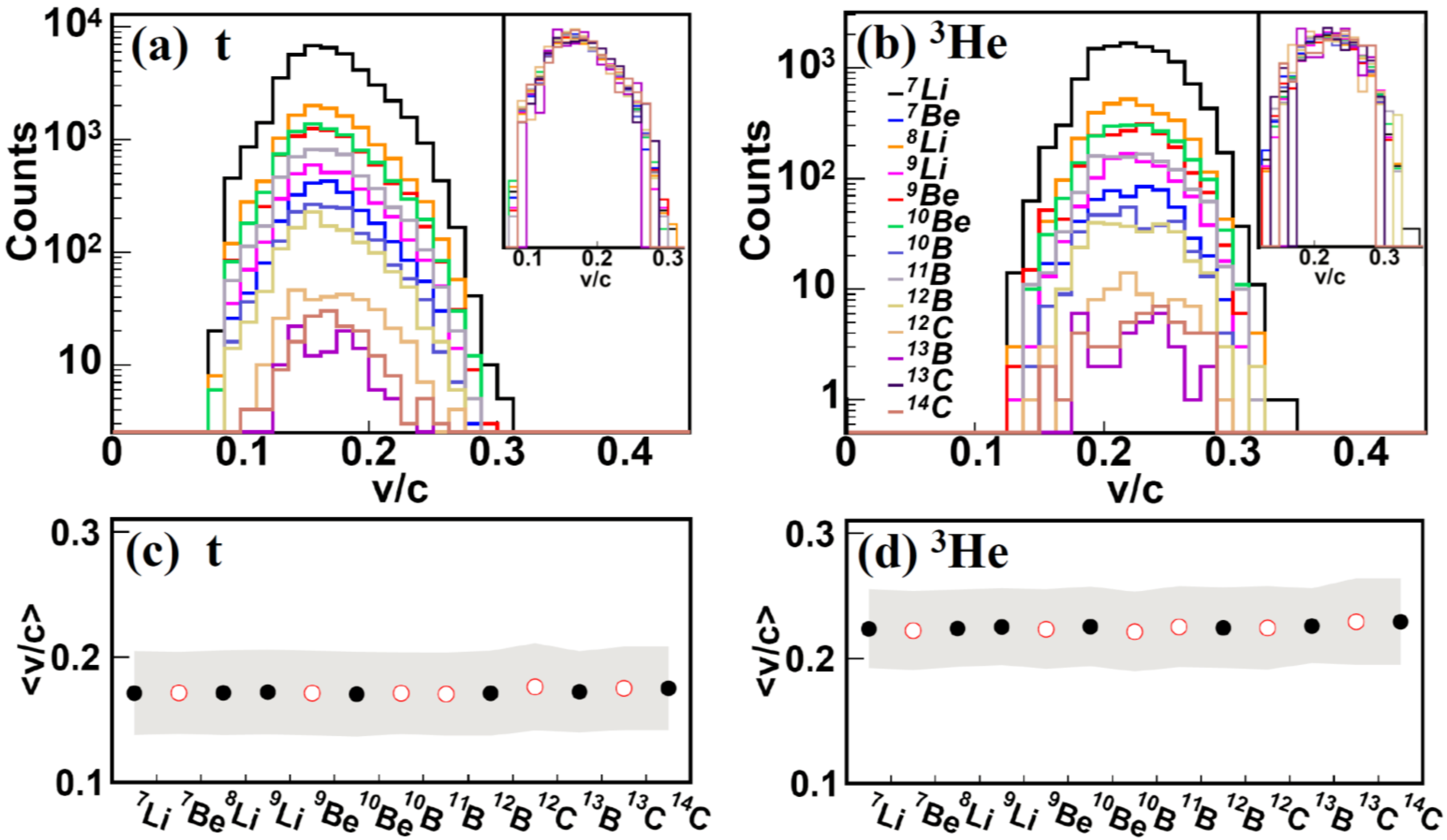
1. Introduction: Motivation

2. Experimental Setup

3. Results and Discussions

4. Summary

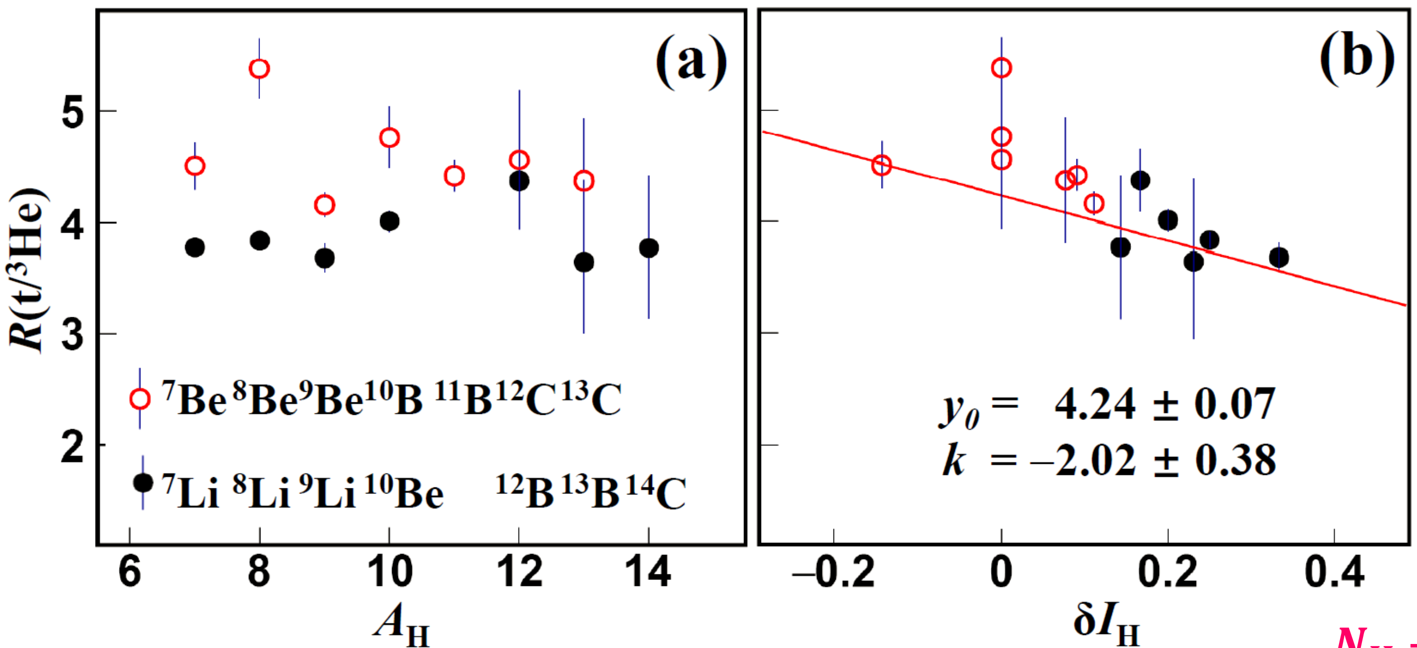
Thermodynamic correlation between light and heavy clusters



- Velocity Spectra of triton and ^{3}He show scaling behavior over the type of the heavy clusters
- $\langle v \rangle$ and σ_v keeps constant against variation of F_H, for both triton and ^{3}He
- Triton and ^{3}He experience the same dynamic process.

arXiv:2209.04079v1 [nucl-ex] 9 Sep 2022

Chemical correlation between light and heavy clusters

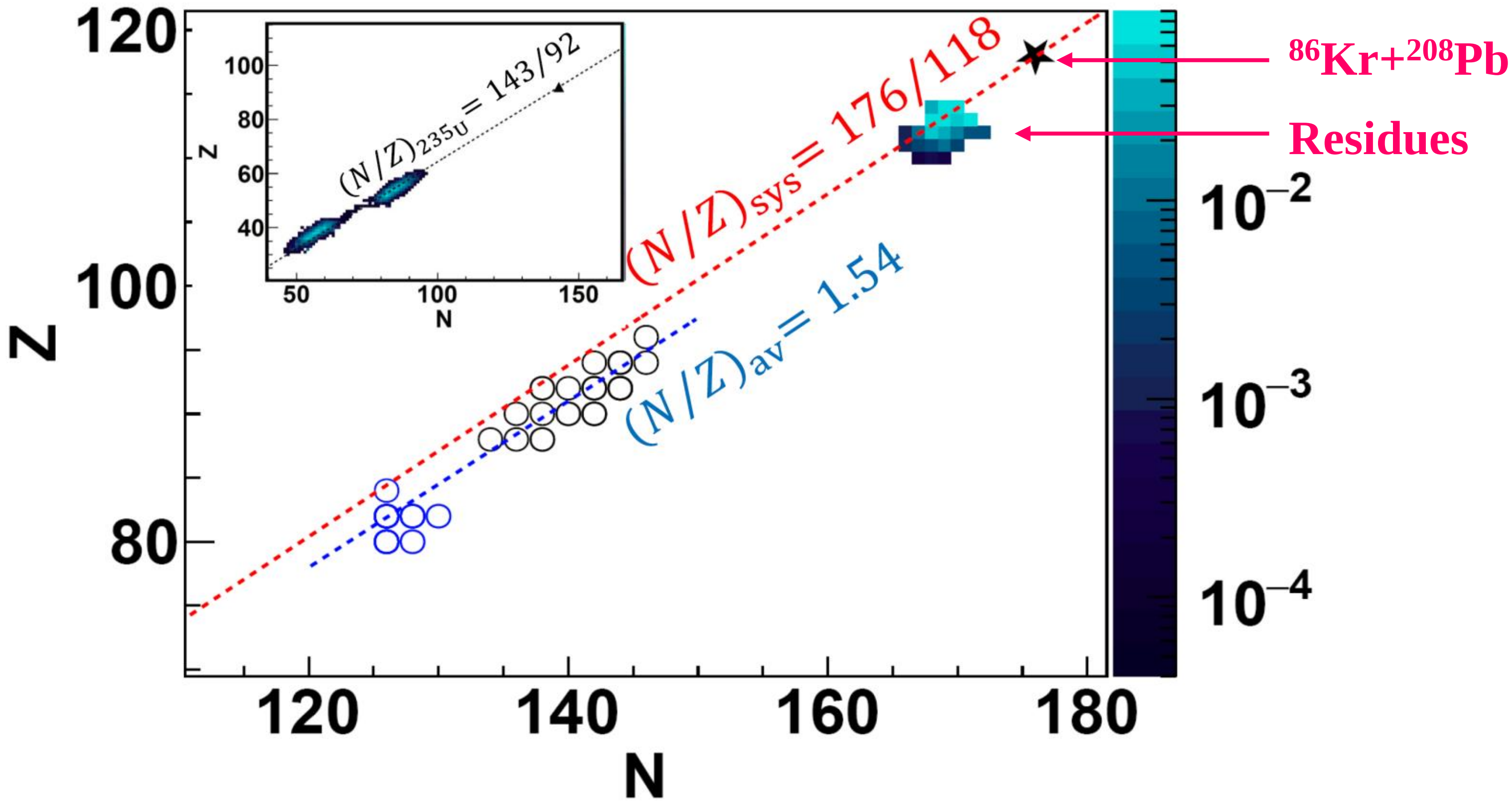


$$\delta I_H = \frac{N_H - Z_H}{A_H}$$

- $R(t/^3He)$ splits into two groups according to the *N/Z* of the heavy cluster (F_H);
- Ping-pong modality evident: F_H n-rich, $R(t/^3He)$ smaller; F_H n-poor, $R(t/^3He)$ larger
- $R(t/^3He)$ exhibits anti-correlation to δI_H, as a consequence of n and p conservation in such a finite system.

arXiv:2209.04079v1 [nucl-ex] 9 Sep 2022

Commonality of the *N/Z* in cluster emission



- Counting the (Z, N) of the residue by subtracting F_L and F_H;
- The residues situate on the line with $N/Z = 176/118 = 1.49$;
- Similar phenomena are observed in cluster decay and fission of super heavy nuclei;
- The commonality is extended to cluster emission in heavy ion reactions (high excitation).

arXiv:2209.04079v1 [nucl-ex] 9 Sep 2022

Comparison to ImQMD Calculations

Model: ImQMD05 + Gemini

[Ying-xun Zhang, et al., Frontier of Physics, 15(2020)54301]

Equations of motion of the nucleons：

$$\dot{\vec{r}}_i = \frac{\partial H}{\partial \vec{p}_i}, \qquad \dot{\vec{p}}_i = \frac{\partial H}{\partial \vec{r}_i}$$

$$H = T + U, \qquad U = U_{nuc} + U_{Coul}$$

The local nuclear potential energy density functional :

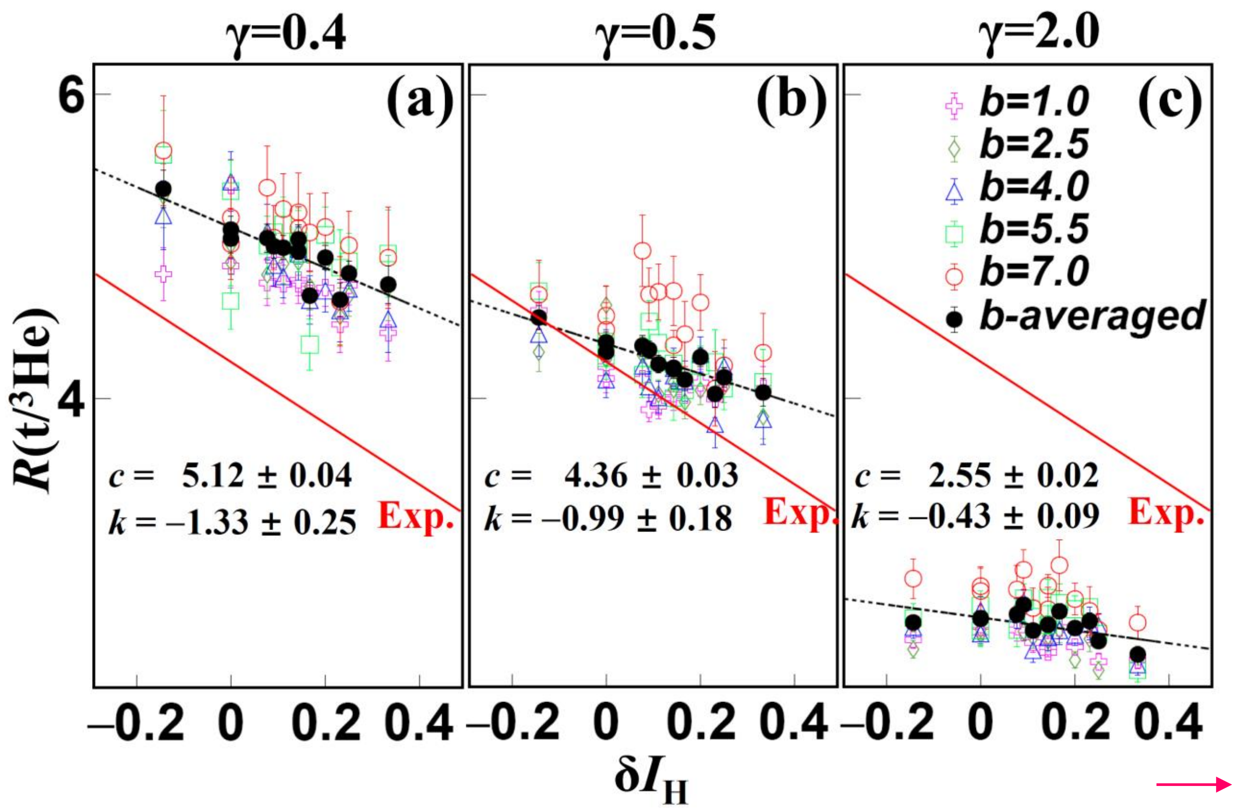
$$u_\rho = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\eta+1}\frac{\rho^{\eta+1}}{\rho_0^{\eta}} + \frac{g_{sur}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{iso}}{2\rho_0}\left[\nabla(\rho_n - \rho_p)\right]^2 + \frac{C_s}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}\delta^2\rho + g_{\rho\tau}\frac{\rho^{8/3}}{\rho_0^{5/3}}$$

Where parameter set MSL0 is used [Phys. Rev. C 82 (2010) 024321.]

TABLE 1. Parameter set used in the ImQMD calculations.

α (MeV)	β (MeV)	η	g_{sur} (MeV fm^2)	$g_{\mathrm{sur,iso}}$ (MeV fm^2)	$g_{\rho\tau}$ (MeV)	C_{s} (MeV)	ρ_0 (fm^{-3})
-254.2	185.8	1.24	21.1	-0.82	5.51	35.90	0.160

Comparison to ImQMD calculations



$$\delta I_{\mathrm{H}} = \frac{N_{\mathrm{H}} - Z_{\mathrm{H}}}{A_{\mathrm{H}}}$$

- $R(\mathrm{t}/^{3}\mathrm{He})$ depends slightly on b, significantly on γ;
- The $R - \delta I_{\mathrm{H}}$ anti-correlation is qualitatively reproduced, particularly at $\gamma = 0.5$; while $\gamma = 0.4$ *or* 2.0 are disfavored;
- Slopes are not quantitatively reproduced.

arXiv:2209.04079v1 [nucl-ex] 9 Sep 2022

Summary

- ✓ Thermodynamic and chemical correlations are investigated in 25 MeV/u ^{86}Kr+^{208}Pb by analyzing the yield and kinetic variables of the $A = 3$ isobars in coincidence with the heavy clusters of $7 \leq A \leq 14$.
- ✓ The velocity spectra of both t and ^{3}He exhibit scaling behavior over the type of the heavy clusters; the yield ratio $R(\mathrm{t}/{}^{3}\mathrm{He})$ correlates reversely to the N/Z of the latter, showing the ping-pong motion modality.
- ✓ The commonality, that the N/Z of the residues keeps the initial system value, is extended to the cluster emission in heavy ion reactions.
- ✓ Transport model reproduce qualitatively, not quantitatively, the The $R - \delta I_{\mathrm{H}}$ anti-correlation, which provides a new line to test the transport model in terms of the description of clustering and isospin dynamics.

Thank you for your attention.