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Fast Fission in heavy ion collisions and the isospin effect on particle emissions

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Outline

- 1. Introduction: Motivation
- 2. Experimental setup
- 3. Results and discussions
- 4. Summary and outlook

Motivation: nuclear symmetry energy

The nucleon specific energy of nuclear matter formed in HIC or in neutron star is written as:

$$E(\rho, \delta) = E_0(\rho) + \delta^2 E_{sym}(\rho), \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

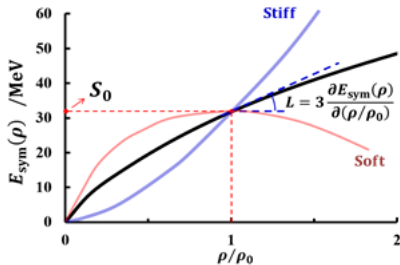
$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2} \left(\frac{\rho - \rho_0}{3\rho_0} \right)^2 + \frac{J_0}{6} \left(\frac{\rho - \rho_0}{3\rho_0} \right)^3 + \dots$$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L \left(\frac{\rho - \rho_0}{3\rho_0} \right) + \frac{K_{sym}}{2} \left(\frac{\rho - \rho_0}{3\rho_0} \right)^2 + \frac{J_{sym}}{6} \left(\frac{\rho - \rho_0}{3\rho_0} \right)^3 + \dots$$

symmetry energy

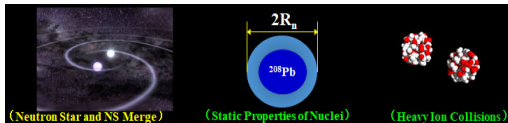
For npe matter, the pressure :

$$P(\rho, \delta) = \rho^2 \frac{\partial E(\rho, \delta)}{\partial \rho} + \frac{1}{4} \rho_e \mu_e = \rho^2 \left[\frac{\partial E_0}{\partial \rho} + \delta^2 \frac{\partial E_{sym}}{\partial \rho} \right] + \frac{1}{2} \delta(1 - \delta) \rho E_{sym}(\rho)$$



When $\delta \rightarrow 1$, $E_{sym}(\rho)$ plays a dominant role;

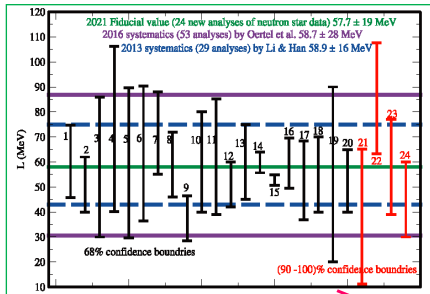
However, $E_{sym}(\rho)$ is largely unknowns!



Combined fiducial constraint of $E_{\text{sym}}(\rho)$

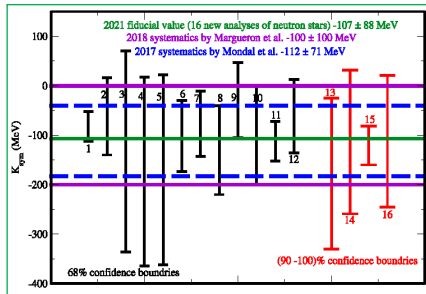
Recent results on L

$$L = 58 \pm 19 \text{ MeV}$$



Recent results on K_{sym}

$$K_{\text{sym}} = -107 \pm 88 \text{ MeV}$$



24 new analysis from the NS observables
In comparison to 2013 and 2016 survey.
In **tention with** the most recent PREX II results.

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

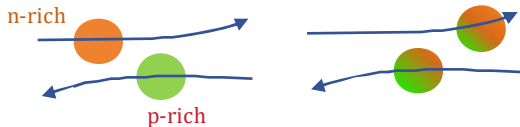
Transport of IDOF in heavy ion collisions

Two mechanisms governs the transport of IDOF in nuclear collisions:

1. Isospin Diffusion :

$$j_{np} = j_n^I - j_p^I = -(D_n^I - D_p^I) \nabla I$$

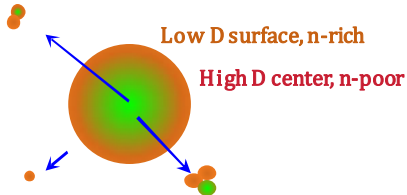
$\curvearrowright D_n^I - D_p^I \propto 4\rho E_{sym}(\rho)$



2. Isospin Drift :

$$j_{np} = j_n^\rho - j_p^\rho = (D_n^\rho - D_p^\rho) \nabla \rho$$

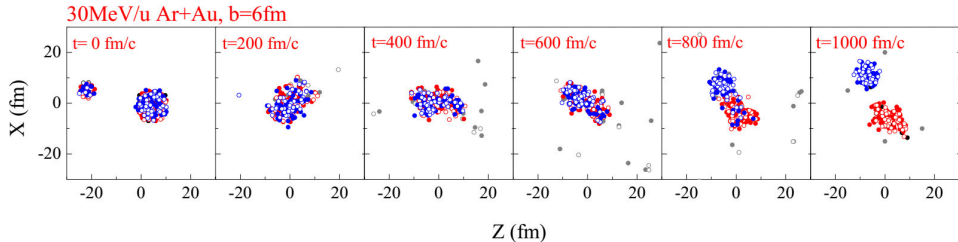
$\curvearrowright D_n^\rho - D_p^\rho \propto 4I \frac{\partial E_{sym}(\rho)}{\partial \rho}$



Where to find good venue to study the isospin effect?

- Two necessary conditions are favored:
 1. Low-density neutron-rich region
 2. A relatively long process for IDOF effect accumulated;

(Fast)fission in HIC seems to be a favorable venue!



Model Simulations

- For fission of heavy nuclei at low excitation energy
 - Micro-macro model
 - Time-dependent Hartree Fock approach
 - and a lot of others...

- Fission following HIC at Fermi energies:
 - Transport model based on ImQMD

A few words about the ImQMD model

Nucleon is represented by Gaussian package: $\varphi_j(r) = (2\pi\sigma_r^2)^{-\frac{3}{4}} \cdot \exp[-\frac{(r-r_j)^2}{4\sigma_r^2} + i\frac{r \cdot p_j}{\hbar}]$

With Wigner transformation:

$$f(r_1, p_1, \dots, r_N, p_N) = \frac{1}{(2\pi\hbar)^N} \iint_{-\infty}^{+\infty} \psi^* \left(x_1 + \frac{y_1}{2}, \dots, x_N + \frac{y_N}{2} \right) \psi \left(x_1 + \frac{y_1}{2}, \dots, x_N - \frac{y_N}{2} \right) e^{i(p_1 y_1 + \dots + p_N y_N)/\hbar} dy_1 \dots dy_N$$

Hamilton equation of motion of each package center: $\dot{r}_j = \frac{\partial H}{\partial p_j}, \quad \dot{p}_j = -\frac{\partial H}{\partial r_j}$

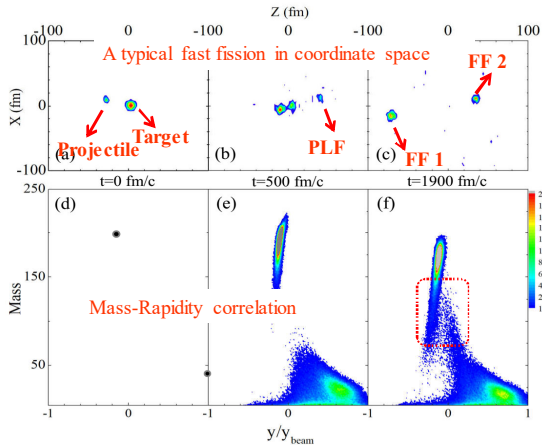
Where the Hamiltonian writes $H = U + E_k$

The potential is obtained from the Skyrme energy density functional, which is written by

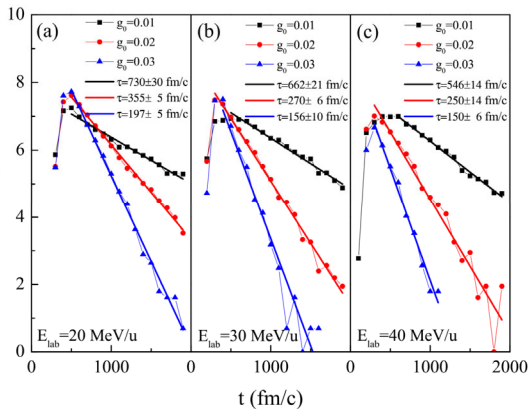
$$U = U_{loc} + U_{Coul}, \quad U_{loc} = \int H_{loc}(\mathbf{r}) d\mathbf{r}$$

Transport model studies on the fast fission in HICs

30 MeV/u $^{40}\text{Ar} + ^{197}\text{Au}$



Fission timescale depends on the E_{beam} & Surface energy coefficient g_0



Effect of $E_{\text{sym}}(\rho)$ on particle emissions in coincidence with fast fission

30 MeV/u $^{40}\text{Ar} + ^{197}\text{Au}$

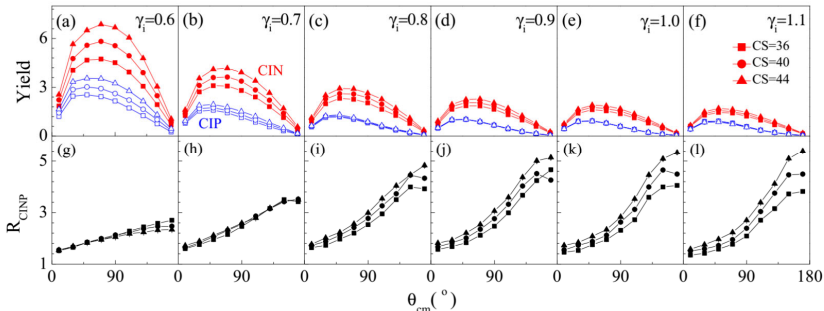
$$V_{\text{loc}} = \frac{\alpha}{2} \frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1} \frac{\rho^{\gamma+1}}{\rho_0^\gamma} + \frac{g_{\text{sur}}}{2\rho_0} (\nabla\rho)^2 + \frac{g_{\text{sur.iso}}}{2\rho_0} [\nabla(\rho_n - \rho_p)]^2$$

Symmetry Energy term

$$+ \frac{C_s}{2} \left(\frac{\rho}{\rho_0}\right)^{\gamma_i} \delta^2 \rho + g_{\rho\tau} \frac{\rho^{\eta+1}}{\rho_0^\eta}$$

$$Y_{\text{CIN}} = \sum_i N_i Y_i(N, P)$$

$$Y_{\text{CIP}} = \sum_i P_i Y_i(N, P)$$



> Both CIP and CIN varies with the slope parameter γ , The ratio of CIN/CIP is enhanced in mid angle in c.m.
 > γ dependence is more pronounced in fast fission events, due to the formation of large surface and neutron-rich neck.

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- **2. Experimental setup**
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2 Experiment setup

Compact Spectrometer for Heavy Ion Experiment

紧凑型重离子实验谱仪

Running at HIRFL-RIBLL1



NST cover story (2025.7)



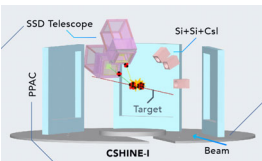
NST cover story (2021.1)

Five beam Experiment campaigns with CSHINE

CSHINE
Compact Spectrometer for Heavy Ion Experiments

2018

02

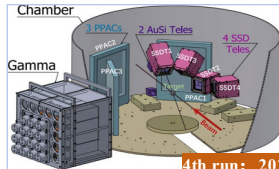


2nd run: 2019

30 MeV/u $^{40}\text{Ar}+^{197}\text{Au}$

2022

04

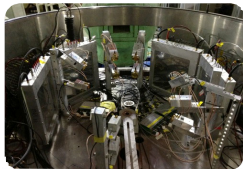


4th run: 2022

25 MeV/u $^{86}\text{Kr}+^{124}\text{Sn}$

30 MeV/u * $^{40}\text{Ar}+^{197}\text{Au}$

01 2014



1strun: 2014

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

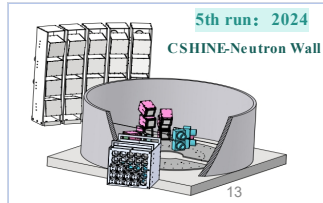
03 2019



3rd run: 2019

25 MeV/u $^{124}\text{Sn}+^{124}\text{Sn}$

05 2024



5th run: 2024

CSHINE-Neutron Wall

Publications with CSHINE

Technique Papers:

> Neutron Wall Construction

NIMA 1070,170055 (2025)

> High Energy γ array

NIMA 1053 168330 (2023),
NIMA 1080, 170787 (2025)

> FPGA Trigger Techniques

NST 33, 162(2022)

> PPACs for Fission Fragments

✓ NST 33, 40 (2022)

> Silicon Strip Detectors for LCPs

✓NIMA 1029, 166461 (2022),
✓NIMA 1011, 165592 (2021),
NST 32, 4 (2021), NST 36, 132 (2025)

Physics Papers:

> n-n CF and (f_0^{nn}, d_0^{nn})

PRL 134,222301 (2025)

> Bremsstrahlung γ and SRC

PLB 850,138514 (2024)
PLB 857,139009 (2025)
PR Research 7, 043174(2025)
PRC 113,034904 (2026)

> $t/{}^3\text{He}$ ratio and ${}^3\text{He}$ -puzzle in Fission

PRC 107, L041601 (2023)
✓NST 36,155 (2025)

> Isospin Chronology

PLB 825, 136856 (2022)

> Constraint of $E_{\text{sym}}(\rho)$ near $\rho \approx \rho_0$

✓PRC 95, 041602R (2017)

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- 1. Introduction: Motivation
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 - 3.1 Long-time isospin drift process and constraint of $E_{sym}(\rho)$
 - 3.2 Fission reconstruction and the neutron-rich emission from the neck
- 4. Summary and outlook

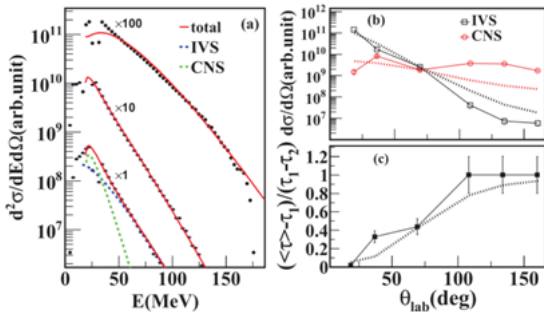
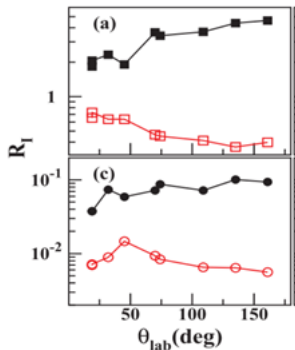
3.1 Long-time isospin drift and constraint of $E_{sym}(\rho)$

> 30 MeV/u $^{40}\text{Ar}+^{197}\text{Au}$

> Isotope-resolved LCPs measured by Si(Au) telescope from 19° to 165°

> Angular distribution can be translated to averaged emission time distribution.

[Easy to understand in the picture of 2-moving-source]



Similar trend with or
without fission

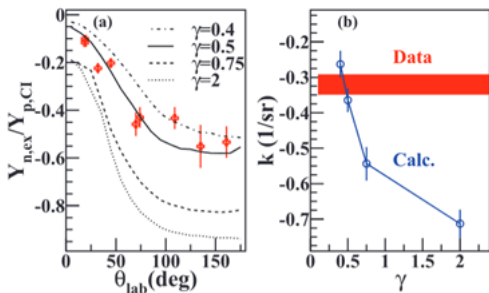
Long-time isospin drift and constraint of $E_{\text{sym}}(\rho)$

- In wide θ_{lab} range, we observed the variation of δ_n/Z (relative neutron excess)
- Using it as a probe of $E_{\text{sym}}(\rho)$, the slope parameter L is extracted.

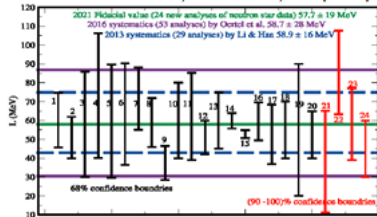
$$\frac{Y_{n,\text{ex}}}{Y_{p,\text{Cl}}} = \frac{\sum y_i (N_i - Z_i)}{\sum y_i Z_i}$$

$$\gamma_i = 0.46 \pm 0.025 \quad \text{or}$$

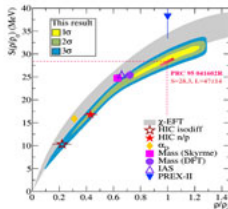
$$L = 47 \pm 14 \text{ MeV (CL = 95\%)} (S_0 = 28.3 \text{ MeV})$$



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



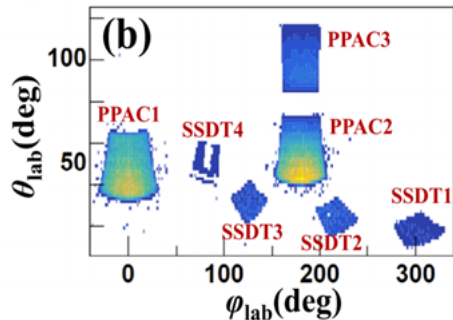
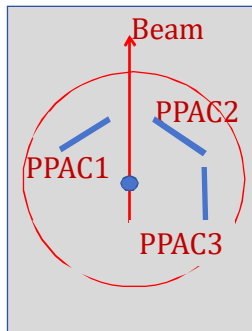
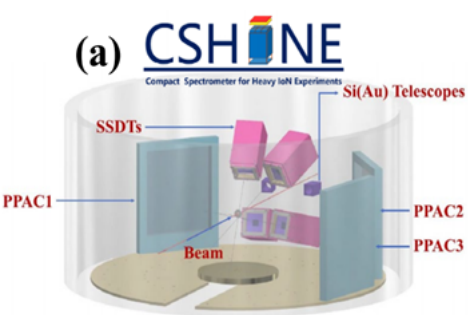
PLB 868, 139815 (2025)



our work

3.2 Fission reconstruction and the neutron-rich neck emission

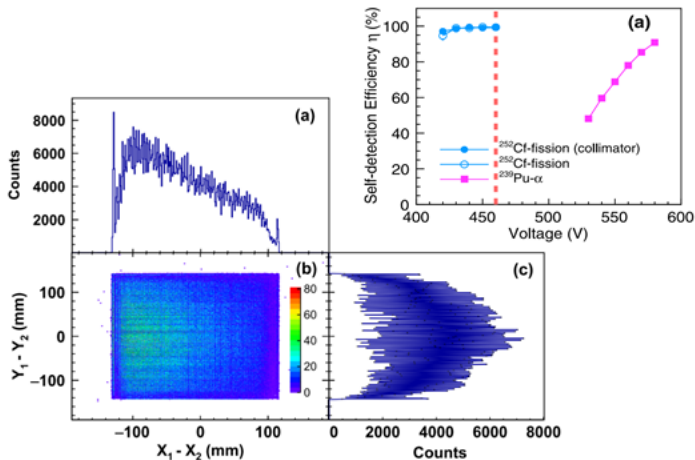
- 25 MeV/u $^{86}\text{Kr}+^{208}\text{Pb}$
- PPACs for FF, and SSDT array for LCP



PPAC1 \times PPAC2 more LMT; PPAC1 \times PPAC3 less LMT

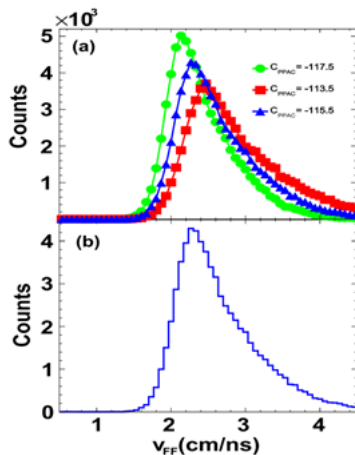
Performance of the fragment detectors - PPACs

F. Guan et al., NIMA 1011 (2021) 165592



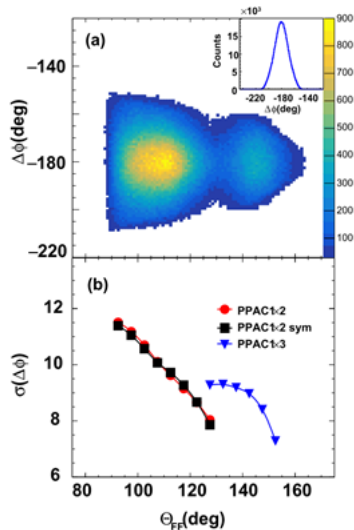
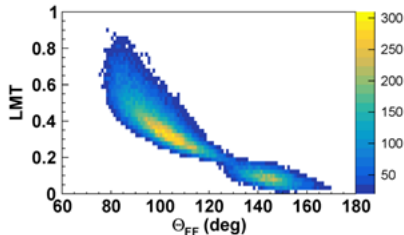
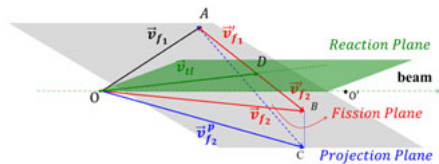
$$\sigma_T = 300 \text{ ps}, \sigma_{XY} = 1.4 \text{ mm}$$

- Fission fragments:
- $\text{TOF} = T_{\text{PPAC}} - T_{\text{RF}} + C_{\text{PPAC}}$



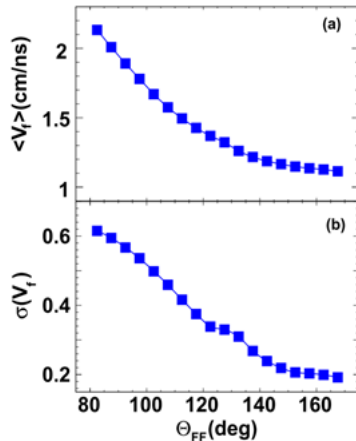
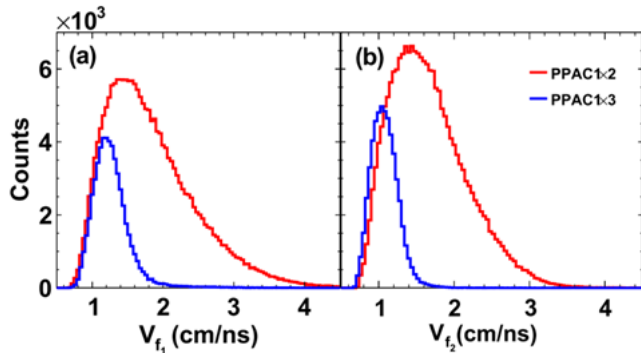
Fission Distribution Properties

- Reconstruction of the (fast) fission events.



Fission Distribution Properties

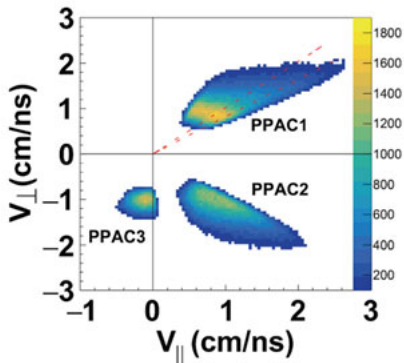
- Reconstruction of the (fast) fission events.



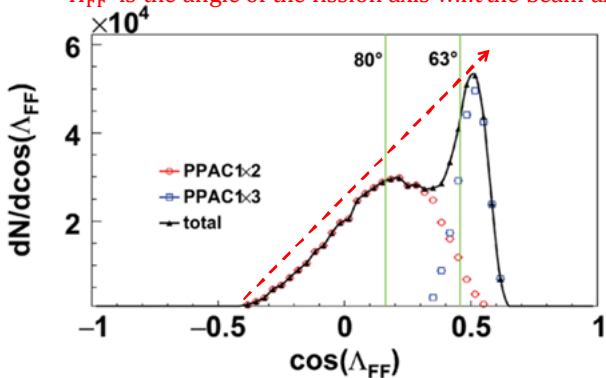
the statistical fluctuation enhances the variance in the velocity of the FF.

Fission Distribution Properties

- 1. Scattering plot of v_{\perp} vs v_{\parallel}



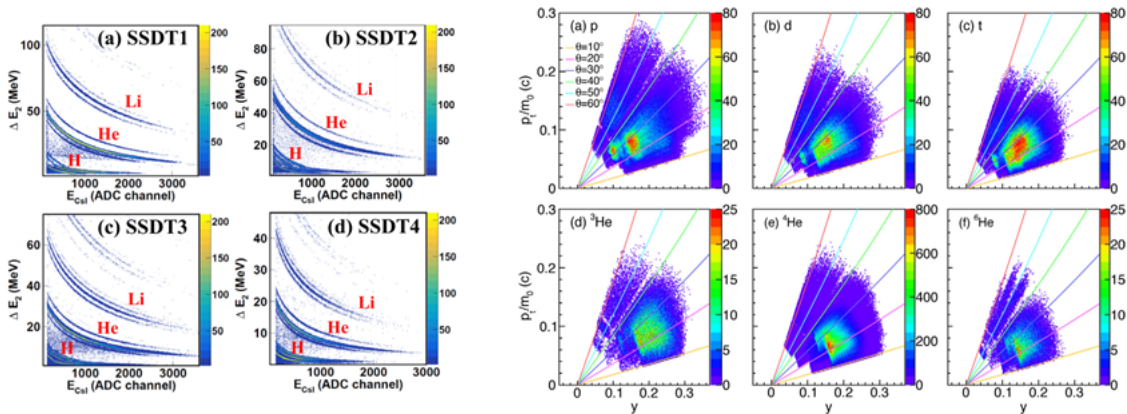
Λ_{FF} is the angle of the fission axis w.r.t the beam axis



The azimuth coverage of PPAC2 and PPAC3 is corrected for each Λ_{FF} bin

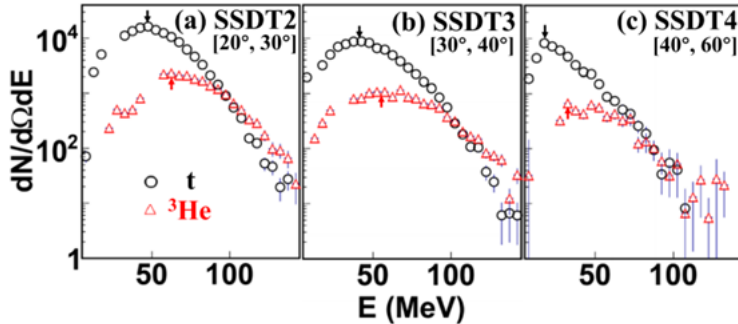
Emissions of light charged particles in coincidence with fission

- PID and phase-space coverage of LCPs



^3He -puzzle in Fission process

- Energy spectra of ^3He is always harder than t in heavy-ion reactions. Not yet quantitatively explained so far.
- **In the fast fission process, ^3He -puzzle exists also! More pronounced at forward angle.**



$t/{}^3\text{He}$ yield-ratio in the fission geometry

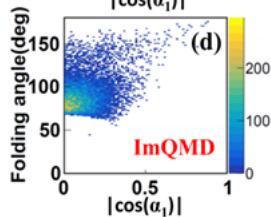
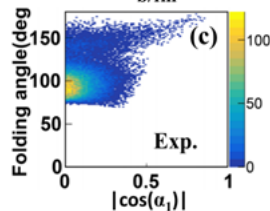
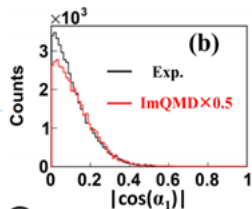
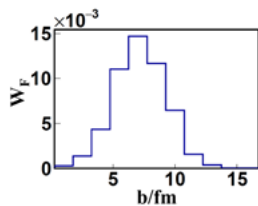
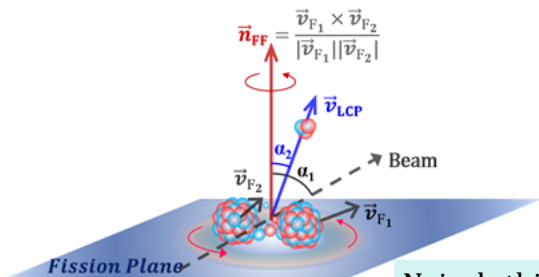
α_1 : $\cos \alpha_1 \rightarrow 0$, beam axis in fission plane

Angle between fission plane normal
and beam direction.

α_2 :

Angle between fission plane normal
and outgoing angle of the LCP.

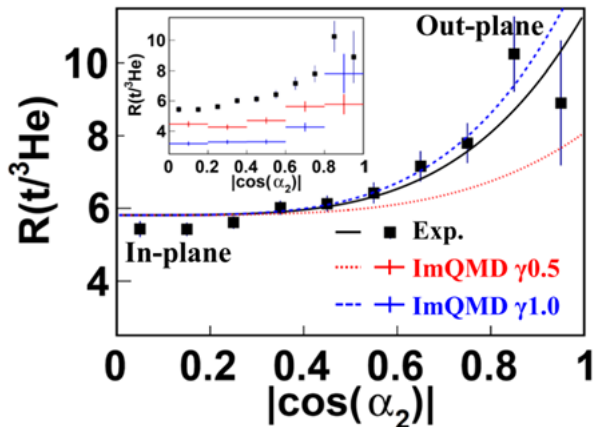
$\cos \alpha_2 \rightarrow 0$, in-plane emission; $\cos \alpha_2 \rightarrow 1$, out-plane emission



Naively thinking, neck emission favors $\cos \alpha_2 \rightarrow 1$

Neutron-Rich neck emission in fast fission

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



$t/{}^3\text{He}$ yield ratio increases as $\cos \alpha_2$, indicating a neutron rich neck emission. The ratio at large $|\cos \alpha_2|$ exhibit sensitive dependence on $E_{\text{sym}}(\rho)$, indicating $0.5 < \gamma < 1$.

Fine constraint relies on good reproduction of the absolute yield of $A=3$ cluster!

Summary and outlook

- 1. (Fast)fission following heavy ion collisions provides an opportunities to constrain the $E_{\text{sym}}(\rho)$, as demonstrated by transport model simulations;
- 2. Wide angular range of isotope-resolved charged particles carry the information of isospin drift process, and enables to constrain the slope parameter of $E_{\text{sym}}(\rho)$, in accordance with world results;
- 3. CSHINE experiment is capable to measure the fission events, using PPACs to detect the fission fragments. Distribution properties of the fission events suggests the dynamic feature of the fission process.
- 4. The ${}^3\text{He}$ -puzzle is presented in fast fission process. the $t/{}^3\text{He}$ yield ratio as a function of the angle with respect to the fission axis reveals a neutron-rich feature of neck emission. The sensitivity of the neck emission on $E_{\text{sym}}(\rho)$ motivate further measurement at large $\cos\theta_2$.