Korea-China joint workshop for rare isotope physics

2025年7月6日至10日
Benisiam Hall, Benikea Hotel, Jeju island
Asia/Seoul 时区

Nuclear cluster and hypernucleus production in intermediate-energy heavy-ion collisions

Zhao-Qing Feng (冯兆庆)

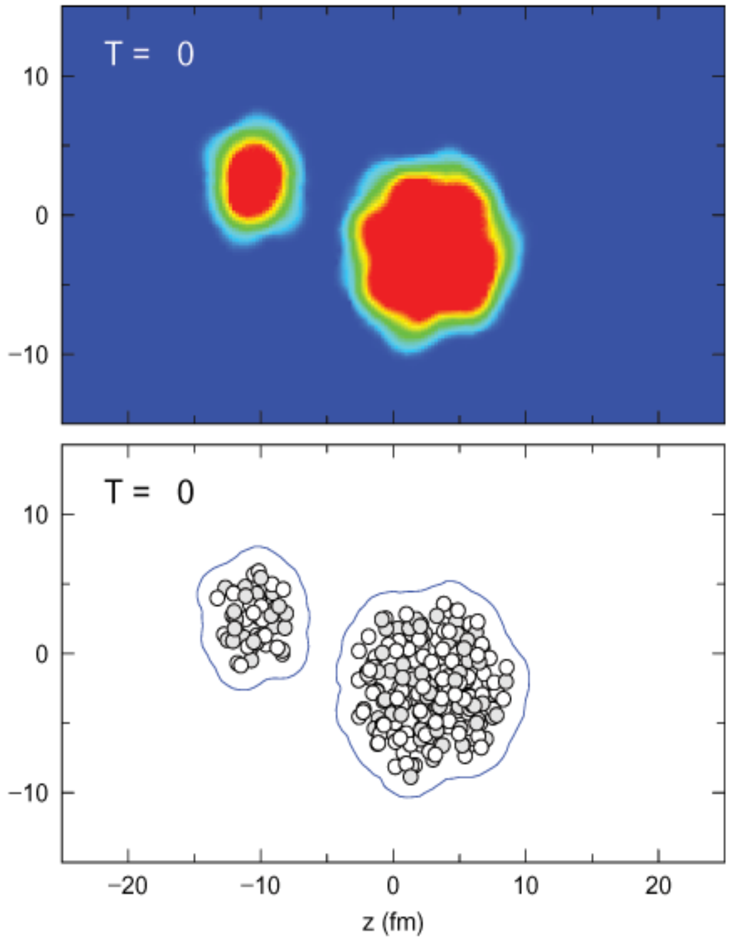
School of Physics and Optoelectronics, South China University of Technology, Guangzhou

*Email: fengzhq@scut.edu.cn

Outline

- Cluster, hyperon and hypercluster production via heavy-ion collision for investigating neutron-star matter properties
- LQMD transport model
- Hyperon-nucleon interaction in dense nuclear matter via HICs
- Fragmentation reaction and hyperfragment production in HICs
- Summary and perspective

^{56}Fe 800 MeV/nucleon on ^{208}Pb



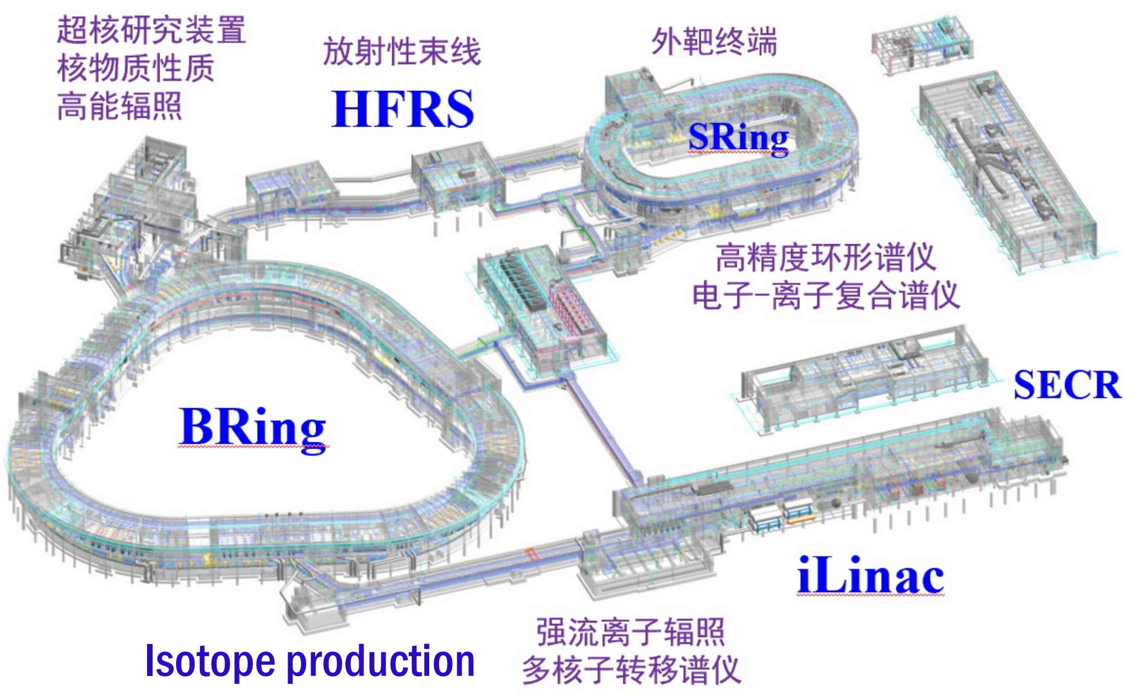
Slide from Jian-Cheng Yang (杨建成 研究员，HIAF总工程师)，2023全国核反应会议邀请报告

强流重离子加速器-HIAF

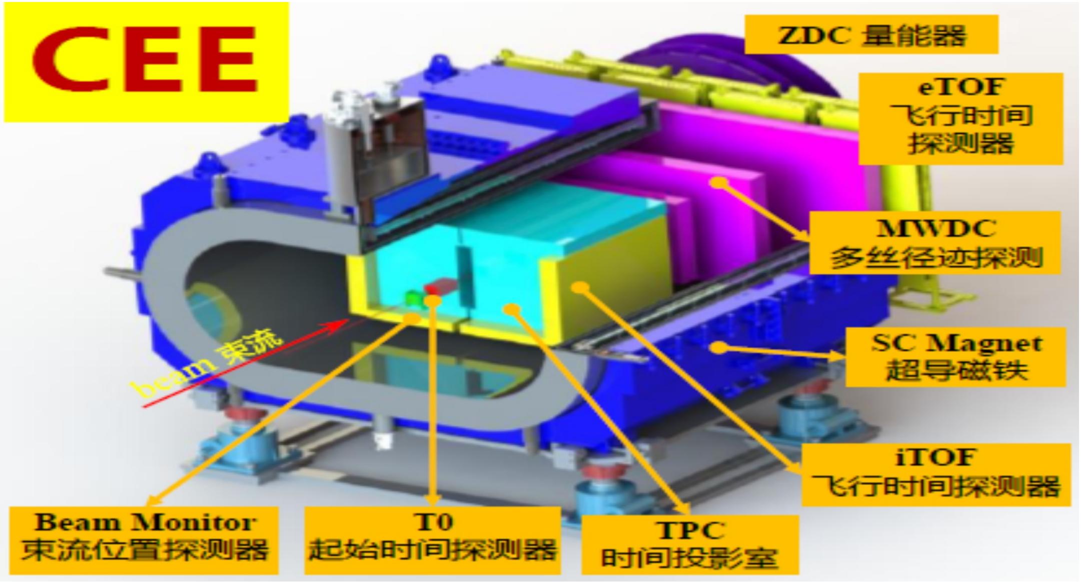
□ 科学目标

集成离子超导直线加速器和环形同步加速器最先进的技术，**建造**一台束流指标先进、多学科用途的重离子科学综合研究装置—“强流重离子加速器研究装置”（HIAF），为核物理和核天体物理基础研究、原子物理、重离子束应用研究提供国际领先水平的实验平台。**基于HIAF，打造在国际上有重大影响的重离子科学研究中心**

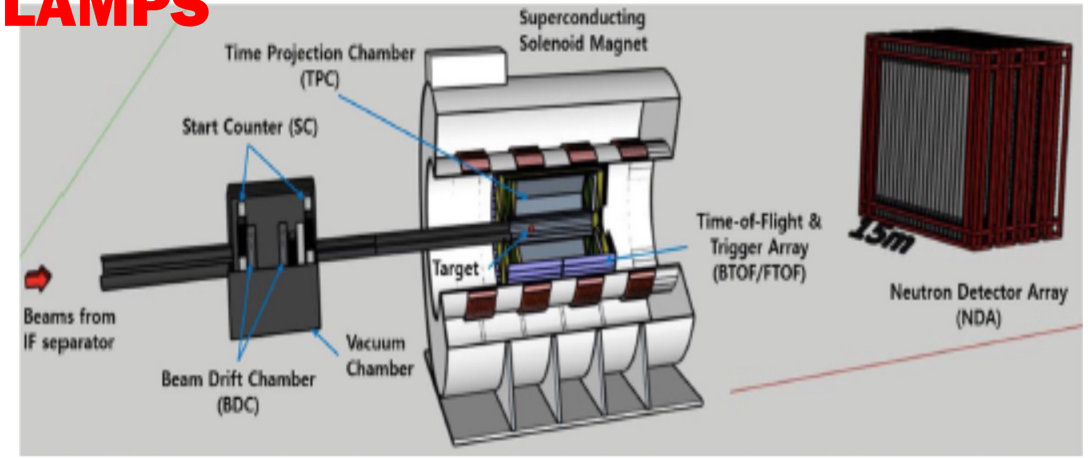
总体方案：强流超导直线、快循环同步环、多实验终端结合

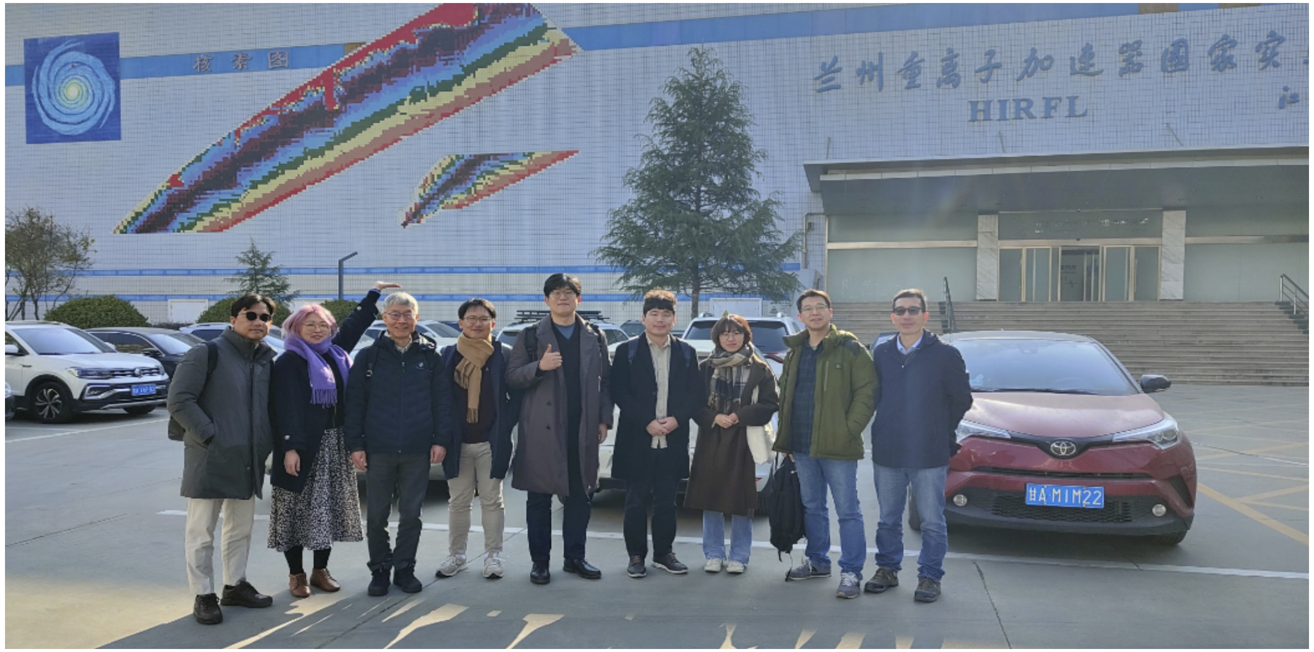


Korea-China cooperation for rare isotope physics



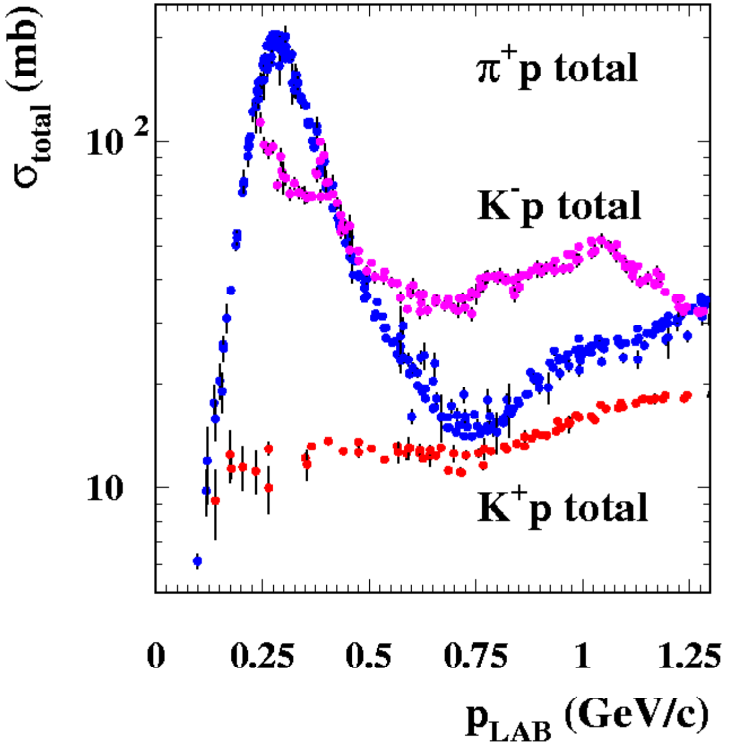
LAMPS



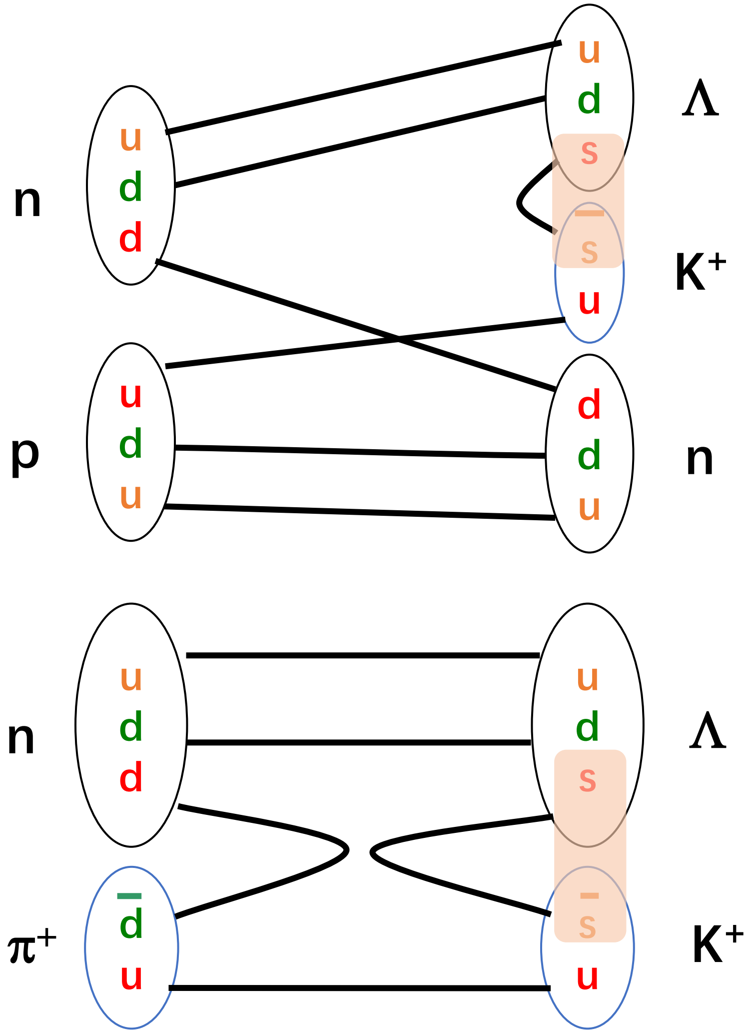


I. Cluster, hyperon and hypercluster production via HICs and hadron induced reactions

1. Strange particle production in hadron-hadron collisions



mean free path at ρ_0:
$\lambda(\pi) = 0.3$ fm
$\lambda(K^+) = 5$ fm
$\lambda(K^-) = 0.8$ fm



科学通报 2018 年 第 63 卷 第 8 期：735～744
论 文
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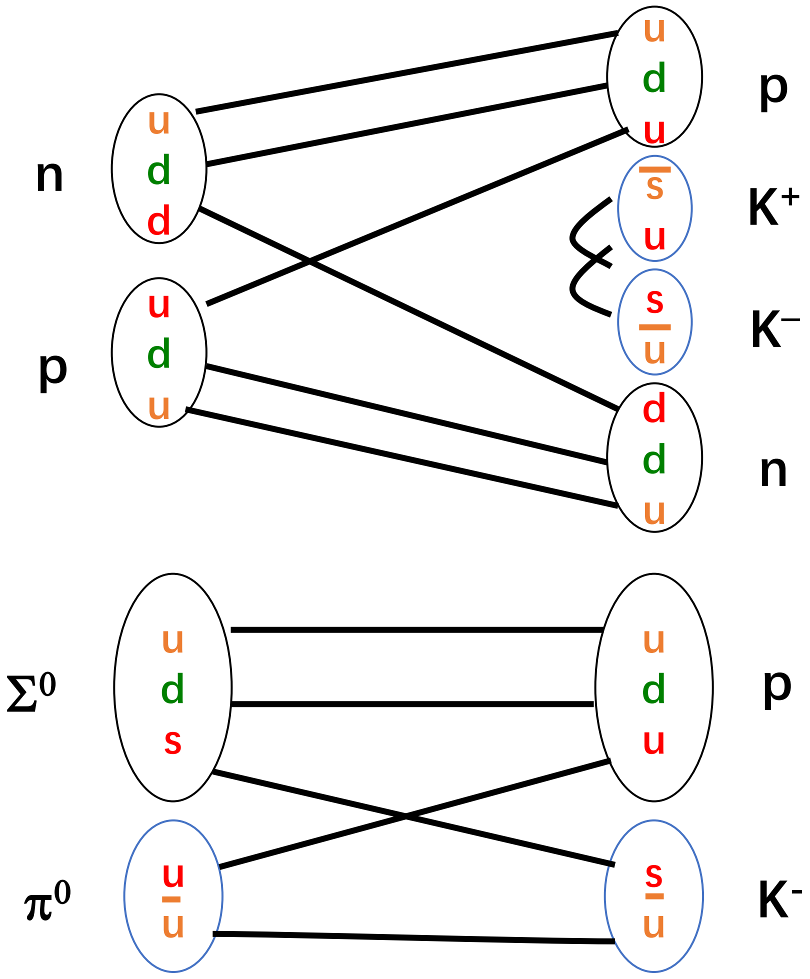
中高能重离子碰撞中奇异粒子产生和超核形成机制

冯兆庆



2. Cluster production in heavy-ion collisions

Experiments:

SSC and CSR(HIRFL), INDRA (GANIL), CHIMERA (LNS), NSCL (MSU), FOPI and HADES (GSI) …

Cluster production measurement at FOPI

Multiplicities and charge balance for Au + Au at $E/A = 0.15$ GeV and $b_0 < 0.15$.

$Z = 1$	59.9 ± 3.0	p	24.1 ± 1.2	$Z = 2$	25.0 ± 1.8	^{3}He	8.4 ± 0.9
		d	20.4 ± 1.4			^{4}He	16.6 ± 1.7
		t	15.1 ± 1.5				
		Li	5.0 ± 0.5	Be	1.69 ± 0.17		
		B	1.44 ± 0.15	C	0.90 ± 0.09		
		N	0.50 ± 0.05	O	0.26 ± 0.03		

Multiplicities and charge balance for Ni + Ni at $E/A = 0.25$ GeV and $b_0 < 0.15$.

$Z = 1$	34.9 ± 1.8	p	19.2 ± 1.0	$Z = 2$	9.0 ± 0.7	^{3}He	3.24 ± 0.33
		d	10.5 ± 0.8			^{4}He	5.79 ± 0.58
		t	5.1 ± 0.5				
		Li	0.91 ± 0.09	Be	0.26 ± 0.03		
		B	0.10 ± 0.01				

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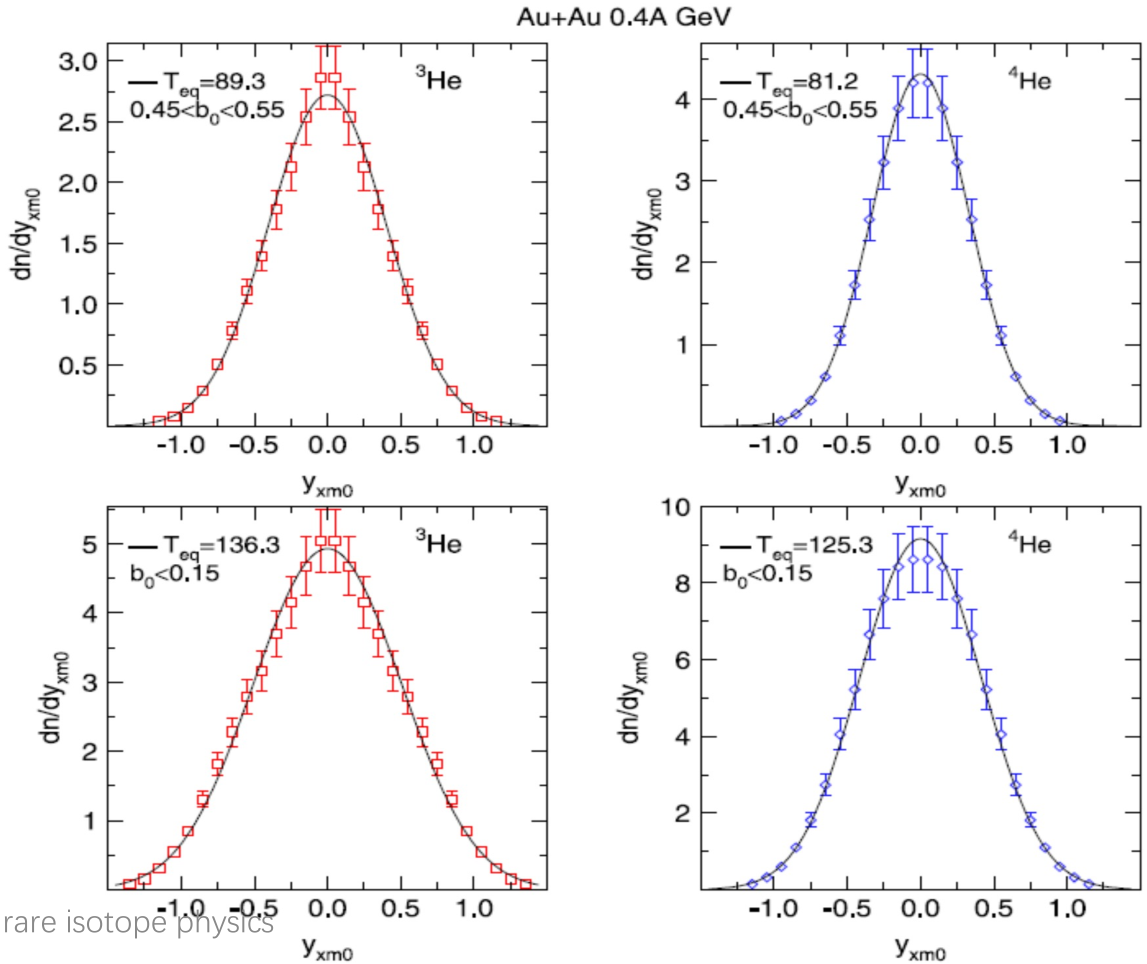
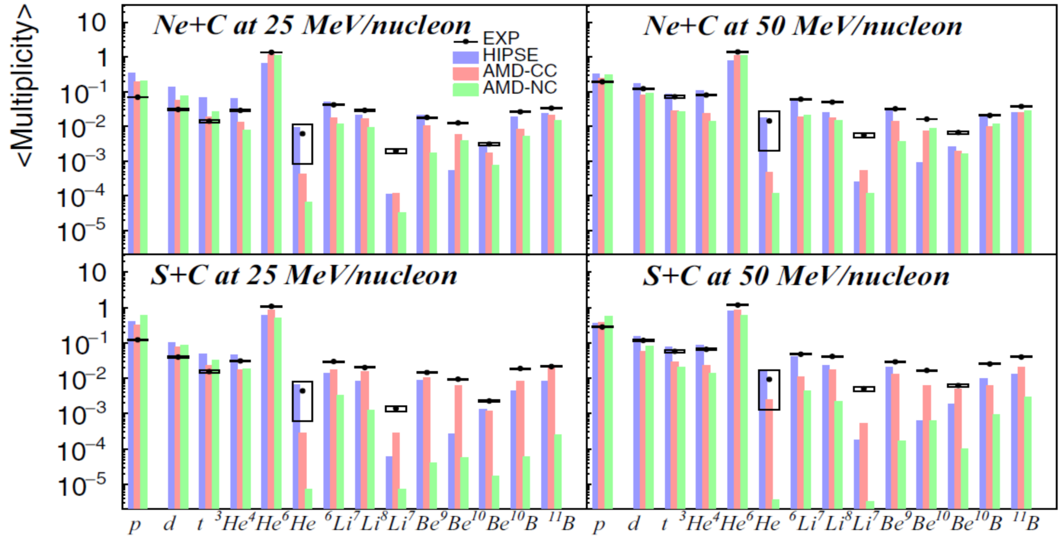
Nuclear Physics A 848 (2010) 366–427
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

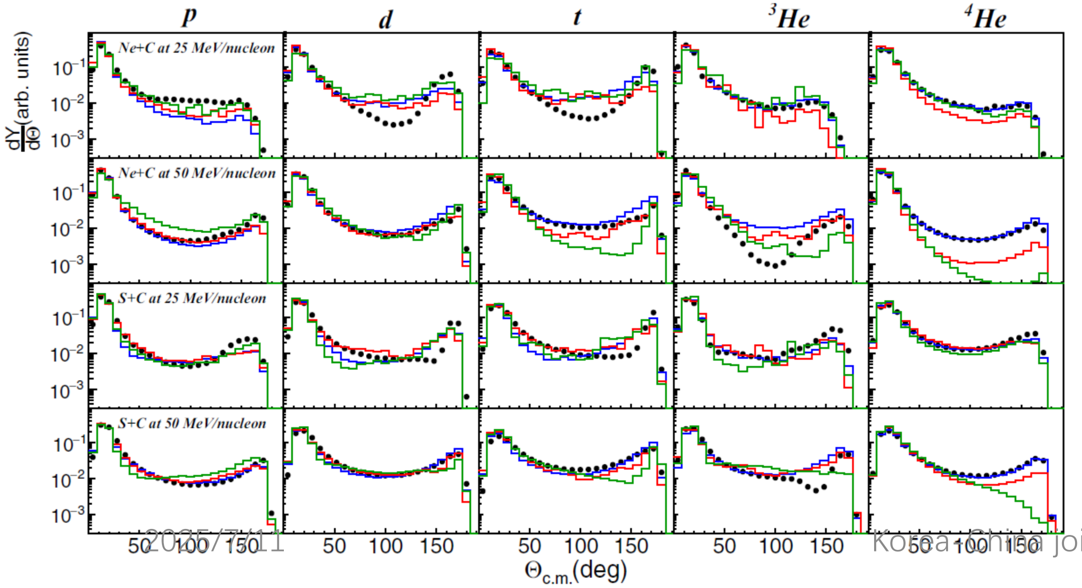
Systematics of central heavy ion collisions in the 1*A* GeV regime

FOPI Collaboration



Cluster production measurement by INDRA-FAZIA at INFN-LNS



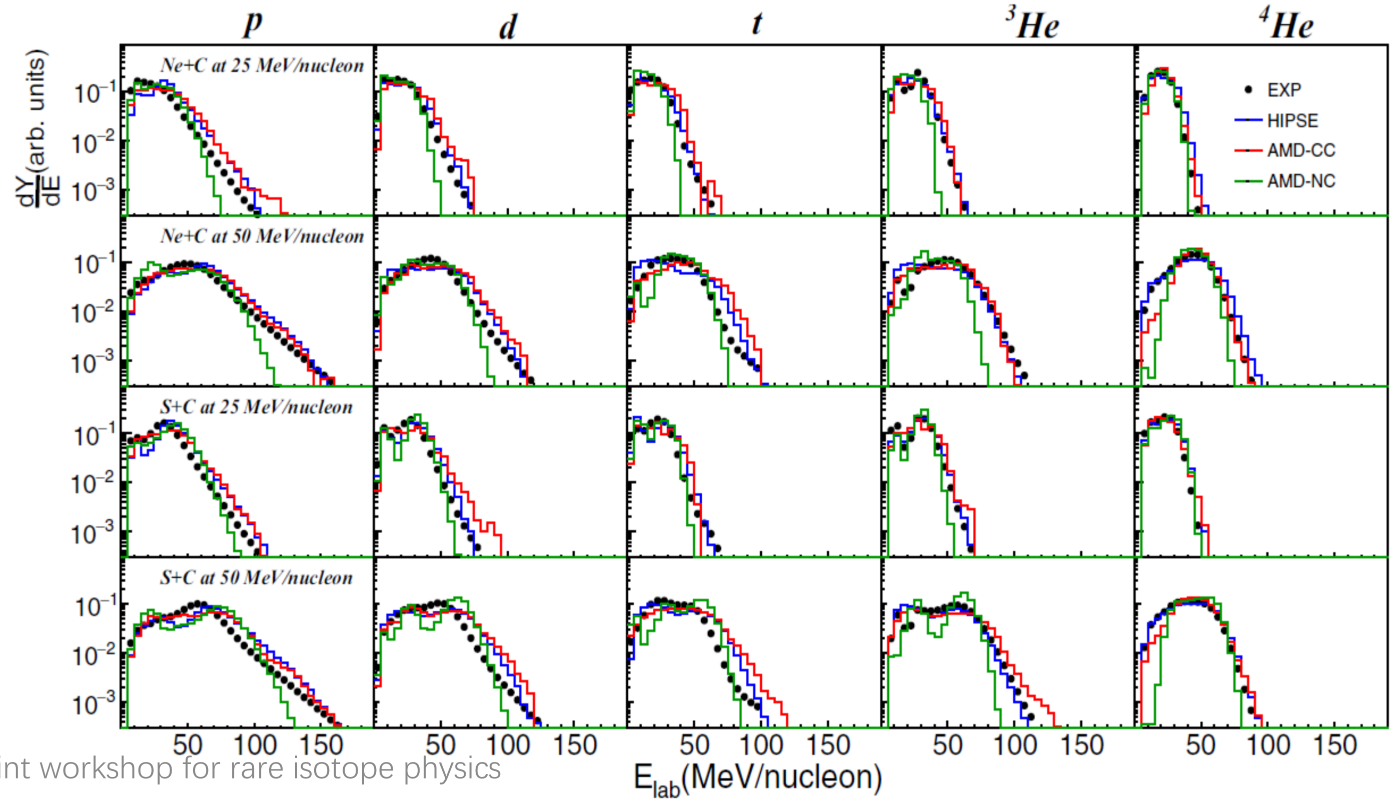


PHYSICAL REVIEW C **107**, 044614 (2023)

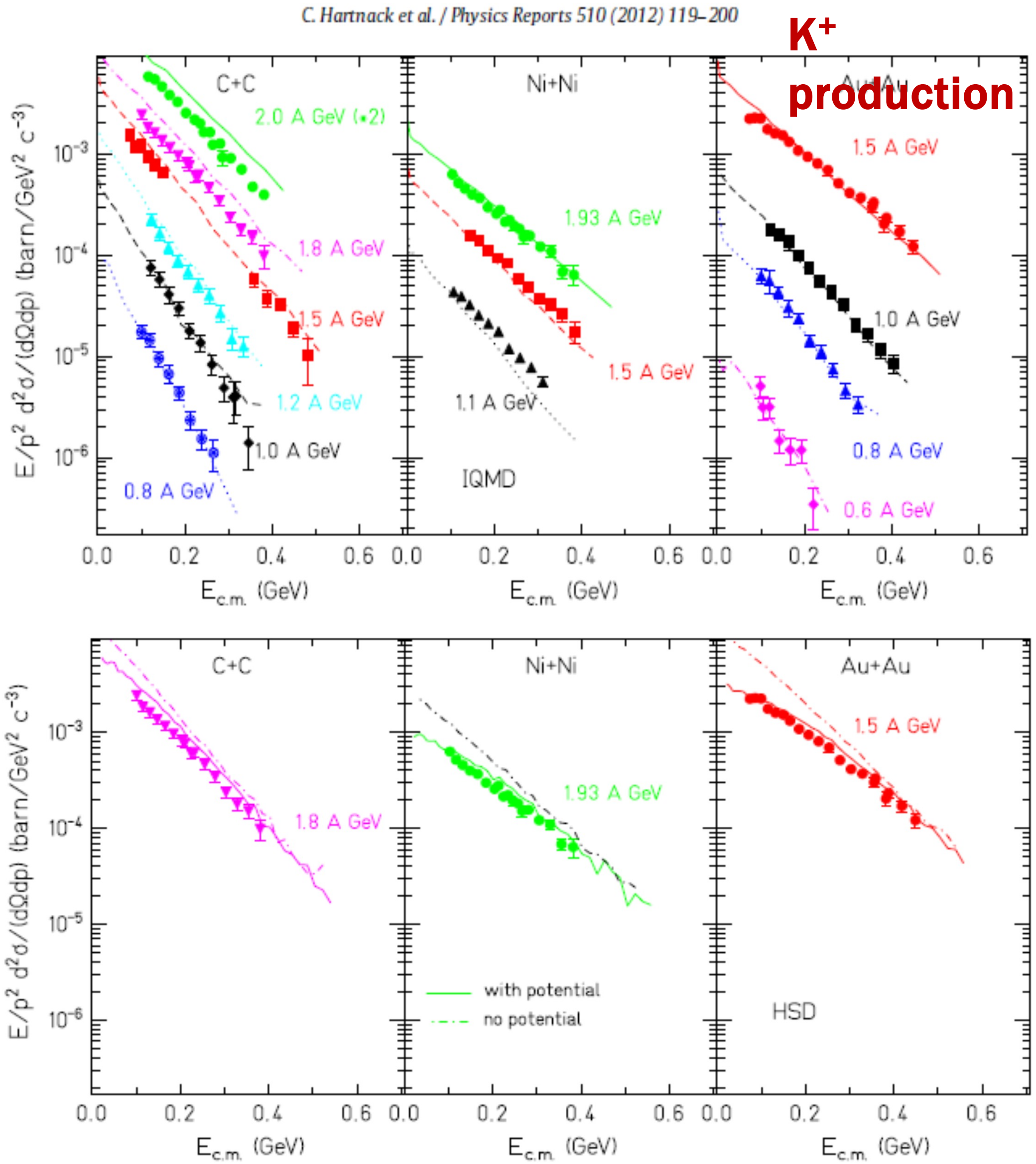
Featured in Physics

Examination of cluster production in excited light systems at Fermi energies from new experimental data and comparison with transport model calculations

C. Frosin,[1,2,*] S. Piantelli,[2] G. Casini,[2] A. Ono,[3] A. Camaiani,[4] L. Baldesi,[2] S. Barlini,[1,2] B. Borderie,[5] R. Bougault,[6] C. Ciampi,[1,2] M. Cicerchia,[7] A. Chbihi,[8] D. Dell'Aquila,[9,10] J. A. Dueñas,[11] D. Fabris,[12] Q. Fable,[13] J. D. Frankland,[8] T. Génard,[8] F. Gramegna,[7] D. Gruyer,[6] M. Henri,[8] B. Hong,[14,15] M. J. Kweon,[16] S. Kim,[17] A. Kordyasz,[18] T. Kozik,[19] I. Lombardo,[20,21] O. Lopez,[6] T. Marchi,[7] K. Mazurek,[22] S. H. Nam,[14,15] J. Lemarié,[8] N. LeNeindre,[6] P. Ottanelli,[2] M. Parlog,[6,23] J. Park,[14,15] G. Pasquali,[1,2] G. Poggi,[1,2] A. Rebillard-Soulié,[6] B. H. Sun,[24] A. A. Stefanini,[1,2] S. Terashima,[24] S. Upadhyaya,[19] S. Valdré,[2] G. Verde,[20,13] E. Vient,[6] and M. Vigilante[25,26]
(INDRA-FAZIA Collaboration)



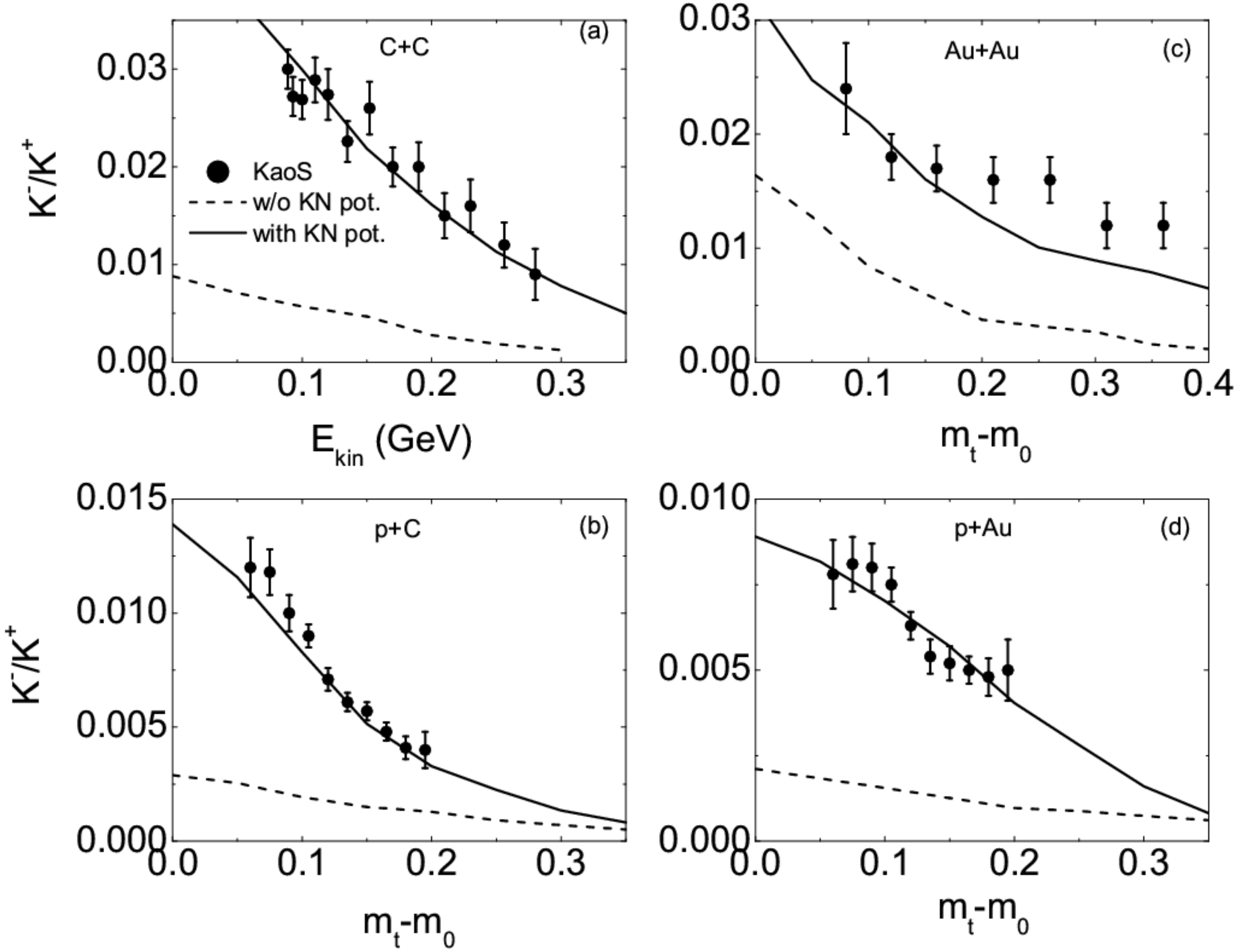
3. Strange particle production in HICs



K⁺ production

The ratio of K^-/K^+ in HICs of ^{12}C + ^{12}C (^{197}Au+ ^{197}Au) at 1.8*A* GeV and proton beams at 2.5 GeV

(Z. Q. Feng et al., Phys. Rev. C 90, 064604 (2014))

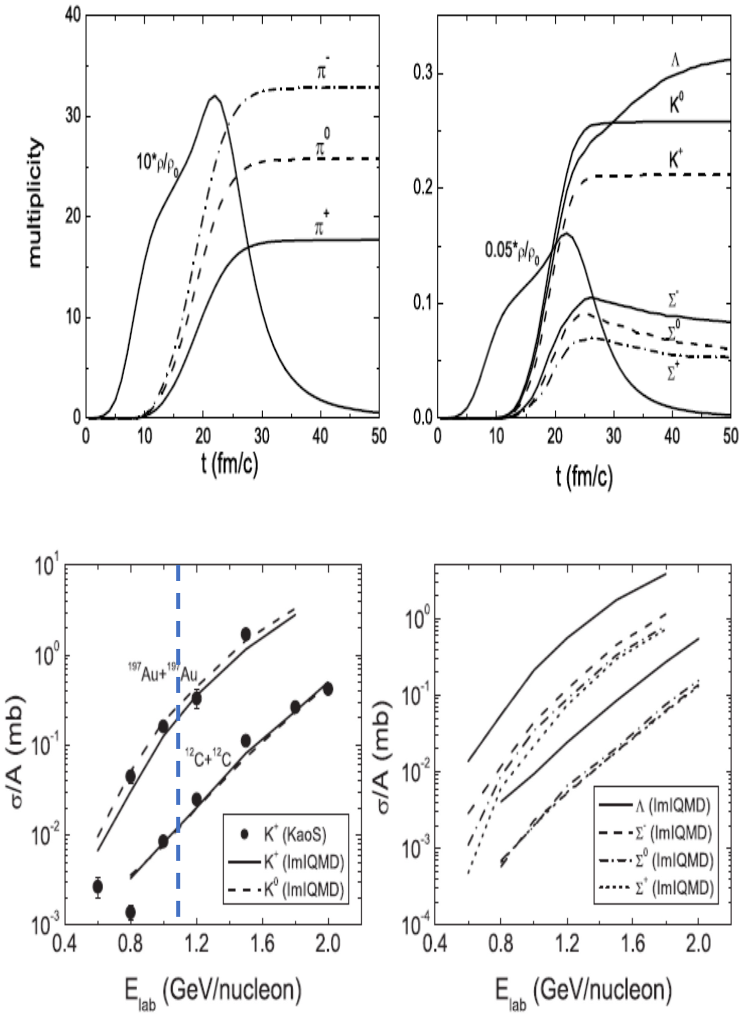


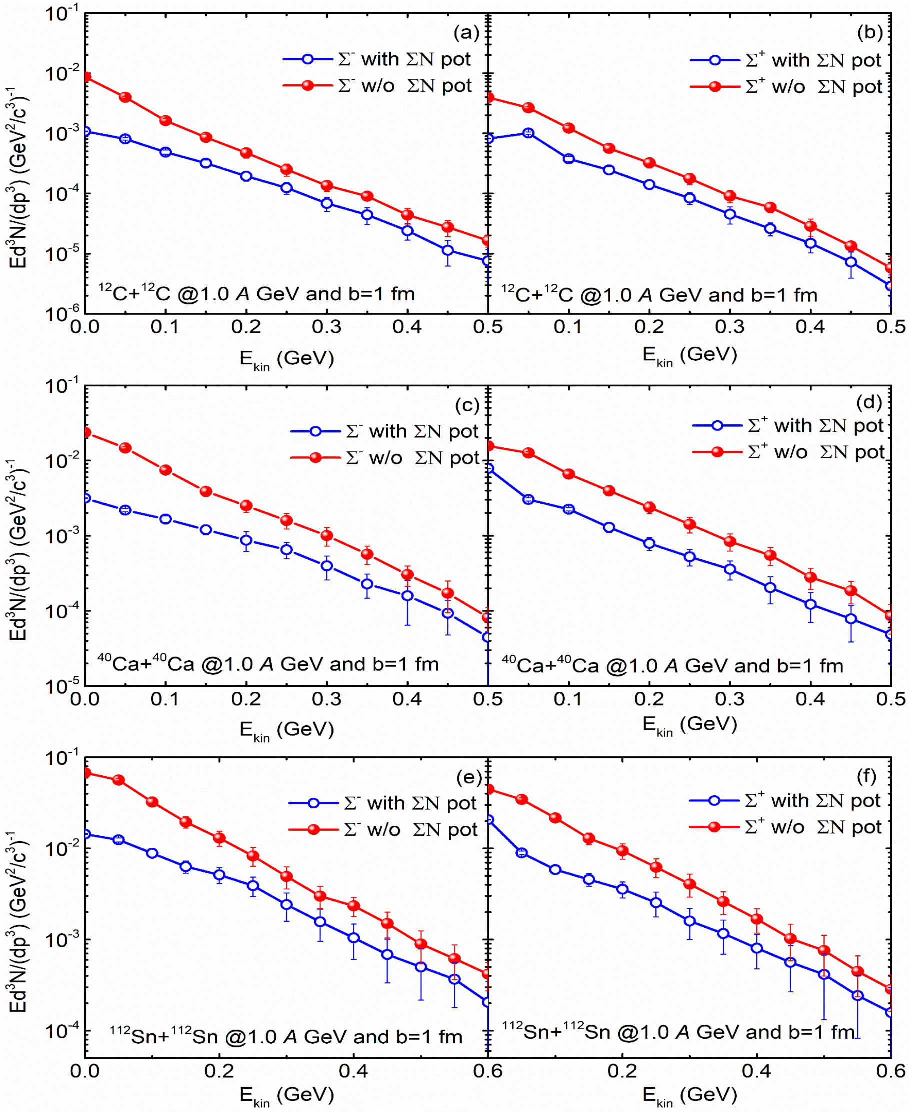
$V_{K+}(\rho_0)$= 28 MeV, $V_{K-}(\rho_0)$= -100 MeV

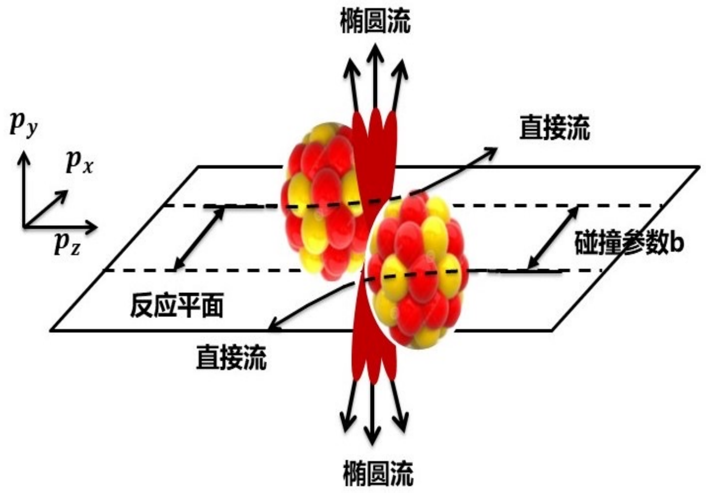
Kaon and hyperon production in HICs (yields, invariant energy spectra, collective flows)

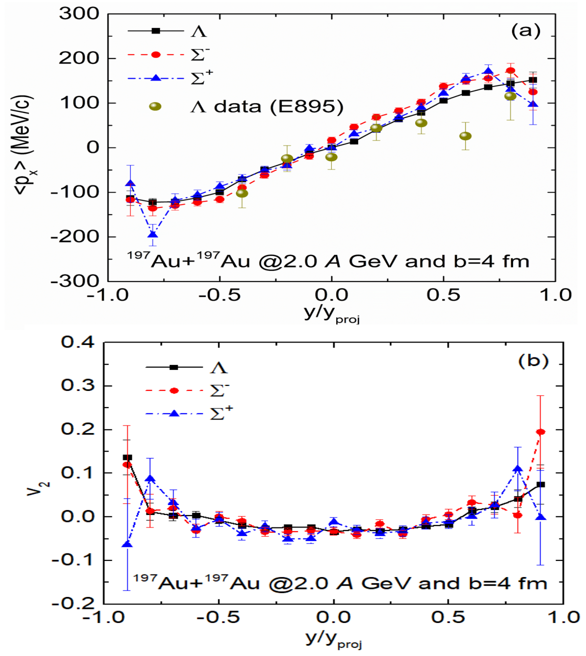
ZQF, Phys. Rev. C 82 (2010) 057901; Phys. Rev. C 87 (2013) 064605; Ding-Chang Zhang et al., Chin. Phys. Lett. 38 (2021) 092501

^{197}Au+^{197}Au@1.5*A*GeV









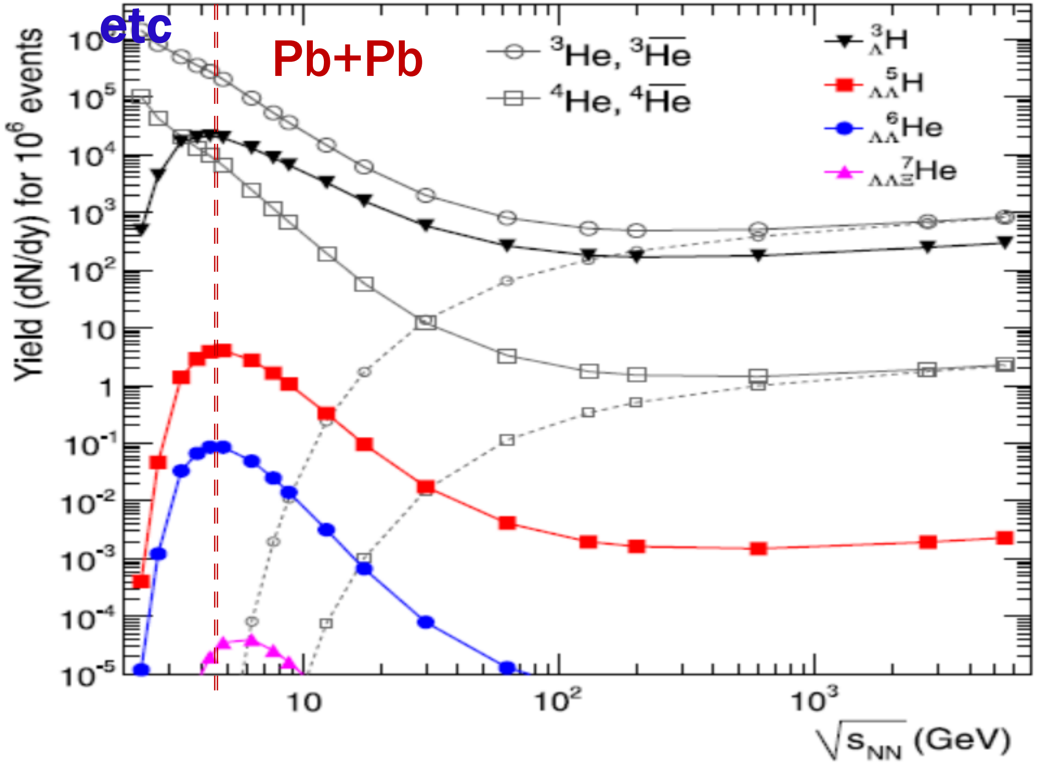
5. Hypernuclear production in HICs

H. Tamura, *Prog. Theor. Exp. Phys.* (2012) 02B012

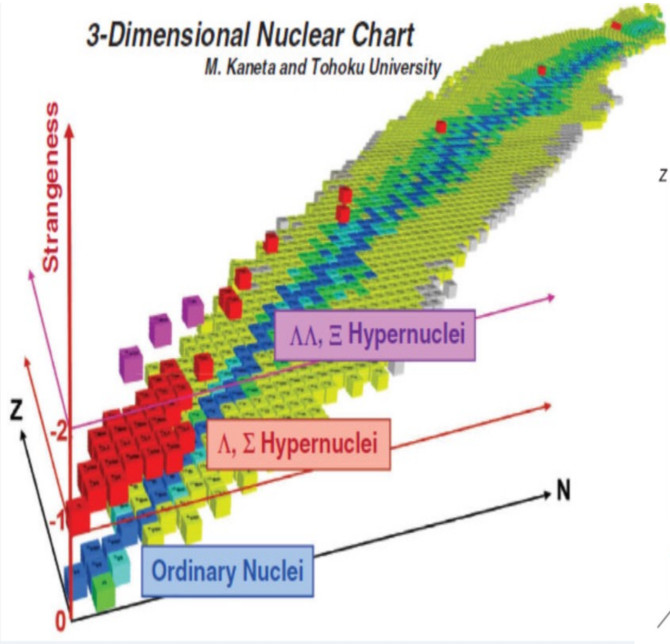
① Neutron-rich/proton-rich HN nuclei and spectroscopies

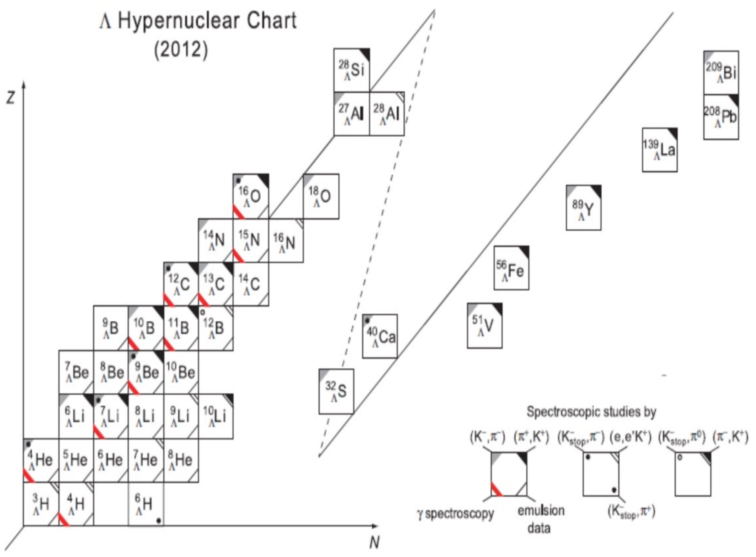
② Multistrangeness HN (S=-2) $_{\Lambda\Lambda}$X和$_{\Xi}$X

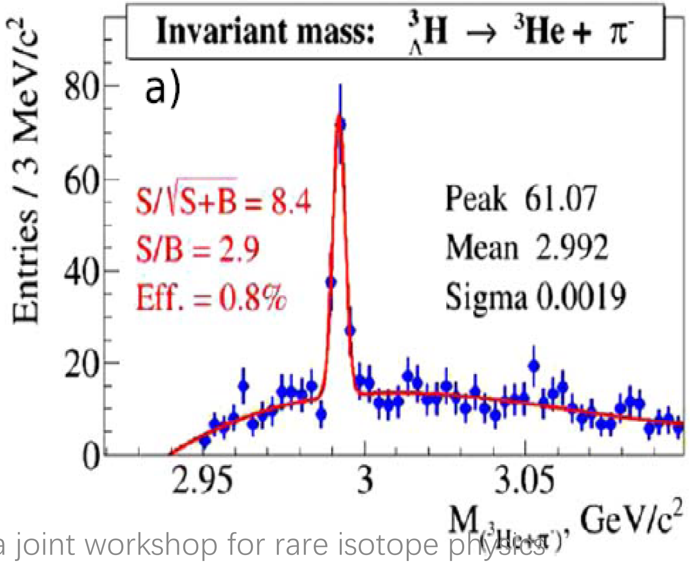
③ Interaction potentials of NΛ, NΞ NNΛ, etc

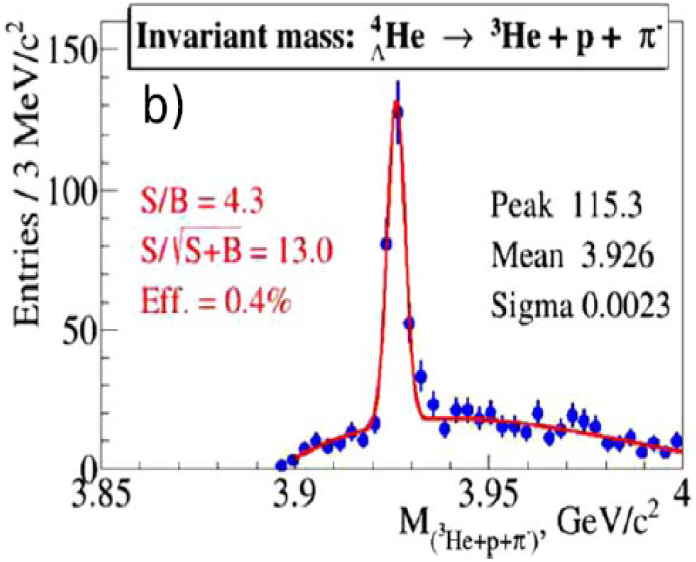


A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, Physics Letters B 697 (2011) 203–207



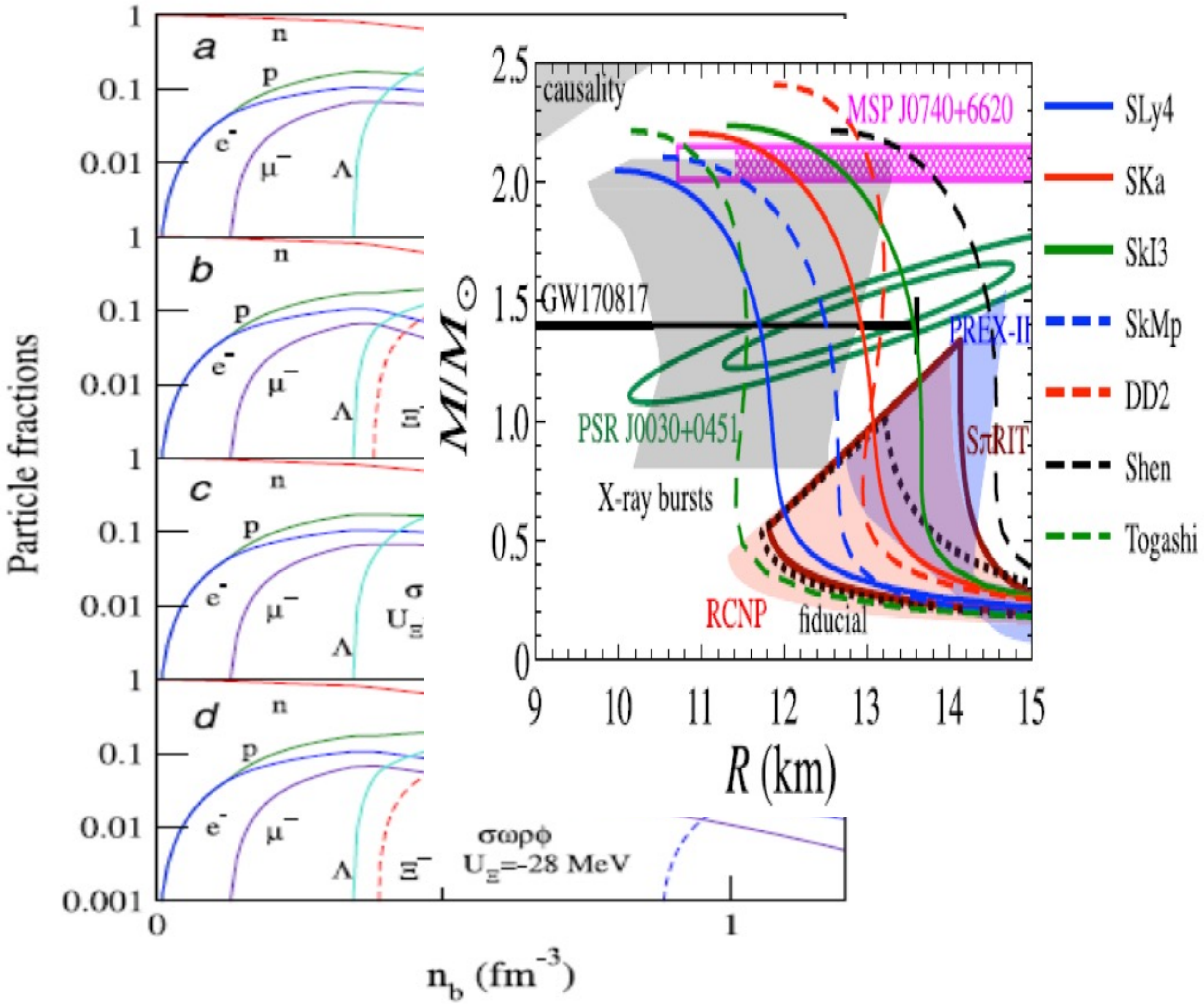


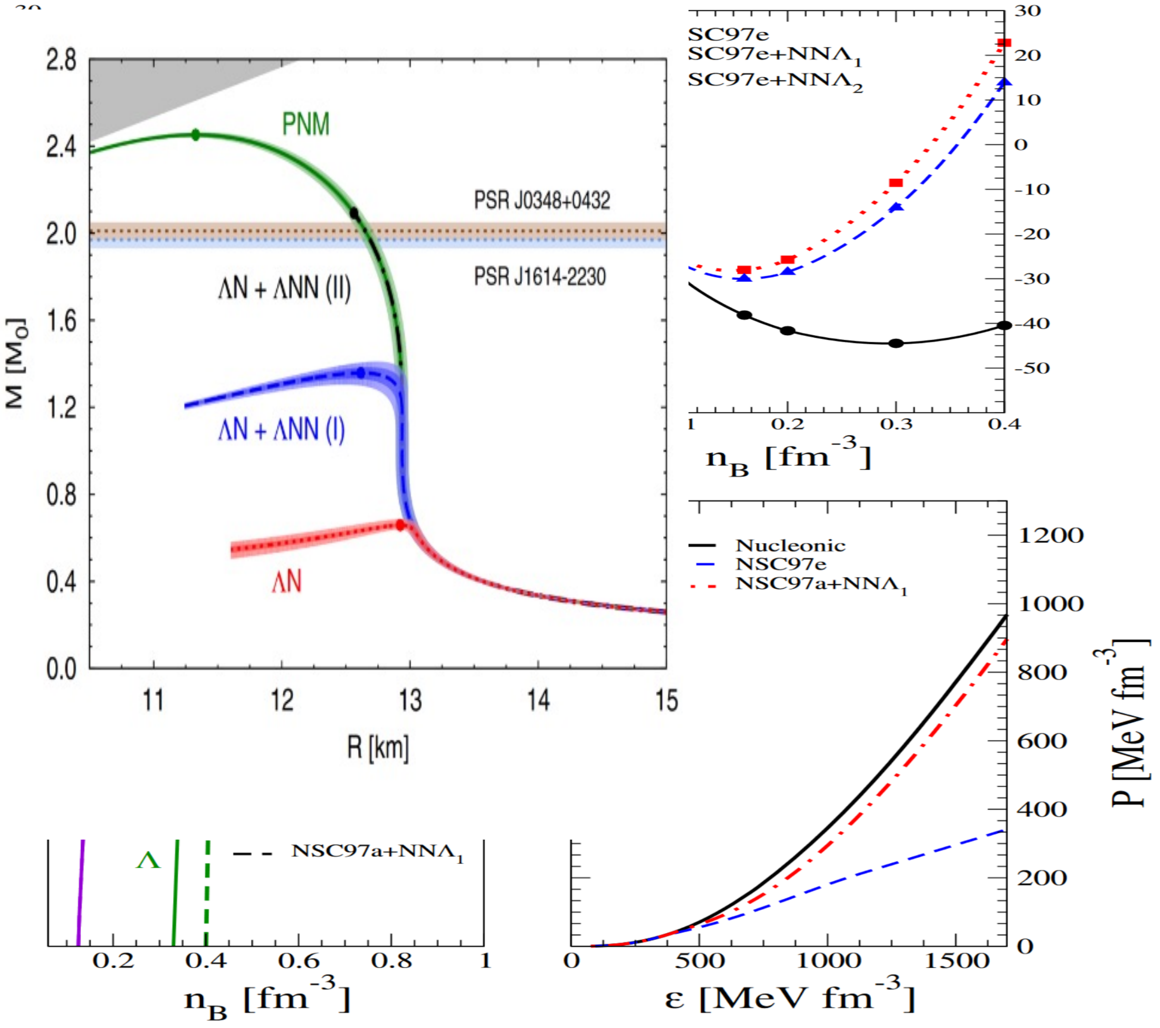




Hyperons in neutron stars (NS)

S. Weissenborn, D. Chatterjee, J. Schaffner-Bielich, Nucl. Phys. A 881, 62 (2012)
W. Z. Jiang, R. Y. Yang, and D. R. Zhang, Phys. Rev. C 87, 064314 (2013)
Diego Lonardoni, Alessandro Lovato, Stefano Gandolfi, and Francesco Pederiva, Phys. Rev. Lett. 114, 092301 (2015)



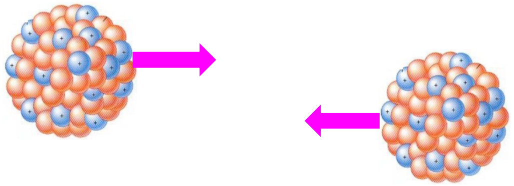


II. LQMD transport model

Lanzhou quantum molecular dynamics transport model (LQMD)

Heavy-ion collisions (5 MeV – 5 GeV/nucleon) and hadron induced reaction (p, $\bar{p}$, π, K, e, etc)

- **LQMD transport model** (Skyrme interaction, Walecka model with σ, ω, ρ, δ)
- **Neutron star equation of state via HICs** (nuclear symmetry energy at sub- and supra- saturation densities in HICs, isospin splitting of nucleon effective mass from HICs, particle production, 2-body and 3-body potential, multi-body correlation)
- **In-medium effects of hadrons** (optical potentials, energy conservation and in-medium effects, i.e., Δ(1232), N*(1440), N*(1535)), hyperons (Λ,Σ,Ξ) and mesons (π,K,η,ρ,ω,ϕ…))
- **Kinetic production of (hyper)clusters and nuclear fragmentation reactions** (production cross section, phase-space distribution, collective flows, cluster transportation, Mott effect, e.g., deuteron, triton, ^{3}He, α, ${}_{\Lambda(\Sigma)}X$, ${}_{\Lambda\Lambda}X$, ${}_{\Xi}X$, ${}_{\bar{\Lambda}}X$)
- **Nuclear collisions of light systems** (e.g., d+α, ^{9}Be+D_2O, d+^{7}Li etc, antisymmetrization with Volkov 2-body force)
- **Spallation reactions induced by p, d, t, α, $\bar{p}$, $\bar{d}$ etc (cascade multi-step collision for thick targets)**



1. Lanzhou quantum molecular dynamics transport model (LQMD-Skyrme)

$$H_B = \sum_i \sqrt{\mathbf{p}_i^2 + \mathbf{m}_i^2} + U_{\mathrm{int}} + U_{\mathrm{mom}}$$

$$U_{loc} = \int V_{loc}(\rho(\mathbf{r}))\, d\mathbf{r}$$

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

$$U_{mom} = \frac{1}{2\rho_0}\sum_{i,j,j\neq i}\sum_{\tau,\tau'} C_{\tau,\tau'}\delta_{\tau,\tau_i}\delta_{\tau',\tau_j}\iiint d\mathbf{p}\, d\mathbf{p}'\, d\mathbf{r}\, f_i(\mathbf{r},\mathbf{p},t) \times[\ln(\epsilon(\mathbf{p}-\mathbf{p}')^2+1)]^2 f_j(\mathbf{r},\mathbf{p}',t).$$

$$\boxed{E_{sym}(\rho) = \frac{1}{3}\frac{\hbar^2}{2m}\left(\frac{3}{2}\pi^2\rho\right)^{2/3} + E_{sym}^{loc}(\rho) + E_{sym}^{mom}(\rho).}$$

$$E_{sym}^{loc}(\rho) = \frac{1}{2}C_{sym}(\rho/\rho_0)^{\gamma_s} \qquad E_{sym}^{loc}(\rho) = a_{sym}(\rho/\rho_0) + b_{sym}(\rho/\rho_0)^2.$$

PHYSICAL REVIEW C 84, 024610 (2011)

Momentum dependence of the symmetry potential and its influence on nuclear reactions

Zhao-Qing Feng*

Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China

(Received 11 July 2011; published 19 August 2011)

Phys. Rev. C 84, 024610 (2011); 85, 014604 (2012)

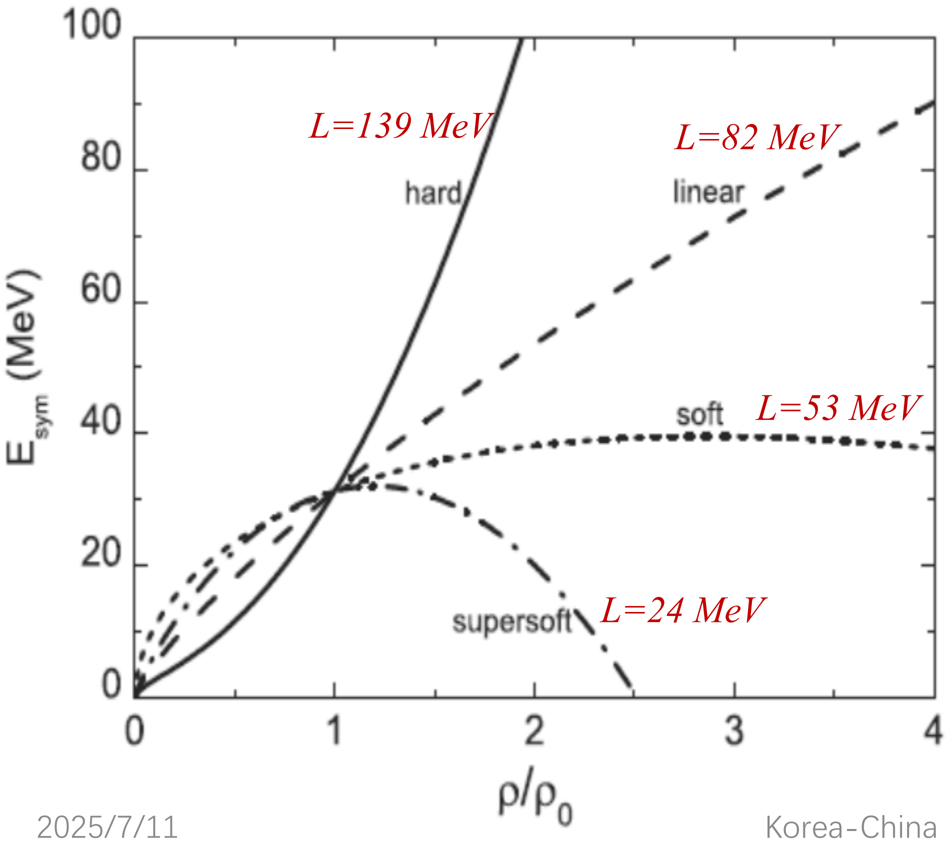
C_{sym}= 38 MeV

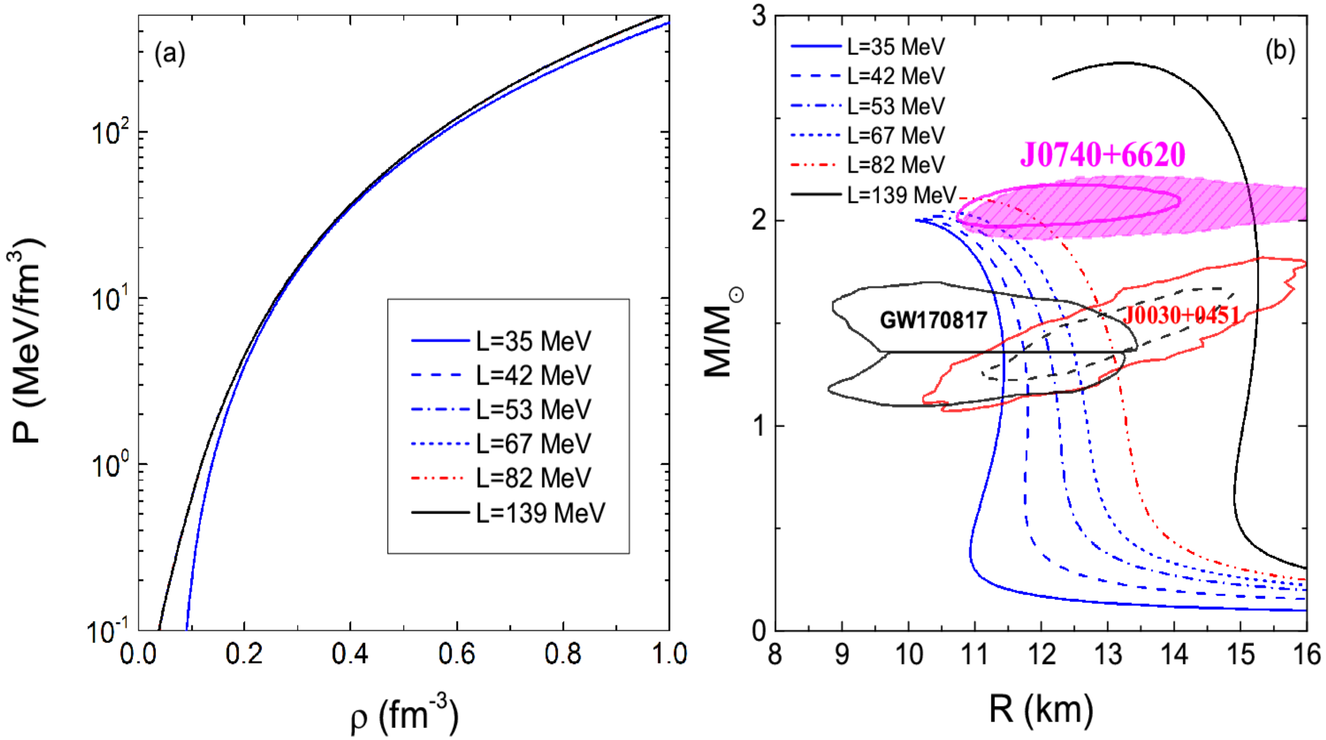
a_{sym}= 37.7 MeV

b_{sym}= -18.7 MeV

Table 1: The parameters and properties of isospin symmetric EoS used in the LQMD model at the density of 0.16 fm^{-3}.

Parameters	α (MeV)	β (MeV)	γ	C_{mom} (MeV)	ϵ (c^2/MeV^2)	m^*_∞/m	K_∞ (MeV)
PAR1	-215.7	142.4	1.322	1.76	5×10^{-4}	0.75	230
PAR2	-226.5	173.7	1.309	0.	0.	1.	230





2. Covariant energy-density functional (LQMD.RMF)

Si-Na Wei, Zhao-Qing Feng,
Nuclear Science and Techniques 35, 15 (2024)
arXiv:2302.09984

$$L = \bar{\psi}[i\gamma_\mu\partial^\mu - (M_N - g_\sigma\varphi - g_\delta\vec{\tau}\cdot\vec{\delta}) - g_\omega\gamma_\mu\omega^\mu - g_\rho\gamma_\mu\vec{\tau}\cdot\vec{b}^\mu]\psi$$
$$+\frac{1}{2}(\partial_\mu\varphi\partial^\mu\varphi - m_\sigma^2\varphi^2) - U(\varphi) + \frac{1}{2}(\partial_\mu\vec{\delta}\partial^\mu\vec{\delta} - m_\sigma^2\vec{\delta}^2)$$
$$+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{b}_\mu\vec{b}^\mu - \frac{1}{4}\vec{G}_{\mu\nu}\vec{G}^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu,$$
$$G_{\mu\nu} = \partial_\mu\vec{b}_\nu - \partial_\nu\vec{b}_\mu,$$
$$U(\varphi) = \frac{g_2}{3}\varphi^3 + \frac{g_3}{4}\varphi^4$$

Energy density functional

$$\varepsilon = \sum_{i=n,p} 2\int\frac{d^3k}{(2\pi)^3}\sqrt{k^2 + M_i^{*2}} + \frac{1}{2}m_\sigma^2\varphi^2 + U(\varphi) + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2 b_0^2 + \frac{1}{2}m_\delta^2\delta_3^2$$

Temporal evolution in phase space

$$\dot{\mathbf{x}} = \frac{\mathbf{p_i}^*}{p_0^*} + \sum_{i\neq j}^{N}\{\frac{g_v^2}{2m_v^2}z_j^{*\mu}u_{i,\mu}B_iB_j\frac{\partial\rho_{ij}}{\partial\mathbf{p_i}} + \frac{g_v^2}{2m_v^2}z_i^{*\mu}u_{j,\mu}B_iB_j\frac{\partial\rho_{ji}}{\partial\mathbf{p_i}} + \frac{g_v^2}{2m_v^2}z_j^{*\mu}\rho_{ji}B_iB_j\frac{\partial u_{i,\mu}}{\partial\mathbf{p_i}}$$
$$+z_j^{*\mu}\frac{B_iB_j\bar{g}_v^2}{2m_v^2}[\frac{\rho_{ij}}{1-p_{T,ij}^2/\Lambda_v^2}\frac{\partial u_{i,\mu}}{\partial\mathbf{p_i}} + \frac{u_{i,\mu}}{1-p_{T,ij}^2/\Lambda_v^2}\frac{\partial\rho_{ij}}{\partial\mathbf{p_i}} + u_{i,\mu}\rho_{ij}\frac{\partial[1/(1-p_{T,ij}^2/\Lambda_v^2)]}{\partial\mathbf{p_i}}]$$
$$+z_i^{*\mu}\frac{B_iB_j\bar{g}_v^2}{2m_v^2}[\frac{u_{j,\mu}}{1-p_{T,ji}^2/\Lambda_v^2}\frac{\partial\rho_{ji}}{\partial\mathbf{p_i}} + u_{j,\mu}\rho_{ji}\frac{\partial[1/(1-p_{T,ji}^2/\Lambda_v^2)]}{\partial\mathbf{p_i}}]$$
$$-\frac{m_j^*}{p_j^{*0}}\frac{\partial S_j}{\partial\mathbf{p_i}} - \frac{m_i^*}{p_i^{*0}}\frac{\partial S_i}{\partial\mathbf{p_i}}\},$$

$$\dot{\mathbf{p}} = -\sum_{i\neq j}^{N}\{\frac{g_v^2}{2m_v^2}z_j^{*\mu}u_{i,\mu}B_iB_j\frac{\partial\rho_{ij}}{\partial\mathbf{r_i}} + \frac{g_v^2}{2m_v^2}z_i^{*\mu}u_{j,\mu}B_iB_j\frac{\partial\rho_{ji}}{\partial\mathbf{r_i}}$$
$$+z_j^{*\mu}\frac{B_iB_j\bar{g}_v^2}{2m_v^2}\frac{u_{i,\mu}}{1-p_{T,ij}^2/\Lambda_v^2}\frac{\partial\rho_{ij}}{\partial\mathbf{r_i}}$$
$$+z_i^{*\mu}\frac{B_iB_j\bar{g}_v^2}{2m_v^2}\frac{u_{j,\mu}}{1-p_{T,ji}^2/\Lambda_v^2}\frac{\partial\rho_{ji}}{\partial\mathbf{r_i}}$$
$$-\frac{m_j^*}{p_j^{*0}}\frac{\partial S_j}{\partial\mathbf{r_i}} - \frac{m_i^*}{p_i^{*0}}\frac{\partial S_i}{\partial\mathbf{r_i}}\},$$

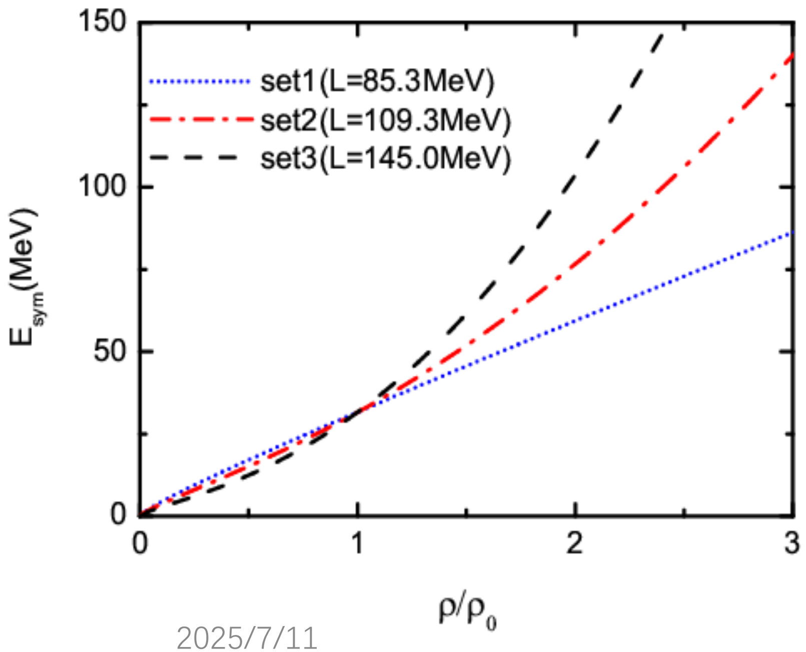
TABLE I: Parameter sets for RMF. The saturation density ρ_0 is set to be 0.16 fm^{-3}. The binding energy of saturation density is $E/A - M_N = -16$ MeV. The isoscalar-vector ω and isovector-vector ρ masses are fixed to their physical values, $m_\omega = 783$ MeV and $m_\rho = 763$ MeV. The remaining meson mass m_σ is set to be 550 MeV.

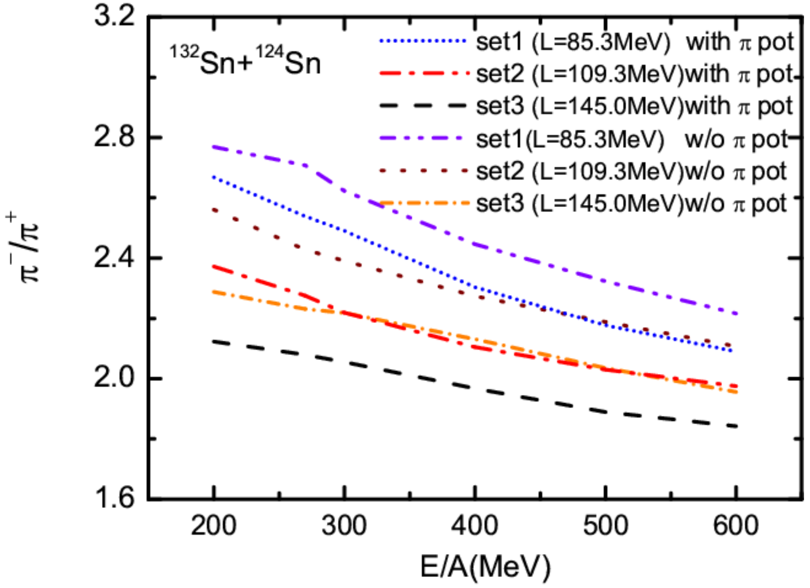
model	g_σ	g_ω	g_2 (fm^{-1})	g_3	g_ρ	g_δ	K (MeV)	$E_{sym}(\rho_0)$ (MeV)	L (ρ_0)(MeV)
set1	8.145	7.570	31.820	28.100	4.049	-	230	31.6	85.3
set2	8.145	7.570	31.820	28.100	8.673	5.347	230	31.6	109.3
set3	8.145	7.570	31.820	28.100	11.768	7.752	230	31.6	145.0

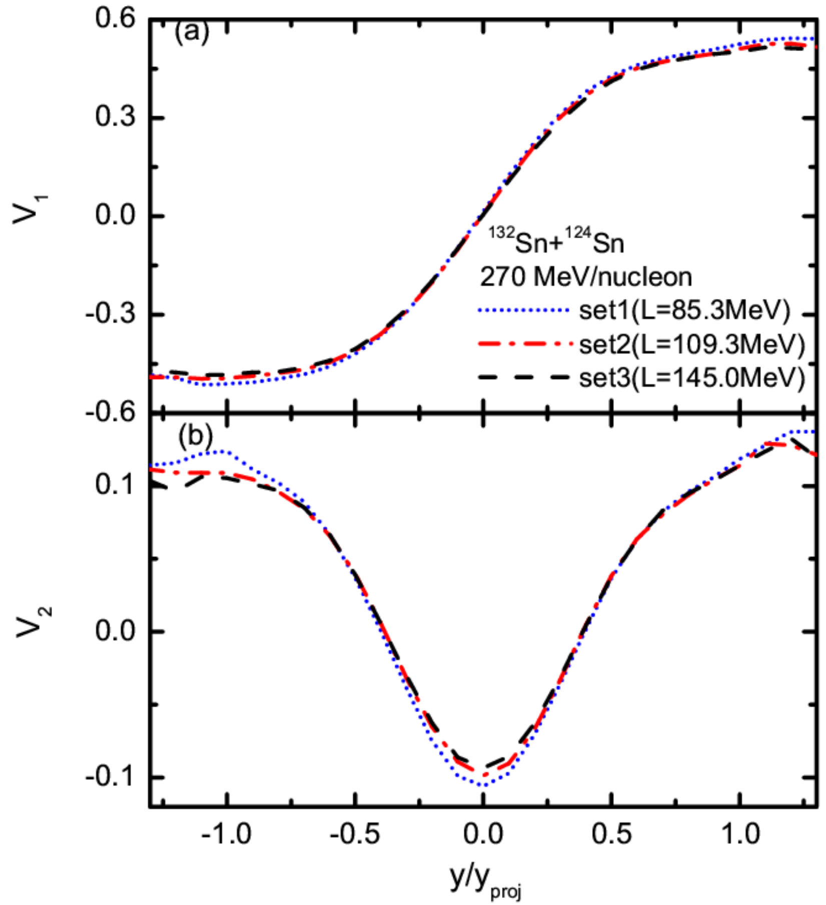
Symmetry energy

$$E_{sym} = \frac{1}{6}\frac{k_F^2}{E_F^*} + \frac{1}{2}\left[f_\rho - f_\delta\left(\frac{M^*}{E_F^*}\right)\right]\rho$$

$$f_{\rho,\delta} = g_{\rho,\delta}/m_{\rho,\delta}$$



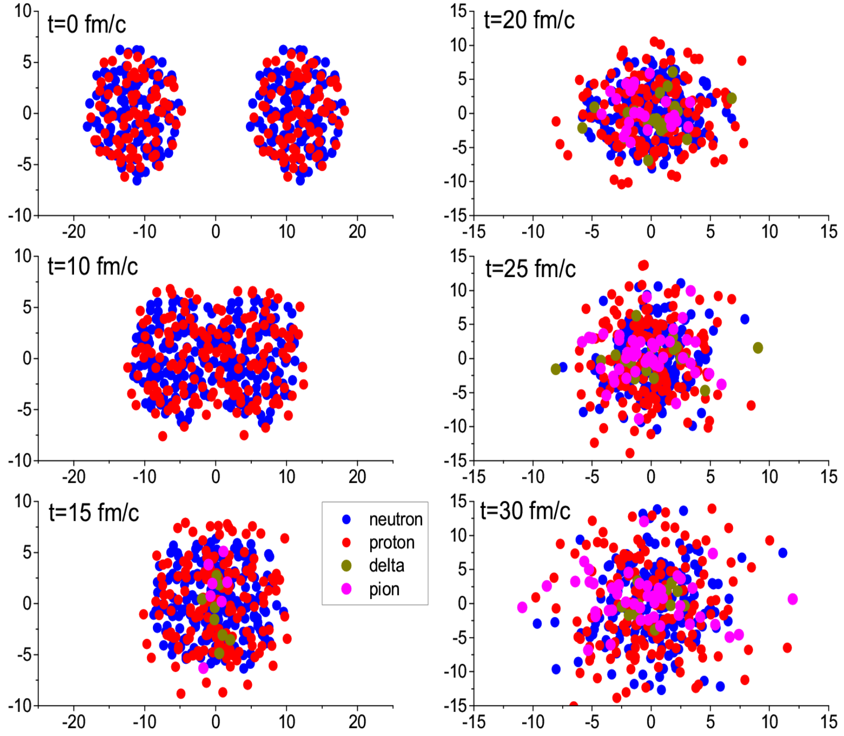




3. Particle production

π and resonances (Δ(1232), N*(1440), N*(1535), …) production:

$$NN \leftrightarrow N\Delta, \quad NN \leftrightarrow NN^*, \quad NN \leftrightarrow \Delta\Delta, \quad \Delta \leftrightarrow N\pi,$$
$$N^* \leftrightarrow N\pi, \quad NN \leftrightarrow NN\pi(s-state), \quad N^*(1535) \leftrightarrow N\eta$$



Collisions between resonances, NN*↔NΔ, NN*↔NN*

Strangeness channels:

$$BB \to BYK, BB \to BBK\overline{K}, B\pi(\eta) \to YK, YK \to B\pi,$$
$$B\pi \to NK\overline{K}, Y\pi \to B\overline{K}, \quad B\overline{K} \to Y\pi, \quad YN \to \overline{K}NN,$$
$$BB \to B\Xi KK, \overline{K}B \leftrightarrow K\Xi, YY \leftrightarrow N\Xi, \overline{K}Y \leftrightarrow \pi\Xi.$$

Reaction channels with antiproton:

$$\bar{p}N \to \overline{N}N, \quad \overline{N}N \to \overline{N}N, \overline{N}N \to \overline{B}B, \overline{N}N \to \overline{Y}Y$$
$$\overline{N}N \to \text{annihilation}(\pi, \eta, \rho, \omega, K, \overline{K}, K^*, \overline{K}^*, \phi)$$

Statistical model with SU(3) symmetry for annihilation
(E.S. Golubeva et al., Nucl. Phys. A 537, 393 (1992))

The **PYTHIA** and **FRITIOF** code are used for baryon(meson)-baryon and antibaryon-baryon collisions at high invariant energies

III. Hyperon-nucleon interaction in dense nuclear matter via HICs

Phys. Lett. B 851 (2024) 138580

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/physletb

ELSEVIER

Letter

Extracting the hyperon-nucleon interaction via collective flows in heavy-ion collisions

Zhao-Qing Feng

School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China

$$H_Y = \sum_{i=1}^{N_Y} V_i^{Coul} + V_{opt}^Y(\mathbf{p}_i, \rho_i) + \sqrt{\mathbf{p}_i^2 + m_Y^2}$$

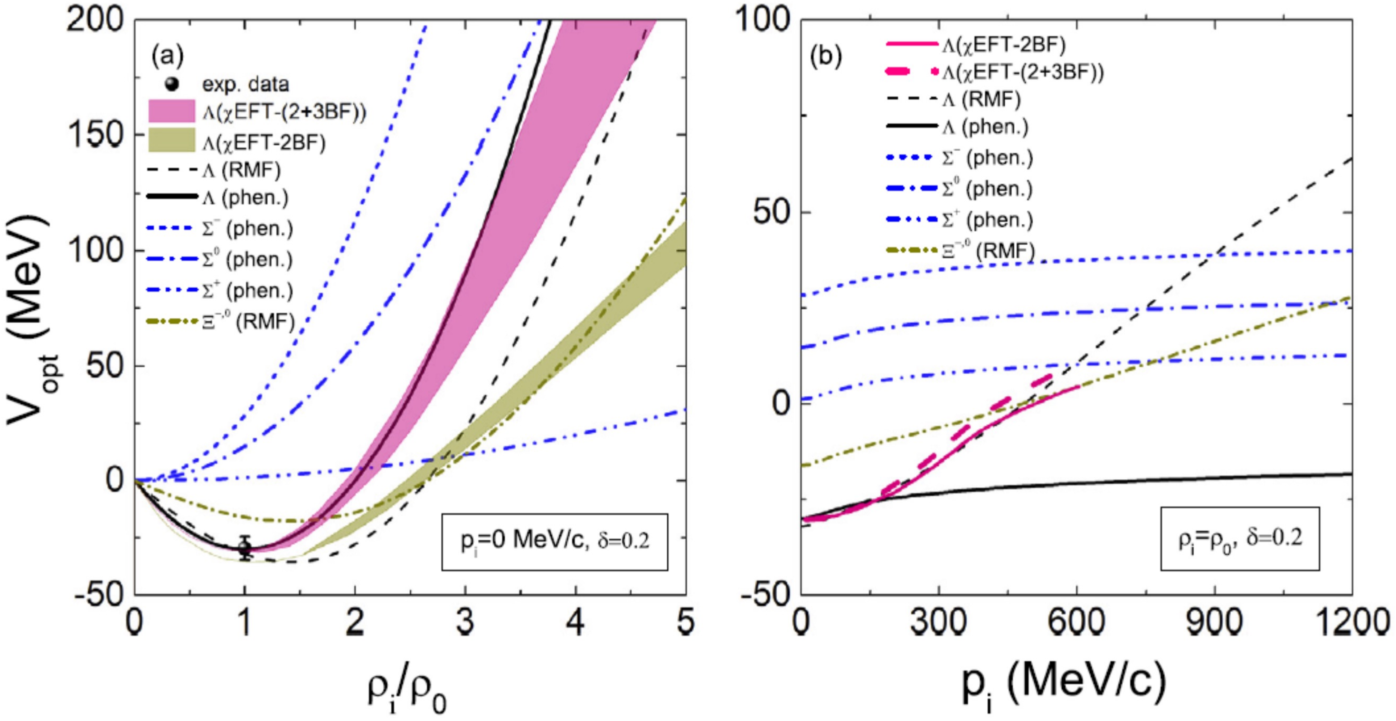
$$V_{opt}^Y(\mathbf{p}_i, \rho_i) = \omega_Y(\mathbf{p}_i, \rho_i) - \sqrt{\mathbf{p}_i^2 + m_Y^2}$$

$$\omega_Y(\mathbf{p}_i, \rho_i) = \sqrt{(m_Y + \Sigma_S^Y)^2 + \mathbf{p}_i^2} + \Sigma_V^Y,$$

Phenomenological potential by fitting the results of chiral effective field theory

$$V_{opt}^\Lambda(\mathbf{p}_i, \rho_i) = V_a(\rho_i/\rho_0) + V_b(\rho_i/\rho_0)^2 + C_{mom}(\rho_i/\rho_0)\ln(\epsilon \mathbf{p}_i^2 + 1)$$

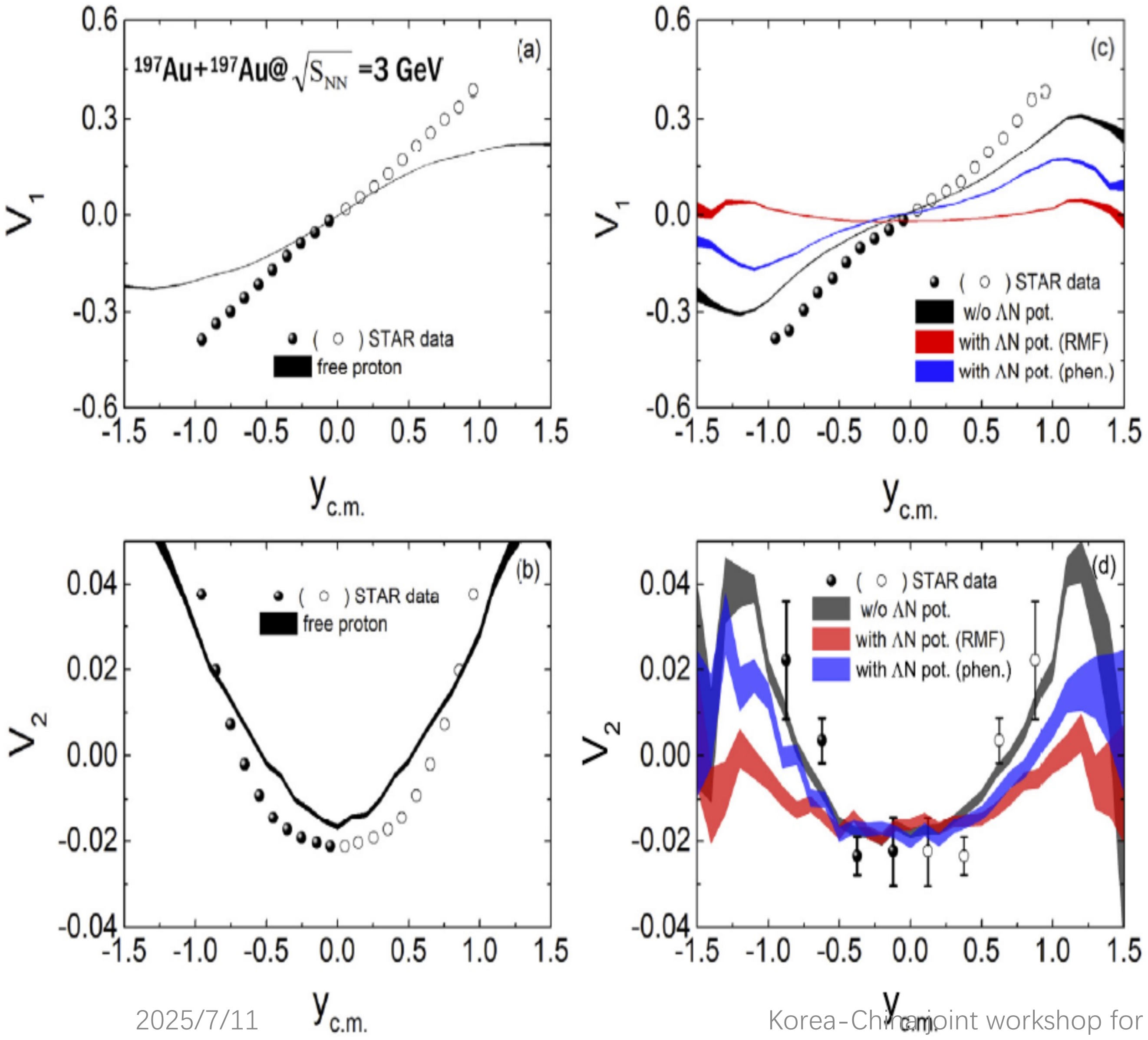
$$V_{opt}^\Sigma(\mathbf{p}_i, \rho_i) = V_0(\rho_i/\rho_0)^{\gamma_s} + V_1(\rho_n - \rho_p)t_\Sigma \rho_i^{\gamma_s -} + C_{mom}(\rho_i/\rho_0)\ln(\epsilon \mathbf{p}_i^2 + 1).$$

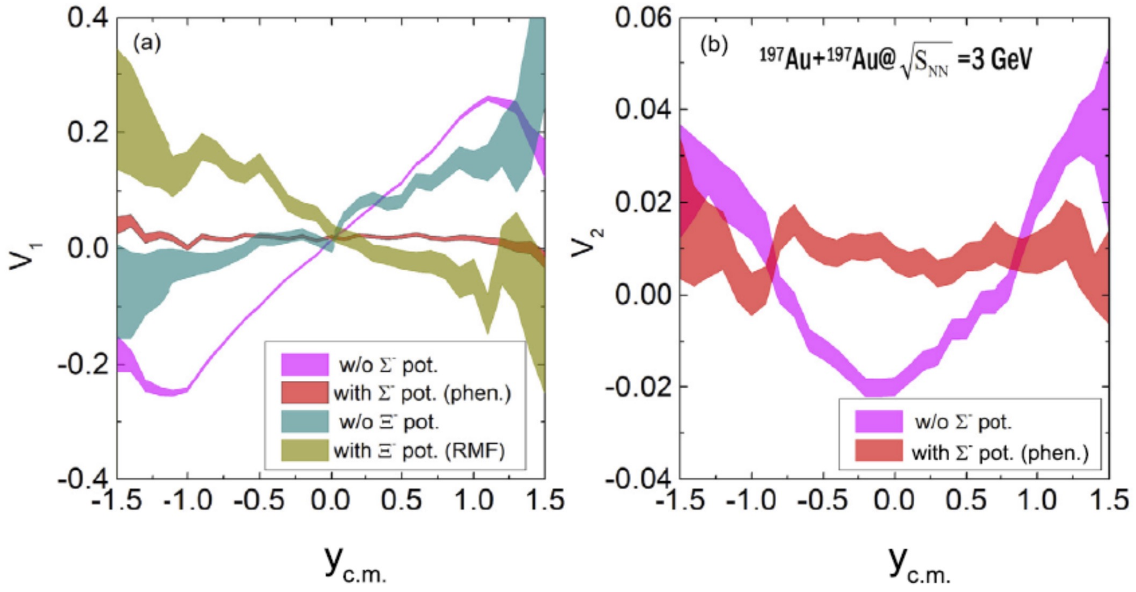


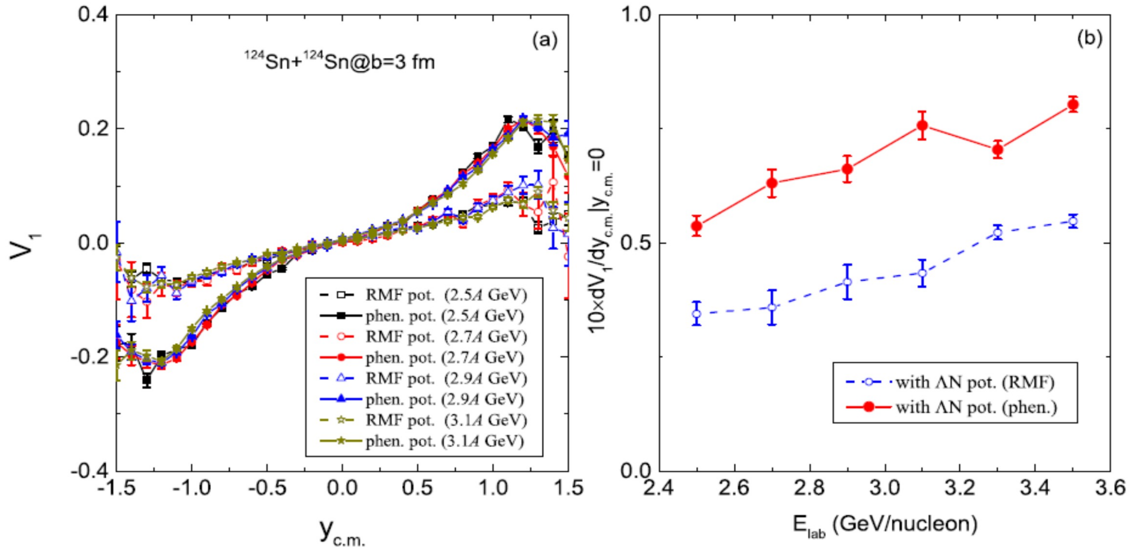
Hyperon-nucleon interaction in dense matter I:

Extracting the hyperon-nucleon interaction via collective flows in heavy-ion collisions

Phys. Lett. B 851 (2024) 138580







Hyperon-nucleon interaction in dense matter I:

The general flavor SU(3) symmetry for hyperon-nucleon potential

$$\mathcal{L}_{int} = \sum_B \bar{\psi}_B [g_{B\sigma}\sigma - \gamma_\mu (g_{B\omega}\omega^\mu + g_{B\phi}\phi^\mu + g_{B\rho}\vec{\tau}\cdot\vec{b}^\mu)$$

$$]\psi_B - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4,$$

$$\frac{g_{\Lambda\omega}}{g_{N\omega}} = \frac{g_{\Sigma\omega}}{g_{N\omega}} = \frac{\sqrt{2}}{\sqrt{2}+\sqrt{3}z},$$

$$\frac{g_{\Lambda\phi}}{g_{N\omega}} = \frac{g_{\Sigma\phi}}{g_{N\omega}} = \frac{-1}{\sqrt{2}+\sqrt{3}z},$$

$$\frac{g_{\Xi\omega}}{g_{N\omega}} = \frac{\sqrt{2}-\sqrt{3}z}{\sqrt{2}+\sqrt{3}z},$$

$$\frac{g_{\Xi\phi}}{g_{N\omega}} = -\frac{1+\sqrt{6}z}{\sqrt{2}+\sqrt{3}z},$$

$$\frac{g_{N\phi}}{g_{N\omega}} = -\frac{\sqrt{6}z-1}{\sqrt{2}+\sqrt{3}z}.$$

Phys. Lett. B 853 (2024) 138658

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ELSEVIER

Letter

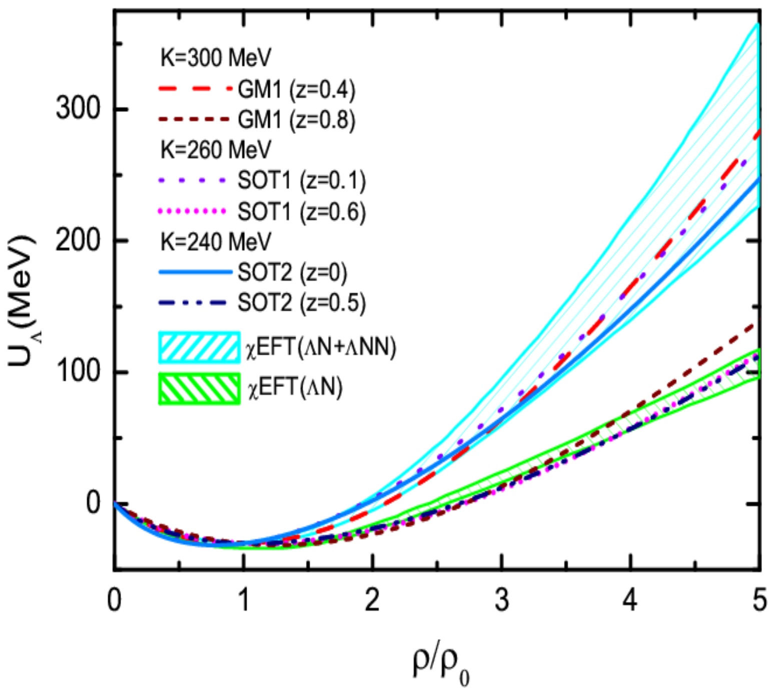
Correlation of the hyperon potential stiffness with hyperon constituents in neutron stars and heavy-ion collisions

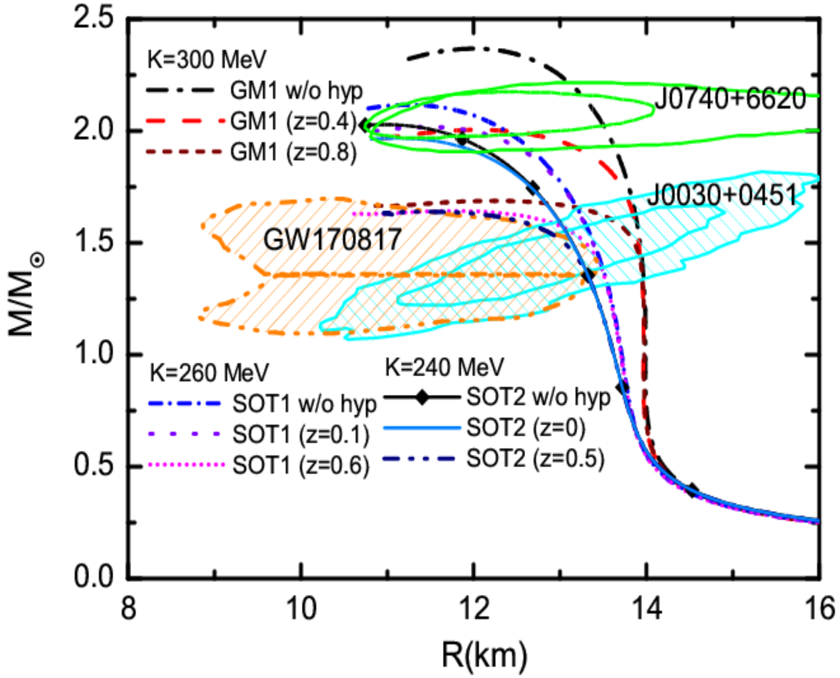
Si-Na Wei [a], Zhao-Qing Feng [b,*], Wei-Zhou Jiang [c]

[a] School of Mathematics and Physics, Guangxi Minzu University, Nanning 530006, China
[b] School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China
[c] School of Physics, Southeast University, Nanjing 211189, China

LQMD.RMF

Phys. Lett. B 853 (2024) 138658

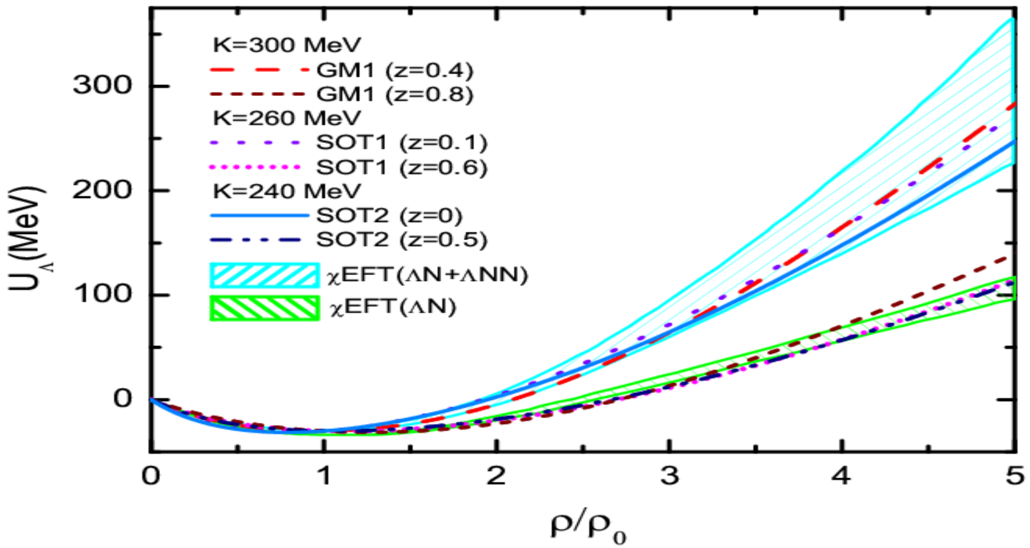


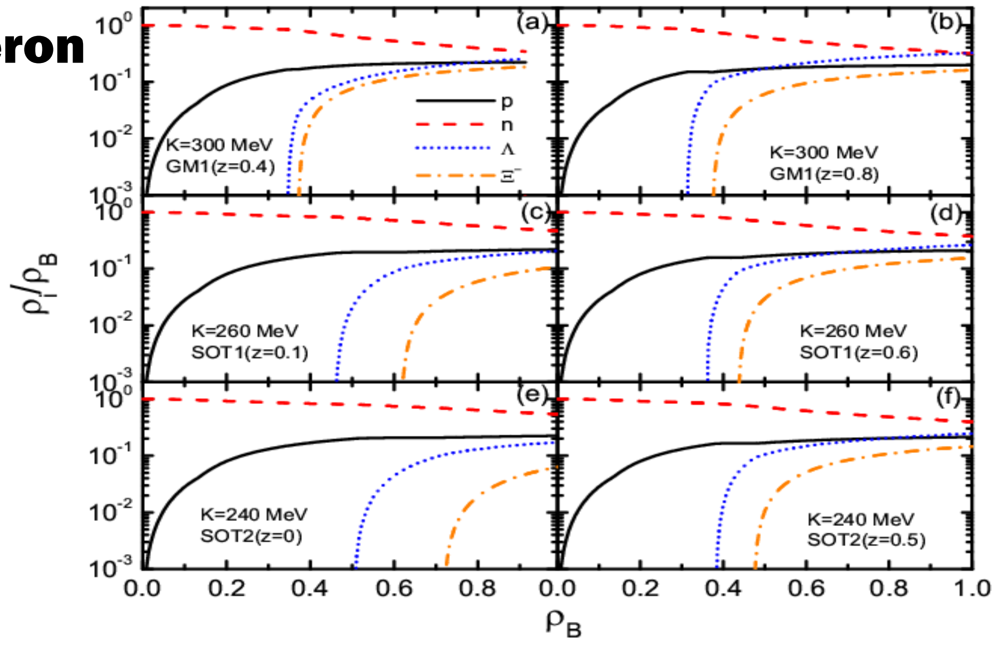


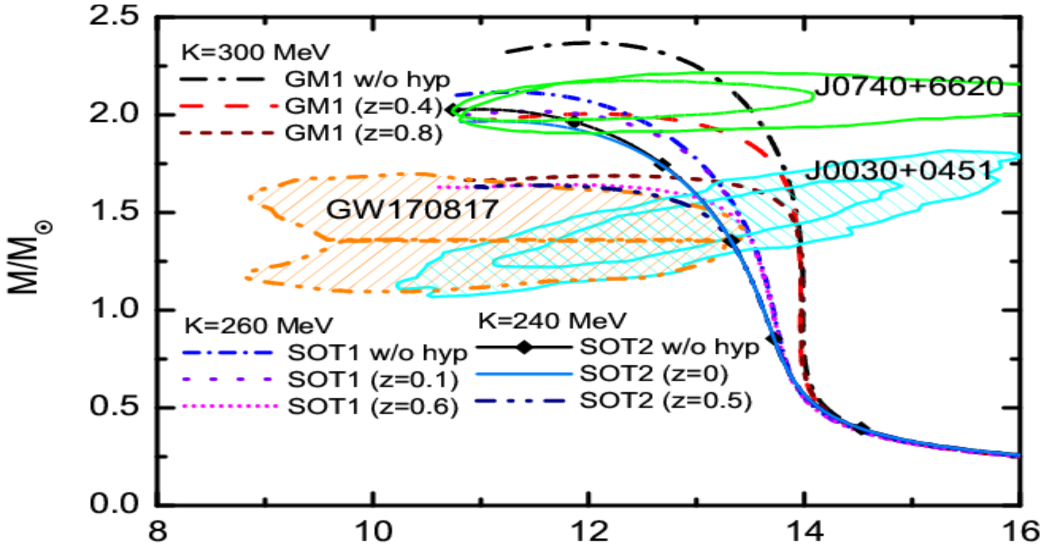
$$U_\Lambda(\rho_0) = -U_\Sigma(\rho_0) = -30\ \text{MeV},\ U_\Xi(\rho_0) = -14\ \text{MeV}$$

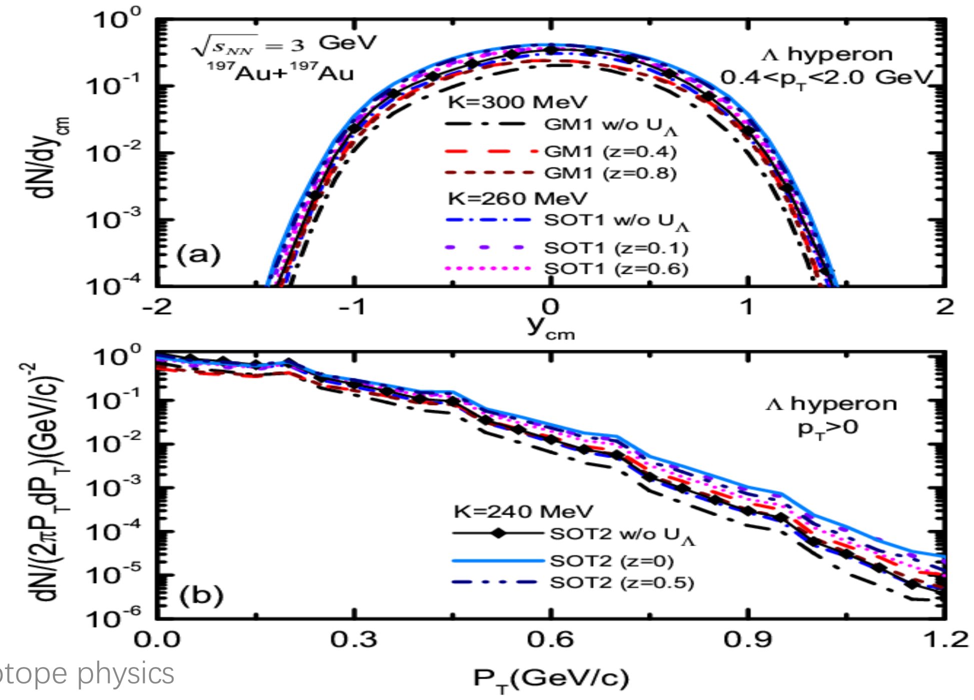
Correlation of the hyperon potential stiffness with hyperon constituents in neutron stars and heavy-ion collisions

Si-Na Wei, ZQF, Wei-Zhou Jiang, PLB 853 (2024) 138658









High-density symmetry energy from hyperon production in heavy-ion collisions, Physics Letters B 846 (2023) 138180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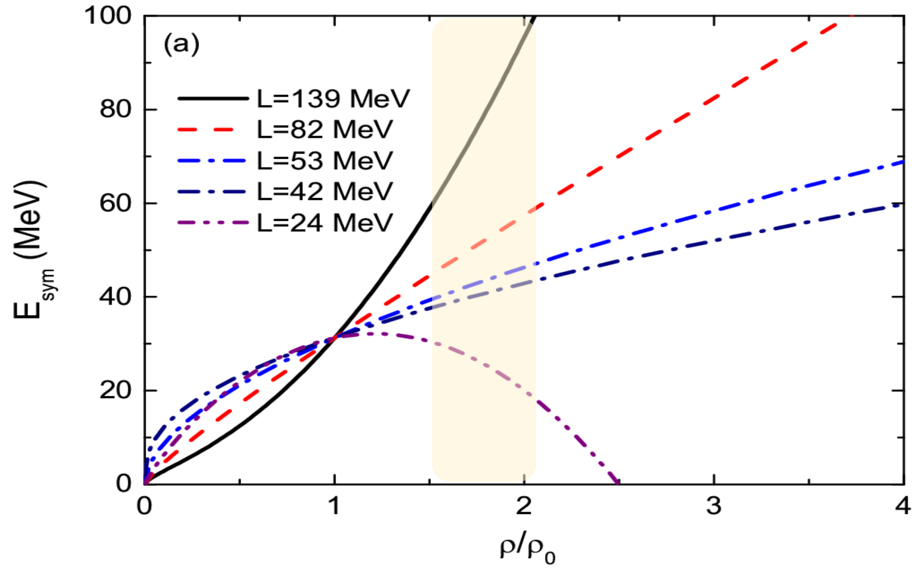
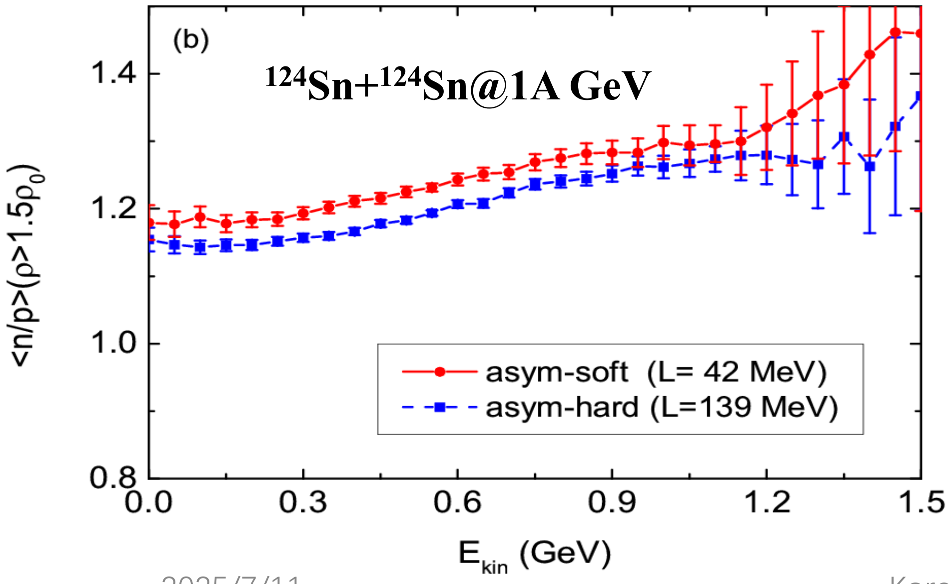
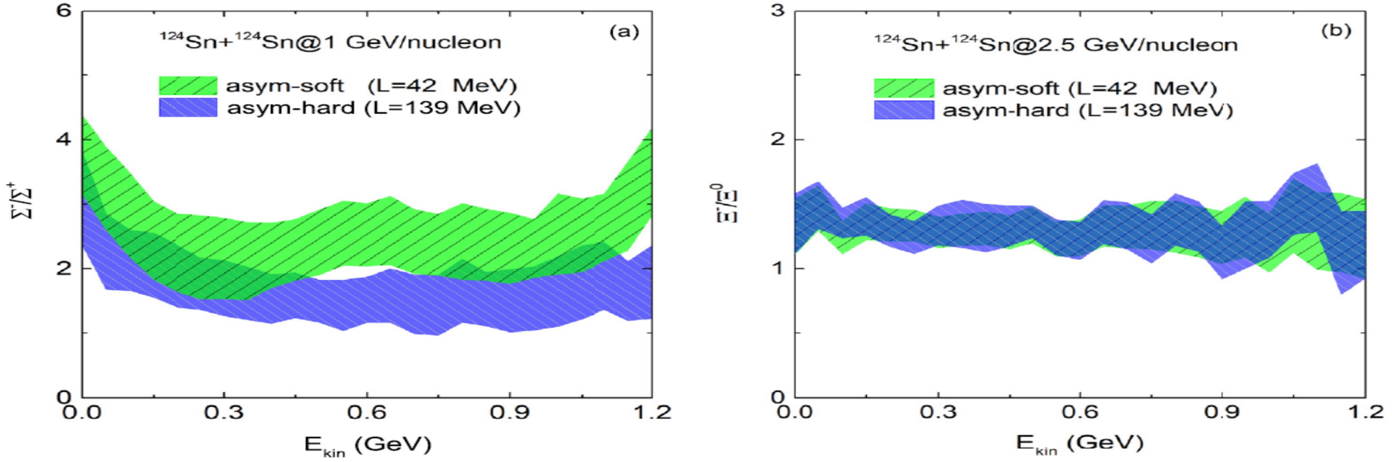
journal homepage: www.elsevier.com/locate/physletb

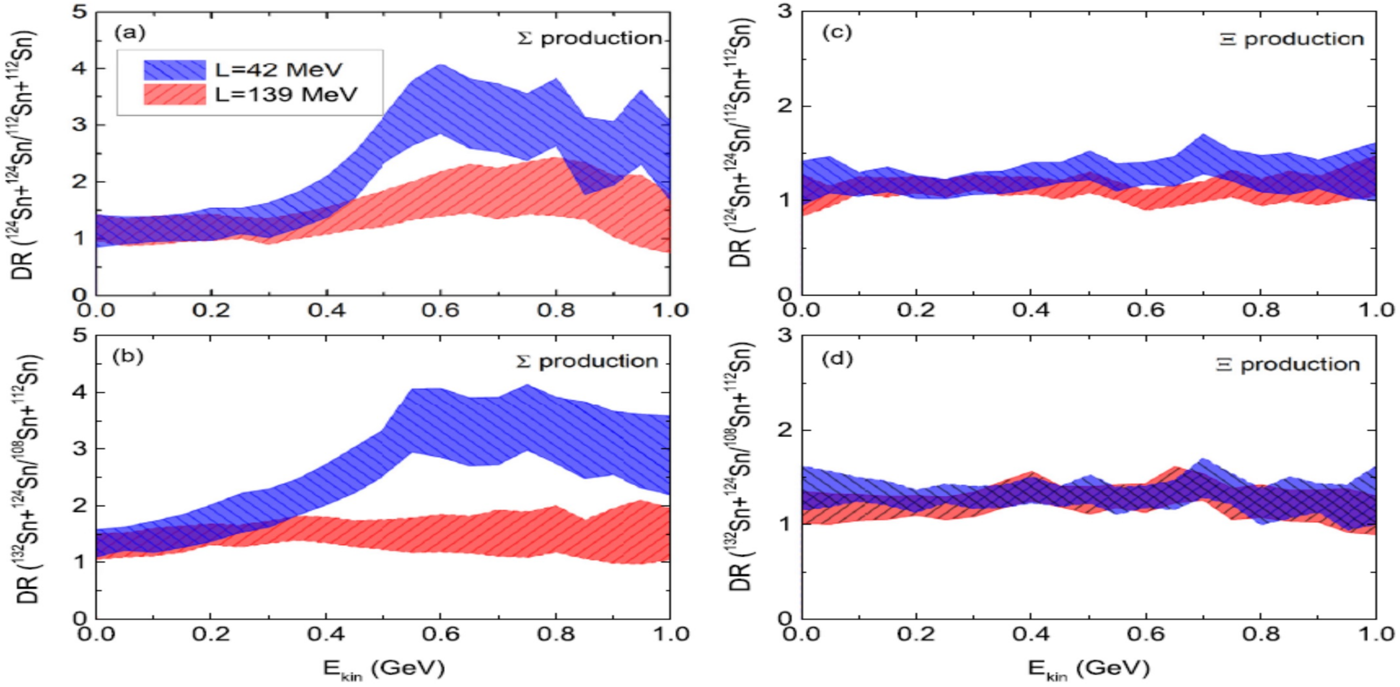
Probing the high-density symmetry energy from subthreshold hyperon production in heavy-ion collisions

Zhao-Qing Feng
School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China







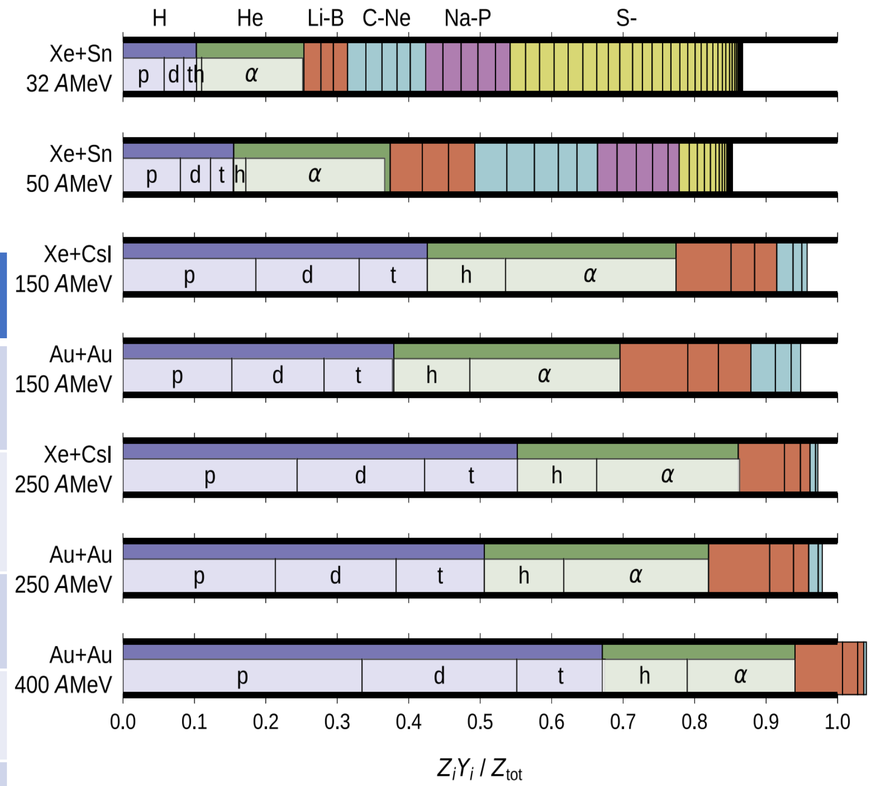


IV. Fragmentation reaction and hyperfragment production in HICs

Kinetic approach (动理学) for cluster production

P. Danielewicz, G. F. Bertsch, Nuclear Physics A 533 (1991) 712-748
Akira Ono, Prog. Part. Nucl. Phys. 105, 139-179 (2019)
R. Wang, Y. G. Ma, L. W. Chen et al., Phys. Rev. C 108, L031601 (2023)
Hui-Gan Cheng, Zhao-Qing Feng, Phys. Rev. C 109, L021602 (2024)

Year	models	Author(s)	Cluster(s)	Energy	Treatment(s)
1991	**pBUU**	P. Danielewicz et al.	d, t, h	fermi /intermediate energies	kinetic, Mott cut
2013	**AMD-cluster**	A. Ono	$2N, 3N, \alpha$	fermi /intermediate energies	kinetic, fermionic mean field
2021	**SMASH**	J. Staudenmaier et al.	d	GeV and higher	kinetic
2022	**PHQMD**	G. Coci et al.	d	GeV and higher	kinetic
2023	**LBUU**	R. Wang et al.	d, t, h, α	intermediate energies	kinetic, Mott cut
2023	**LQMD**	H. G. Cheng and Z. Q. Feng	d, t, h, α	fermi /intermediate energies	Kinetic, binding energy, Pauli effects



Clusters are produced by multinucleon or nucleon-cluster collisions

p+Λ+n+N↔$_{\Lambda}^{3}$H+N′, p+Λ+n+n+N↔$_{\Lambda}^{4}$H+N′, p+Λ+Λ+N↔$_{\Lambda\Lambda}^{3}$H+N′, p+n+Λ+Λ+N ↔$_{\Lambda\Lambda}^{4}$H+N′, p+p+Λ+N↔$_{\Lambda}^{3}$He+N′, p+p+Λ+n+N↔$_{\Lambda}^{4}$He+N′, p+p+Λ+Λ+N↔$_{\Lambda\Lambda}^{4}$He+N′,

n+n+Λ+N↔$_{\Lambda}^{3}$n+N′, n+n+Λ+Λ+N↔$_{\Lambda\Lambda}^{4}$n+N′

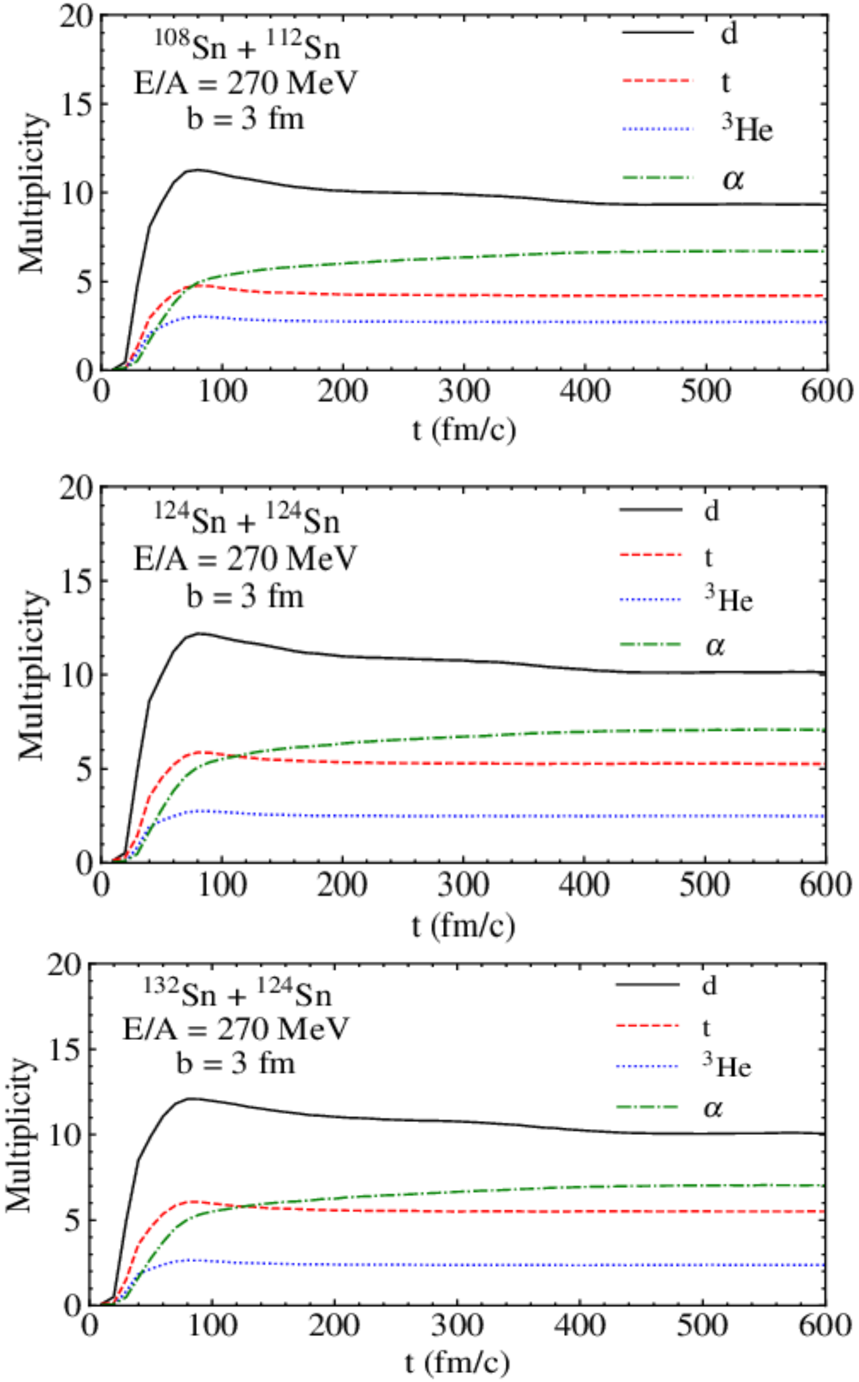
以及π介子催化引起的反应道：

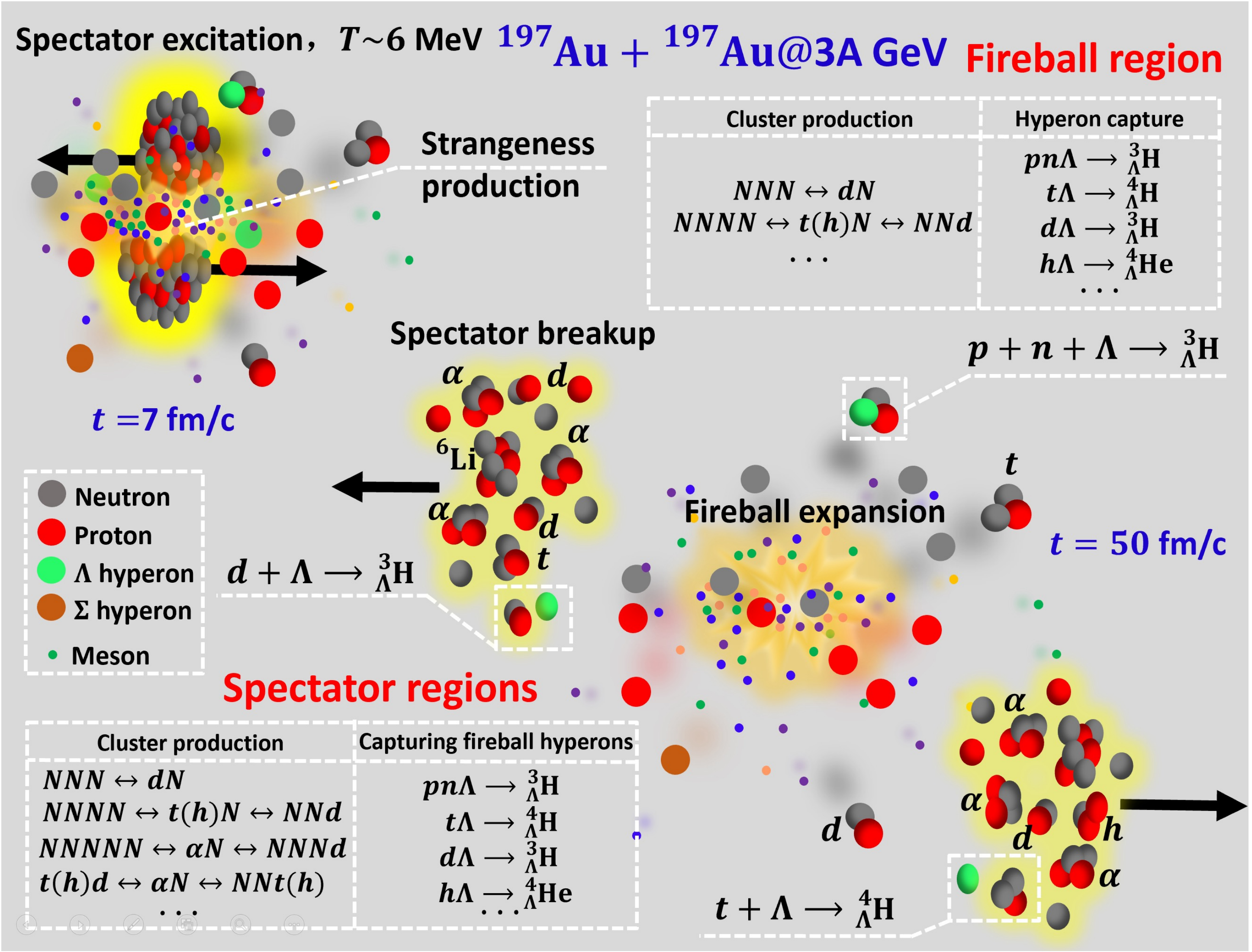
π+N₁+N₂↔π+deuteron, π+N₁+N₂+N↔deuteron+N′, π+N₁+N₂+N₃↔π+triton (helium-3), π+N₁+N₂+N₃+N→π+triton (helium-3)+N′, π+p+n+Λ↔π+$_{\Lambda}^{3}$H, π+p+n+n +Λ↔π+$_{\Lambda}^{4}$H, π+p+p+n+Λ↔π+$_{\Lambda}^{4}$He

…

$$\frac{d\sigma}{d\Omega} = P(C_1 + C_2 \to C_3 + C_4) \times \frac{v_{\tilde{p}_{\rm rel}}}{v} \frac{\left|[\partial e(k)/\partial k]_{k=\tilde{p}_{\rm rel}}\right|}{\left|[\partial H(p_f)/\partial p_f]_{p_f=p_{\rm rel}}\right|} \frac{p_{\rm rel}^2}{\tilde{p}_{\rm rel}^2} \left[\frac{d\sigma_{\rm NN}}{d\Omega}\right]_{\tilde{p}_{\rm rel}}$$

Schematic picture of nuclear cluster and hypercluster in HICs





PHYSICAL REVIEW C **109**, L021602 (2024)

Letter

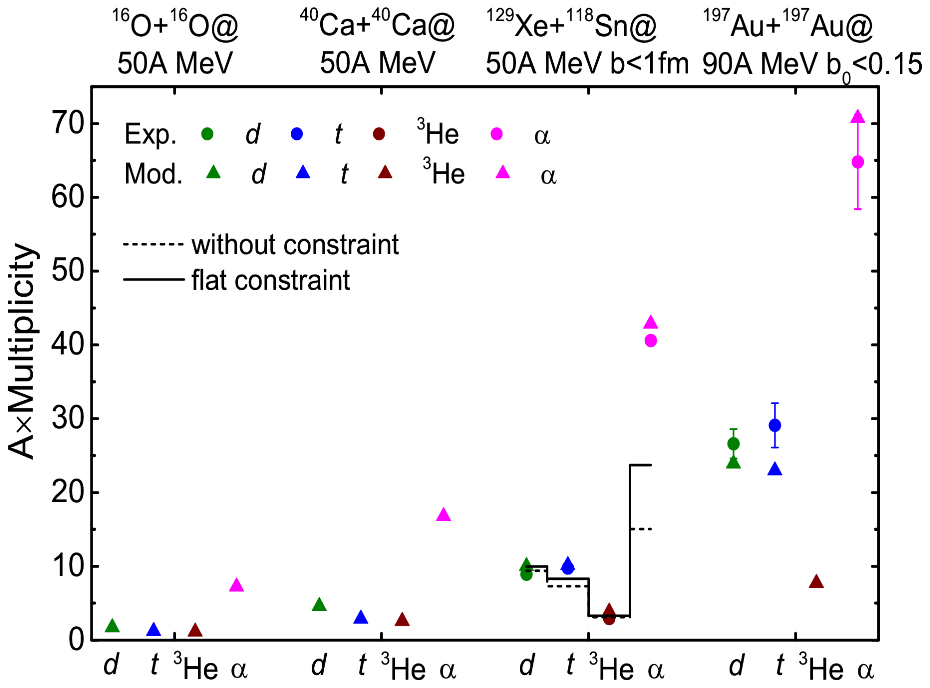
Kinetic approach for cluster production (LQMD.cluster)

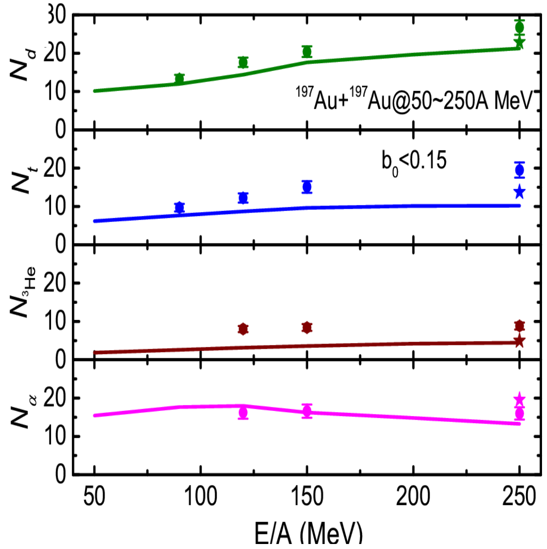
Novel approach to light-cluster production in heavy-ion collisions

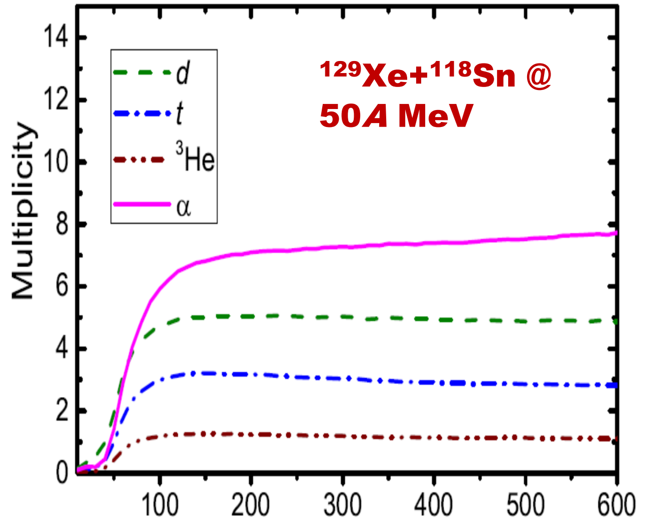
Hui-Gan Cheng and Zhao-Qing Feng*
School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China

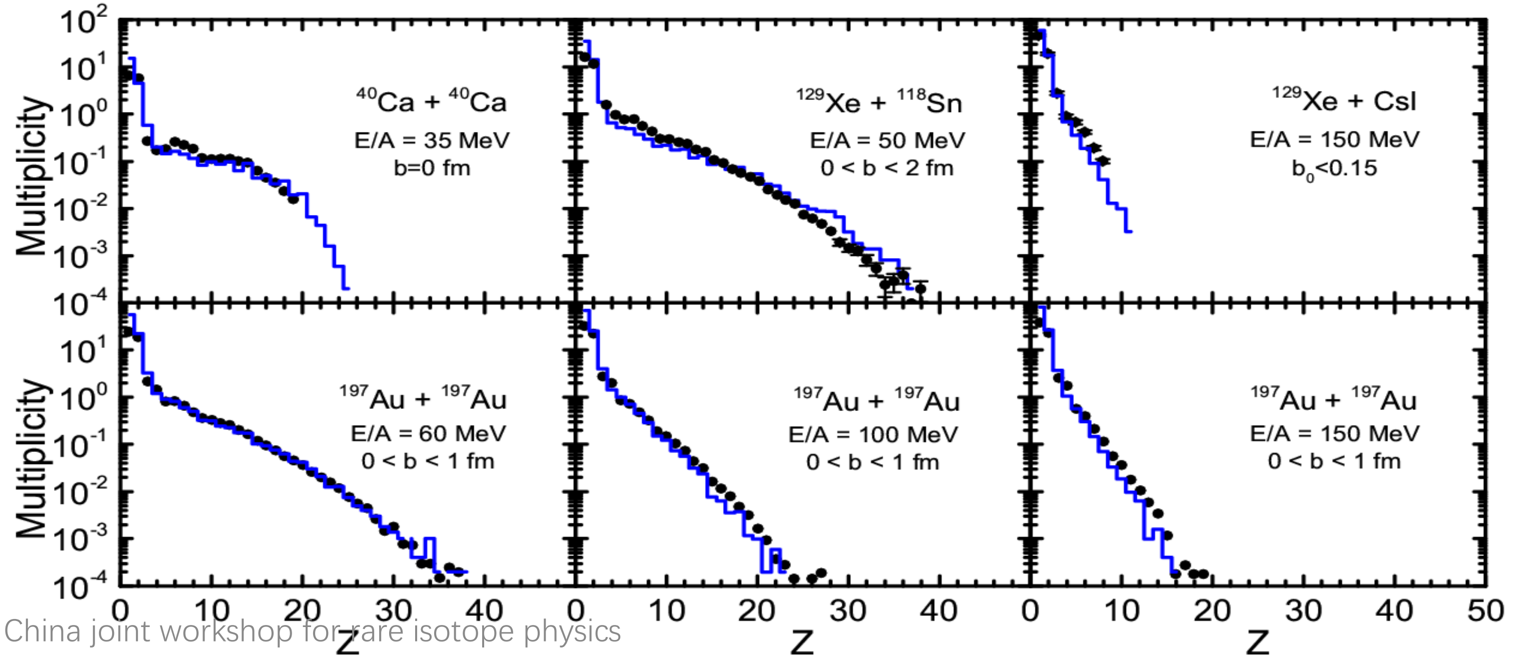
(Received 8 November 2023; accepted 25 January 2024; published 15 February 2024)

$$
\begin{aligned}
H \;&= \sum_i \frac{\mathbf{p}_i{}^2}{2m} + \frac{\alpha}{2}\sum_{\substack{i,j\\ j\neq i}} \frac{\rho_{ij}}{\rho_0} + \frac{\beta}{1+\gamma}\sum_i \left(\sum_{j,j\neq i}\frac{\rho_{ij}}{\rho_0}\right)^{\gamma} \\
&+ \frac{C_{sym}}{2}\sum_{\substack{i,j\\ j\neq i}} t_{z_i}t_{z_j}\frac{\rho_{ij}}{\rho_0} + \frac{g_{\rm sur}}{2}\sum_{\substack{i,j\\ j\neq i}}{}' \left[\frac{3}{2L} - \left(\frac{\mathbf{r}_i-\mathbf{r}_j}{2L}\right)^2\right]\frac{\rho_{ij}}{\rho_0} \\
&+ \sum_i^{N_C} E^i_{\rm z.p.} + \sum_i^{N_d} V_{\rm corr} e^{-r_i{}^2/4L}
\end{aligned}
$$







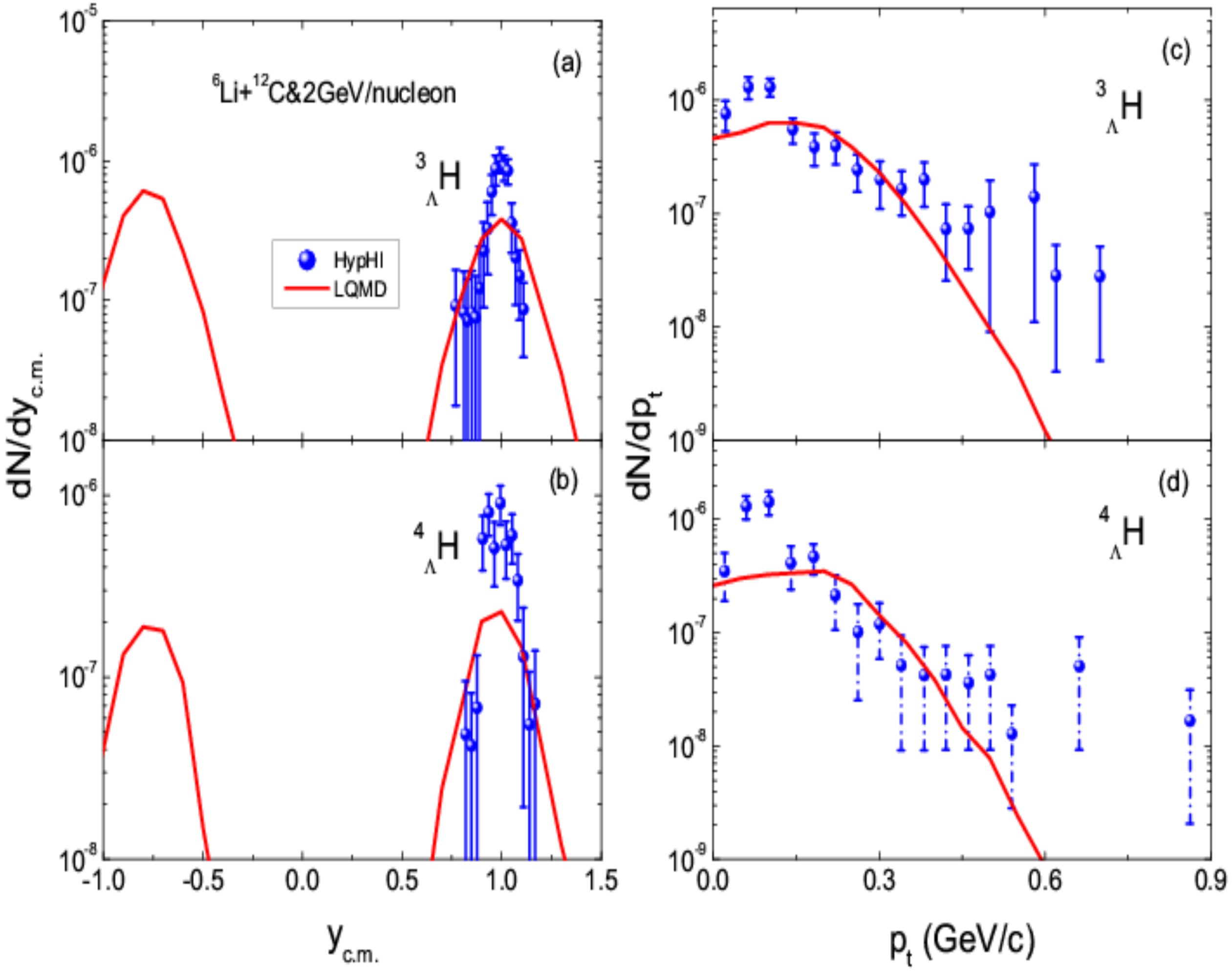


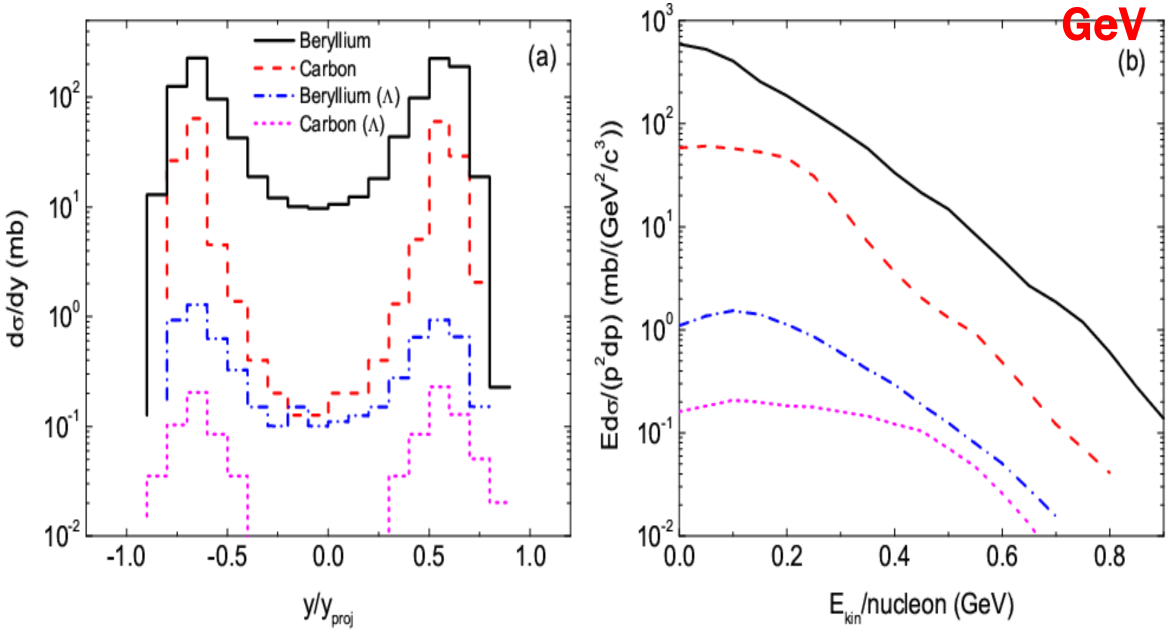
Hypernuclide production via HICs *(Wigner density approach)*

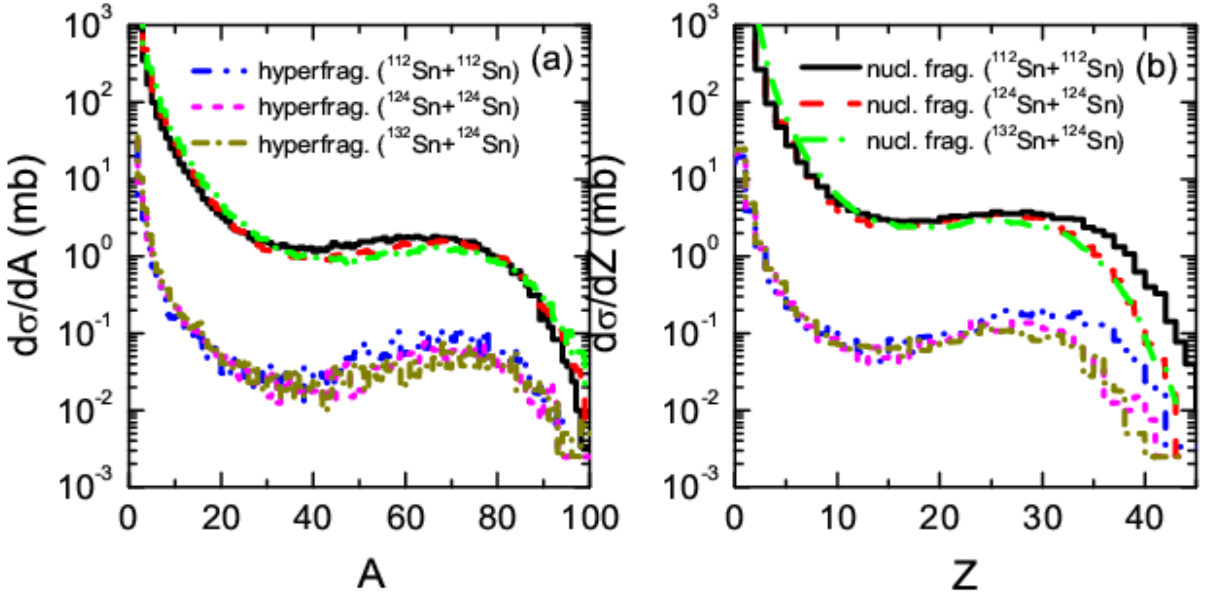
Z. Q. Feng, Phys. Rev. C 102, 044604 (2020)

Data: C. Rappold et al., (HypHI collaboration)
Phys. Lett. B 747, 129 (2015)

^{124}Sn+^{124}Sn@2*A* GeV



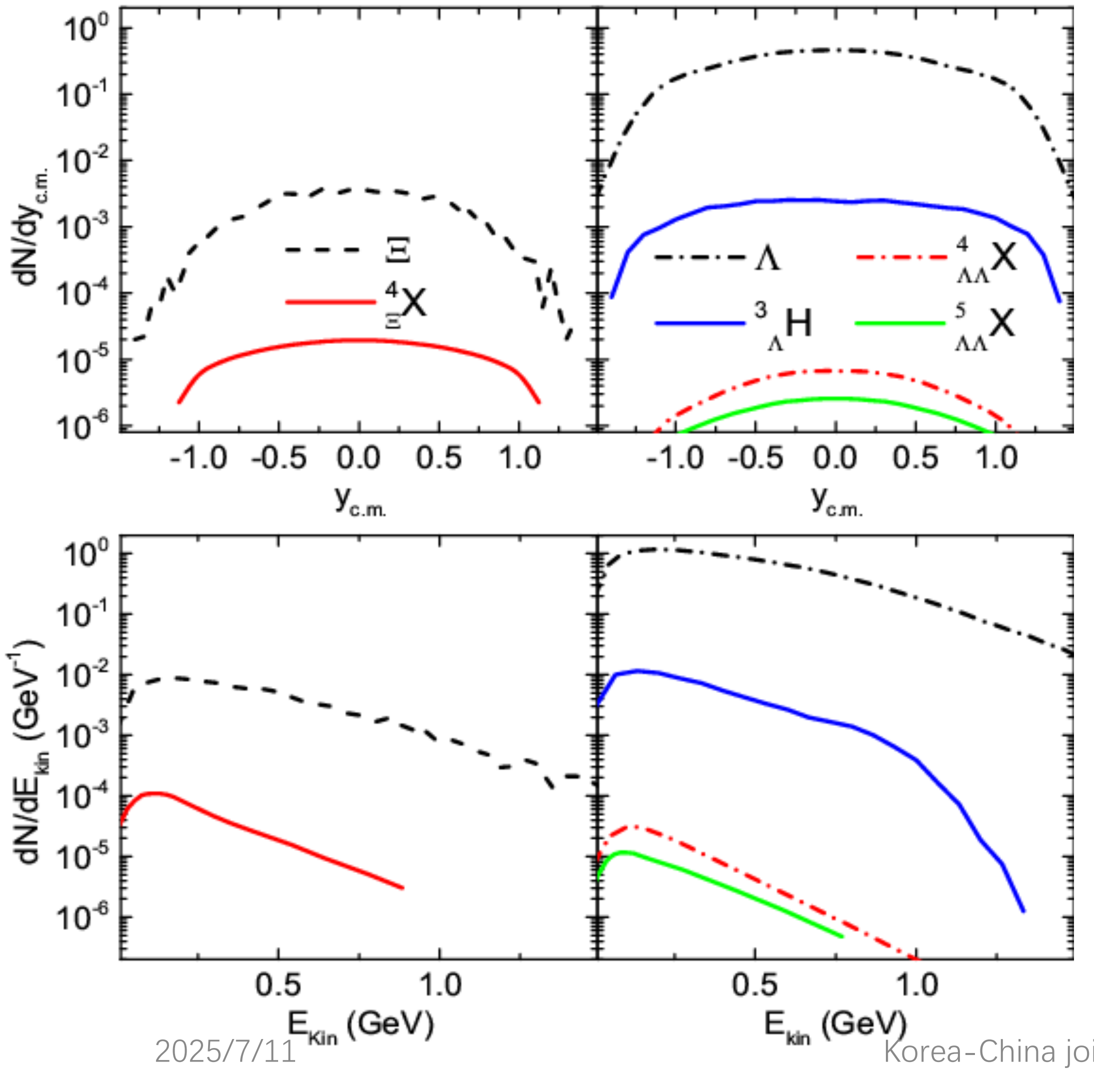


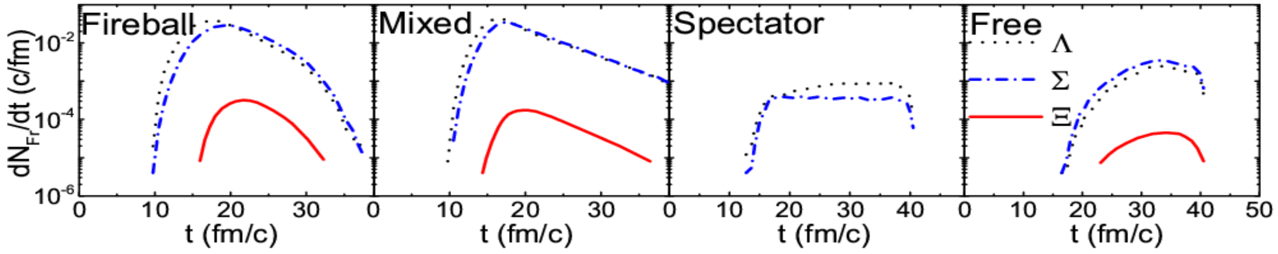


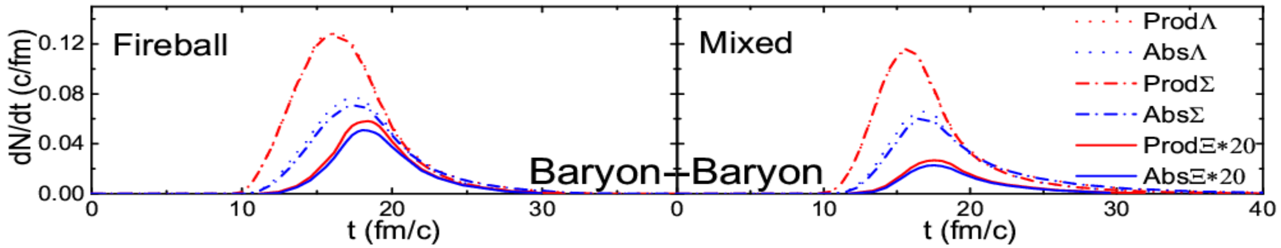
Multi-strangeness hypernuclide production

H.G. Cheng, Z. Q. Feng, Phys. Lett. B 824 (2022) 136849

^{197}Au+^{197}Au@3A GeV







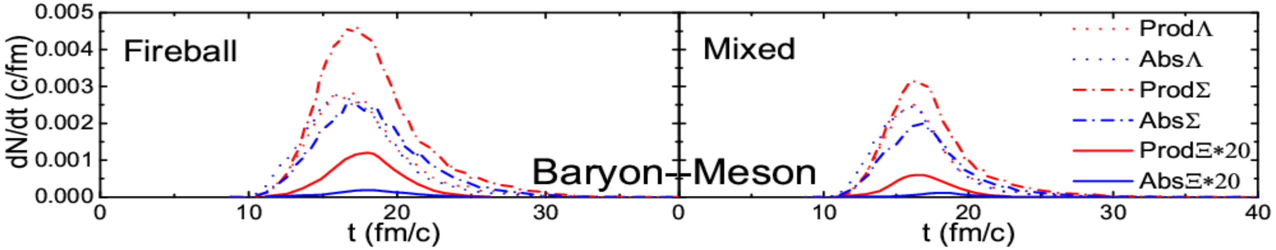


TABLE I. Comparison between cross sections of double lamda hypernuclei calculated with r_0 = 3.5 fm for Λ in ^{197}Au + ^{197}Au and ^{40}Ca + ^{40}Ca collisions at 3A GeV

Hypernuclei	Cross sections (mb)	
	^{197}Au + ^{197}Au	^{40}Ca + ^{40}Ca
$^{4}_{\Lambda\Lambda}$H	2.6×10^{-2}	1.0×10^{-4}
$^{4}_{\Lambda\Lambda}$He	1.0×10^{-2}	$\sim 10^{-5}$
$^{5}_{\Lambda\Lambda}$H	5.9×10^{-3}	$\sim 10^{-5}$
$^{5}_{\Lambda\Lambda}$He	5.1×10^{-3}	$\sim 10^{-5}$
$^{5}_{\Lambda\Lambda}$Li	1.4×10^{-3}	$\sim 10^{-6}$
$^{6}_{\Lambda\Lambda}$He	2.2×10^{-3}	$\sim 10^{-6}$
$^{7}_{\Lambda\Lambda}$He	6.8×10^{-4}	$\lesssim 10^{-6}$

VI. Summary

- The high-density symmetry probes single and double ratios of Σ^-/Σ^+(double ratio) via the isotopic reactions ^{112}Sn+^{112}Sn and ^{124}Sn+^{124}Sn, in particular above 0.4 GeV.
- Hyperon production in heavy-ion collisions at HIAF energies provides a successful way for investigating the hyperon-nucleon potential in **dense nuclear matter,** e.g., ΛNN,ΣNN,ΞNN etc, might be constrained via heavy-ion collisions at HIAF.

- **Kinetic approach** is implemented in the LQMD transport model for the nuclear cluster production in Fermi energy heavy-ion collisions, hypercluster in the near future, in which the binding energy, multinucleon (cluster) collisions, Pauli principle, Mott effect etc are taken into account.

Thanks for your attention！