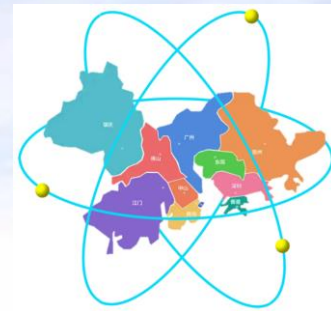


第一届粤港澳核物理会议，2022年7月2-5日



重离子碰撞中超核形成研究

冯兆庆

华南理工大学物理与光电学院

Email: fengzhq@scut.edu.cn



报告内容

- 华南理工大学核物理学科介绍
- 奇异性核物理研究现状
- 重离子碰撞中奇异粒子产生
- 原子核碎裂反应和超核形成
- 总结

华南理工大学地处广州，是直属教育部的全国重点大学，校园分为**五山校区、大学城校区和广州国际校区**，是首届“全国文明校园”获得单位。学校办学源远流长，最早可溯源至1918年成立的广东省立第一甲种工业学校（史称“红色甲工”）；正式组建于1952年全国高等院校调整时期，为新中国“四大工学院”之一；1960年成为全国重点大学；1981年经国务院批准为首批博士和硕士学位授予单位；1993年在全国高校首开部省共建之先河；1995年进入“211工程”行列；**2001年进入“985工程”行列；2017年进入“双一流”建设A类高校行列**，2020年进入上海软科“世界大学学术排名”前200强。



一、物理与光电学院简介



学院简介



华南理工大学物理与光电学院现有物理学一级学科和物理电子学二级学科2个博士点及博士后科研流动站。物理学学科为广州市重点学科，自2011年以来一直位列**ESI全球排名前1%**。学院具备了从本科、硕士、博士到博士后一条完整的人才培养链，设有应用物理学、光电信息科学与工程2个本科专业（全部为国家级一流本科专业建设点），并在**理论物理、凝聚态物理、光学、声学、物理电子学**等5个专业招收硕士、博士研究生和博士后研究人员，现有全日制在校本科生594人、硕士生156人、博士生66人。

现有教职工108人，其中专任教师79人。拥有“双聘院士”1人，长江学者特聘教授1人，国家杰出青年科学基金获得者2人，国家优秀青年科学基金获得者2人，海外高层次人才1人，入选国家重大人才工程2人，教育部新世纪优秀人才计划1人，广东省珠江学者特聘教授2人，广东省杰出青年科学基金获得者5人。

理论物理团队人员概况：本团队现有教授3人，副教授3人，T.T助理教授2名，博士后3人，博士、硕士研究生约20人。

研究方向：原子核物理、重离子碰撞物理、致密星物理、引力物理、黑洞物理、生物物理

理论物理学科：近3年来发表SCI论文30余篇，主持国家自然科学基金项目，广东省基础与应用基础研究项目等10余项。理论物理学科入选广东省“珠江学者”设岗学科。

原子核物理方向：重离子碰撞物理、超核物理、超重原子核形成、核裂变、致密物质性质、短程关联、从头计算等。



二、奇异性核物理现状介绍



◆ 强子的内部结构



Normal baryon



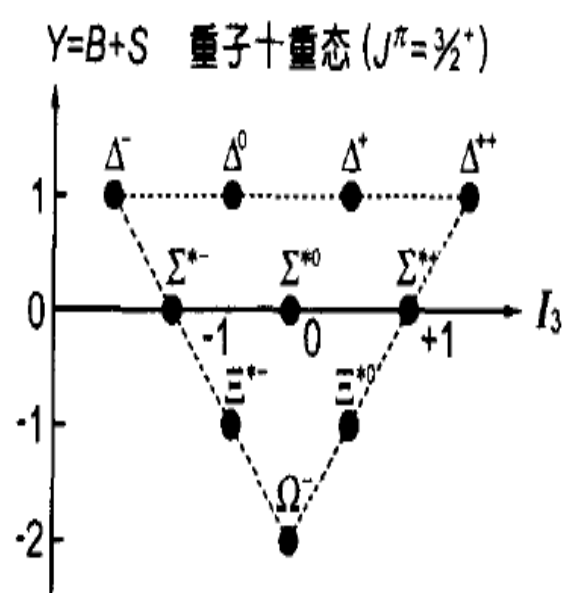
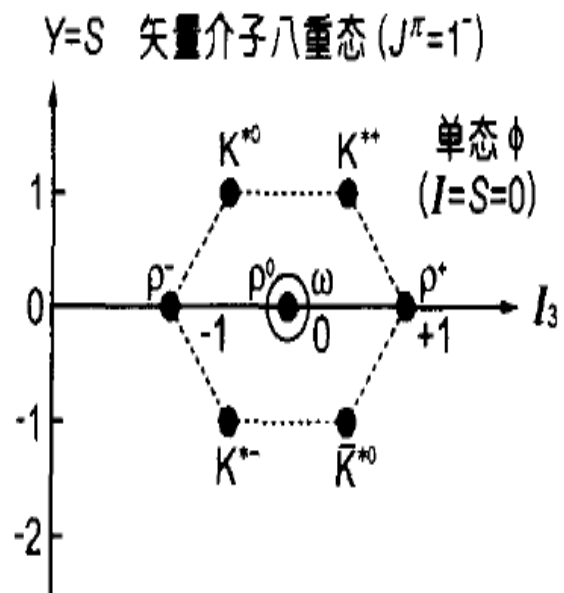
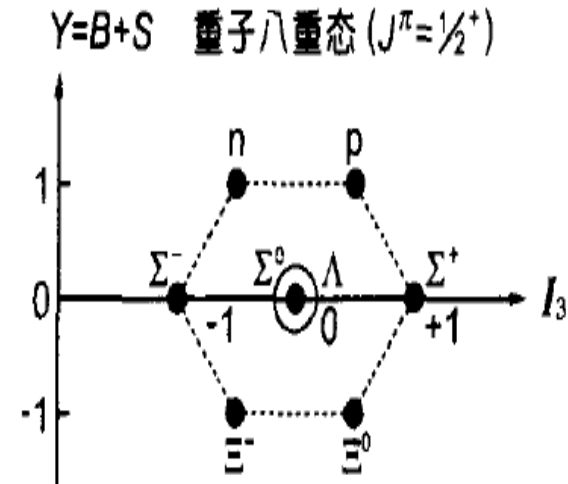
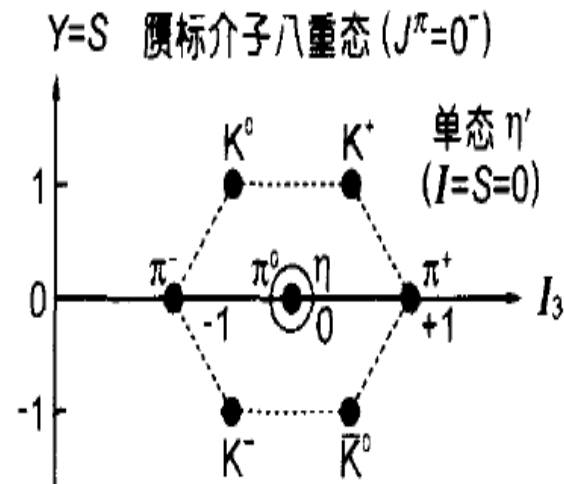
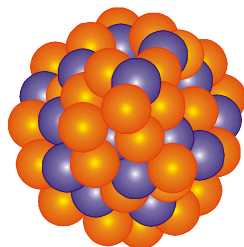
Normal meson

◆ 核子和核子共振态：八(十)重态重子

◆ 介子八重态：矢量介子和赝标量介子

◆ 奇异粒子(含s夸克)主要指介子K (K^0, K^+) 和 \bar{K} (\bar{K}^0, K^-), 超子 Λ, Σ, Ξ 和 Ω

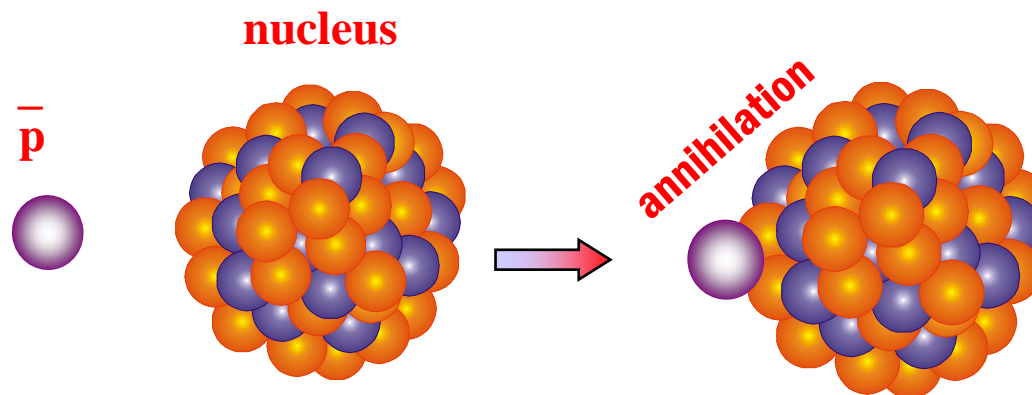
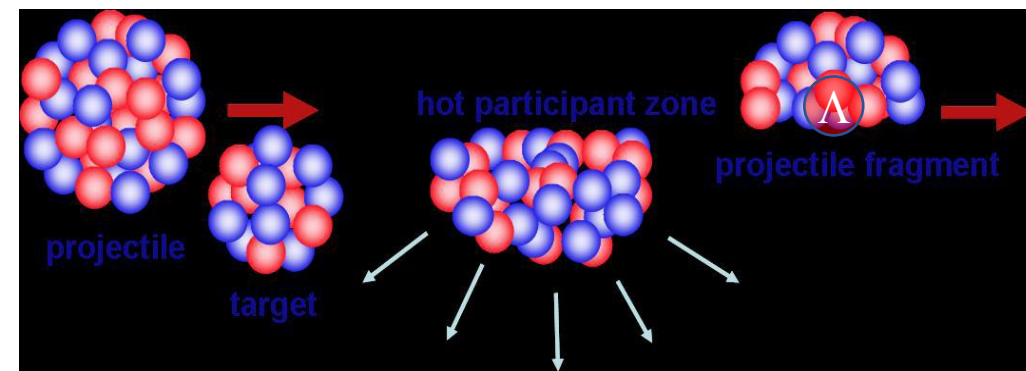
◆ 含有奇异粒子的原子核-超核



奇异粒子产生：

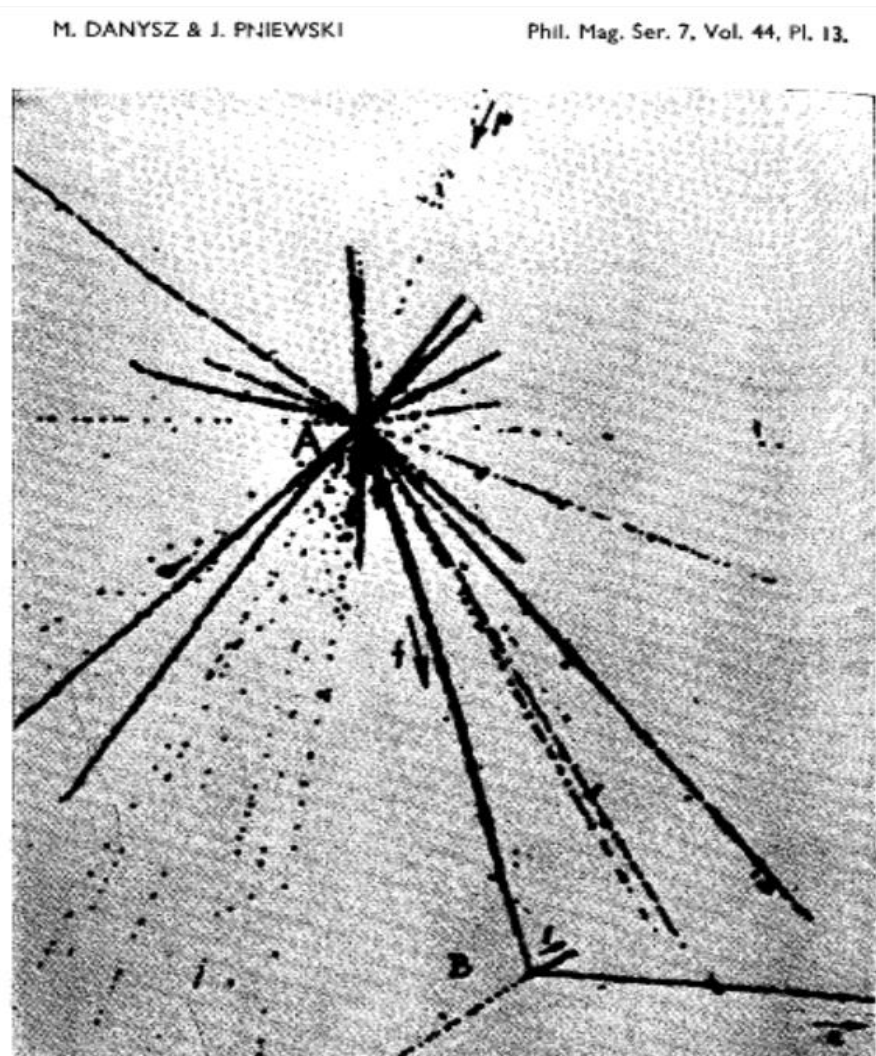
- 重离子碰撞
- 强子(质子, 反质子, 介子)引起的核反应
- 高能电子轰击原子核
- 光核反应

...

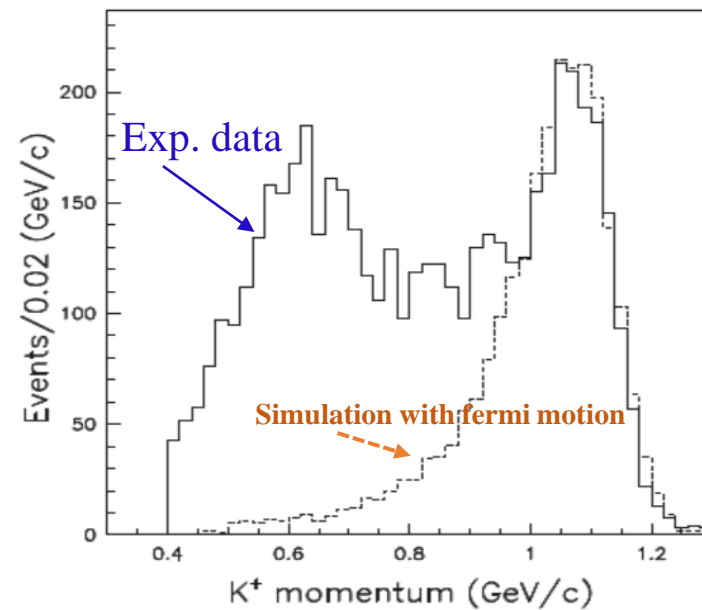
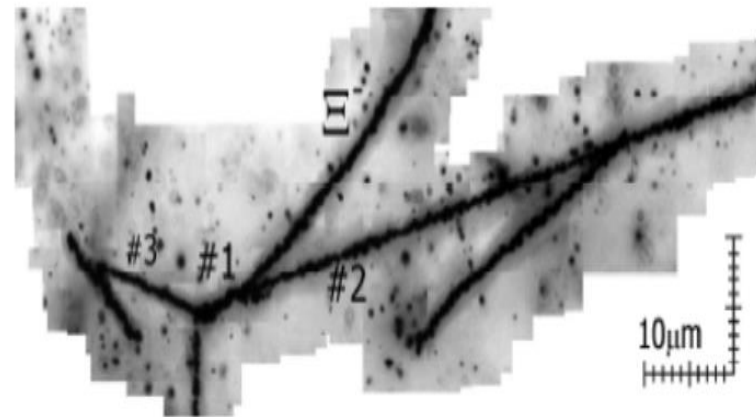


1. 超核实验观测和进展

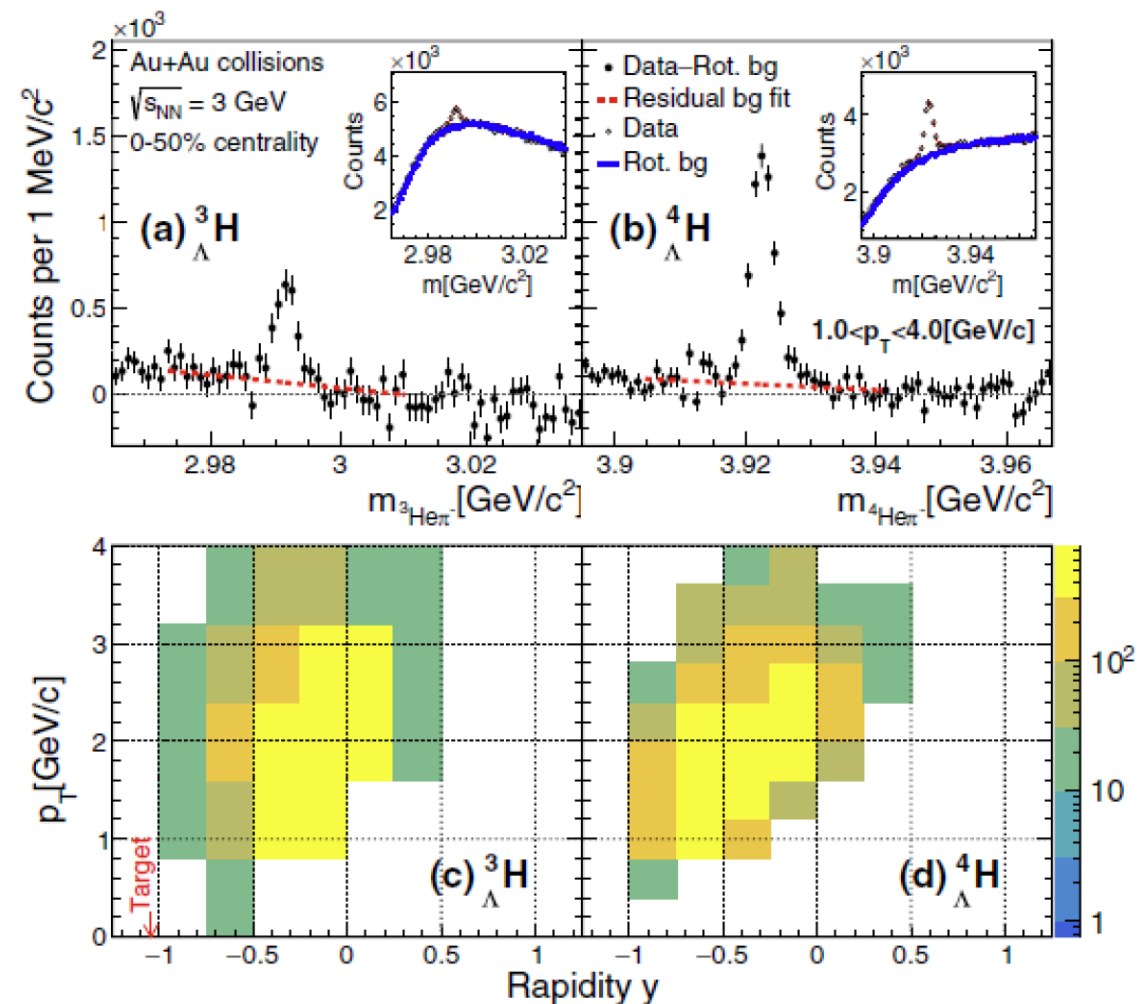
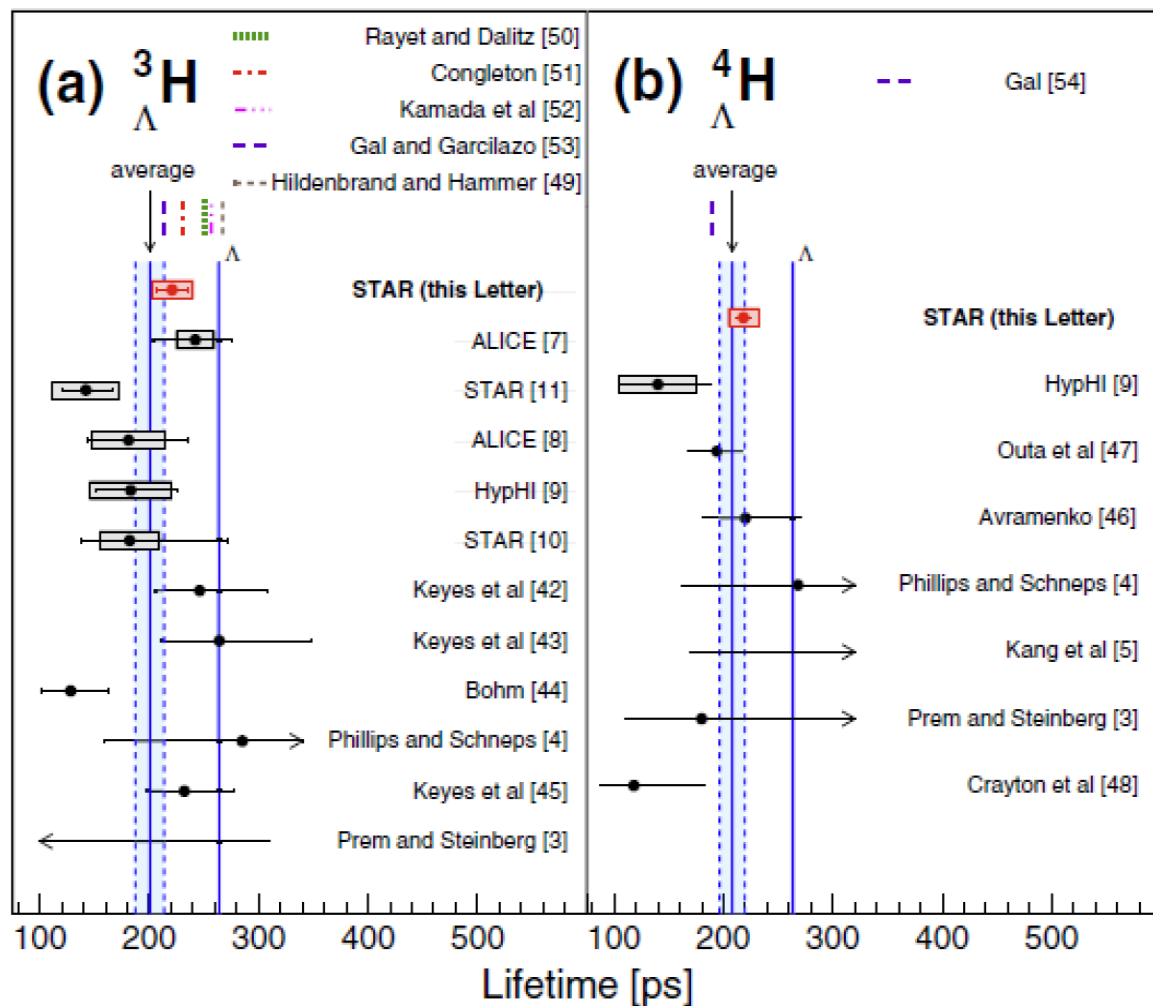
1953年波兰物理学家M. Danysz和J. Pniewski
在宇宙线乳胶实验中首次发现 Λ 超核



利用 (K^-, K^+) 产生 Ξ 超核实验观测
Kazuma Nakazawa et al, J. Phys.: Conf. Ser.
569 (2014) 012082



Hypernuclide ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ measured by STAR Collaboration (Phys. Rev. Lett. 128, 202301 (2022))

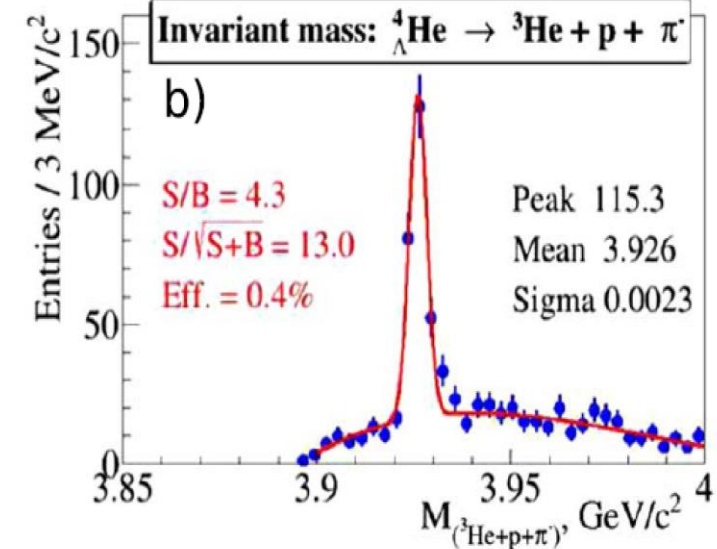
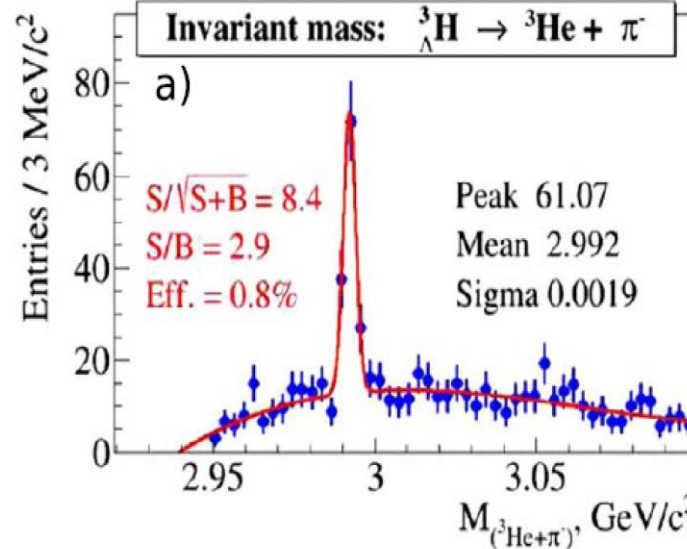
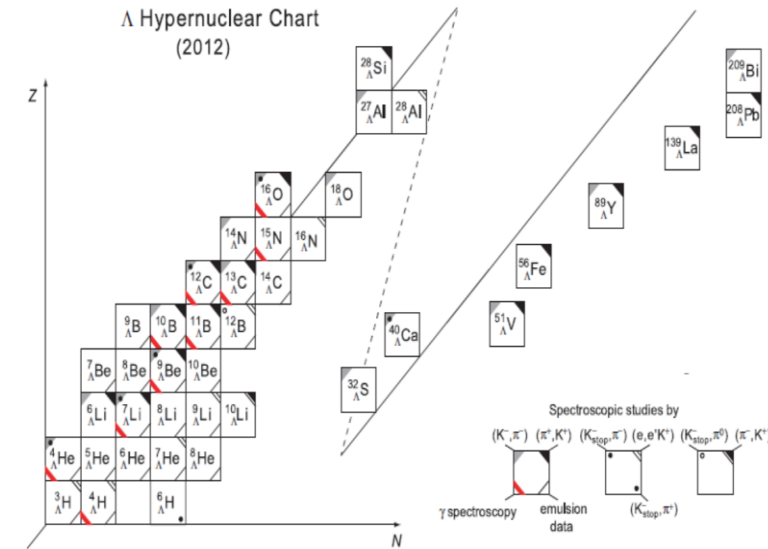
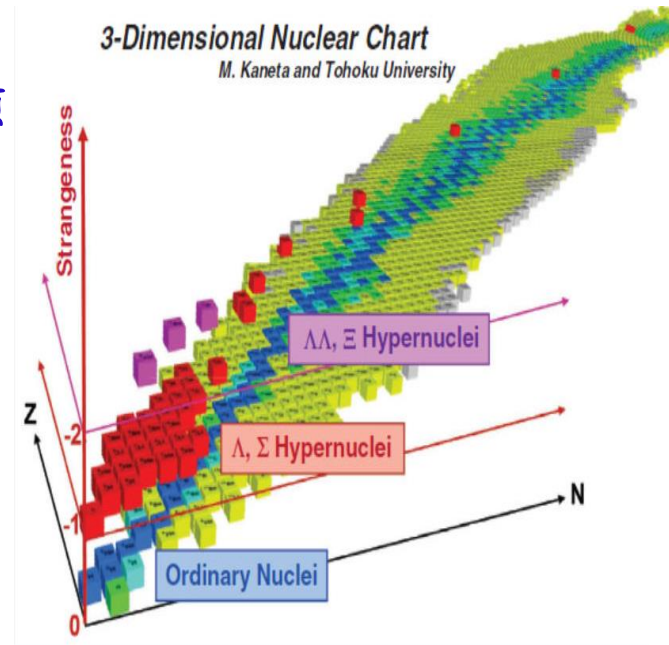
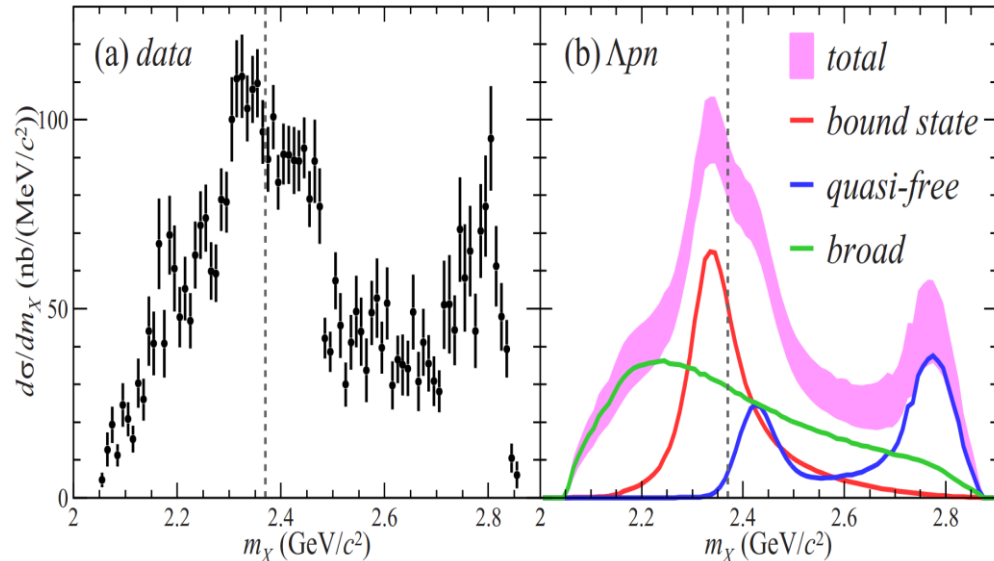


重离子碰撞产生超核的优势

1. 极端丰中子或丰质子超核产生和谱学性质
2. 奇特超核产生 ($s=-2$) $\Lambda\Lambda$ X和 Ξ X
3. 核物质中 Λ - Λ 和 Ξ -N相互作用

PHYSICAL REVIEW C **102**, 044002 (2020)

Observation of a $\bar{K}NN$ bound state in the ${}^3\text{He}(K^-, \Lambda p)n$ reaction



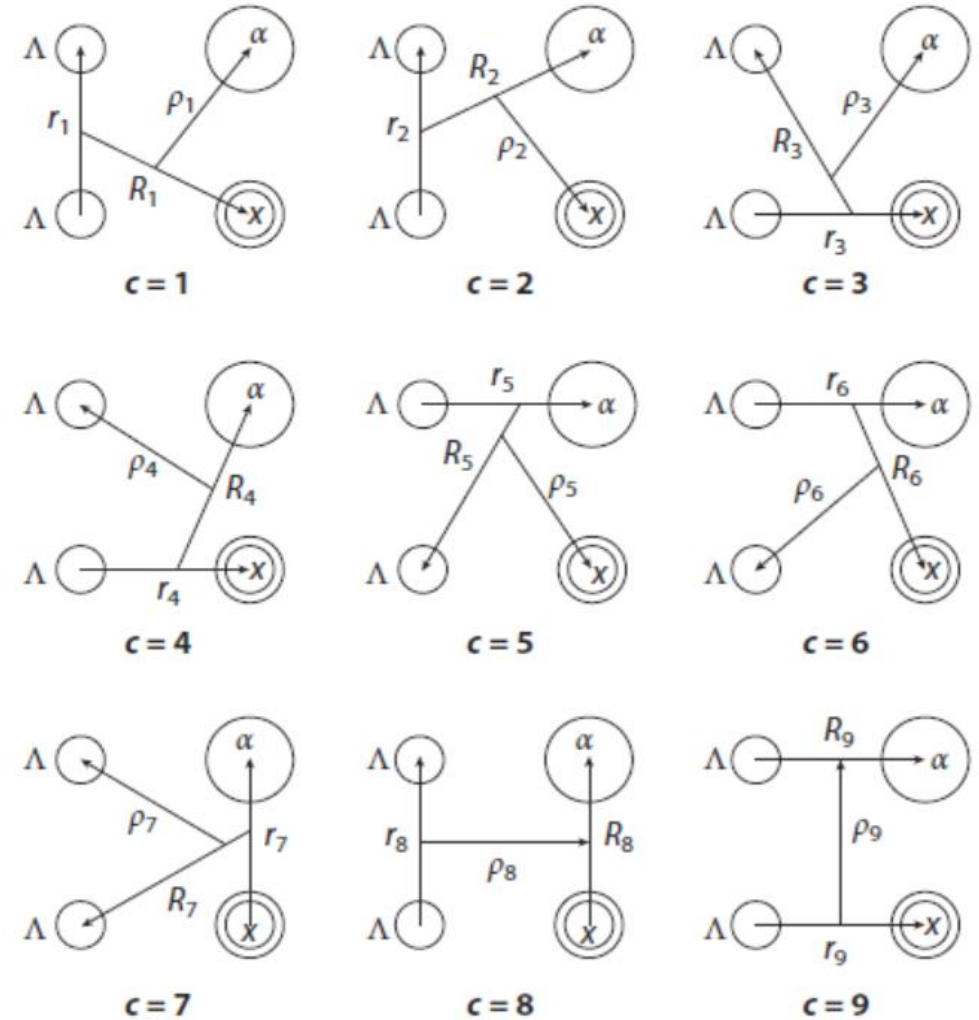
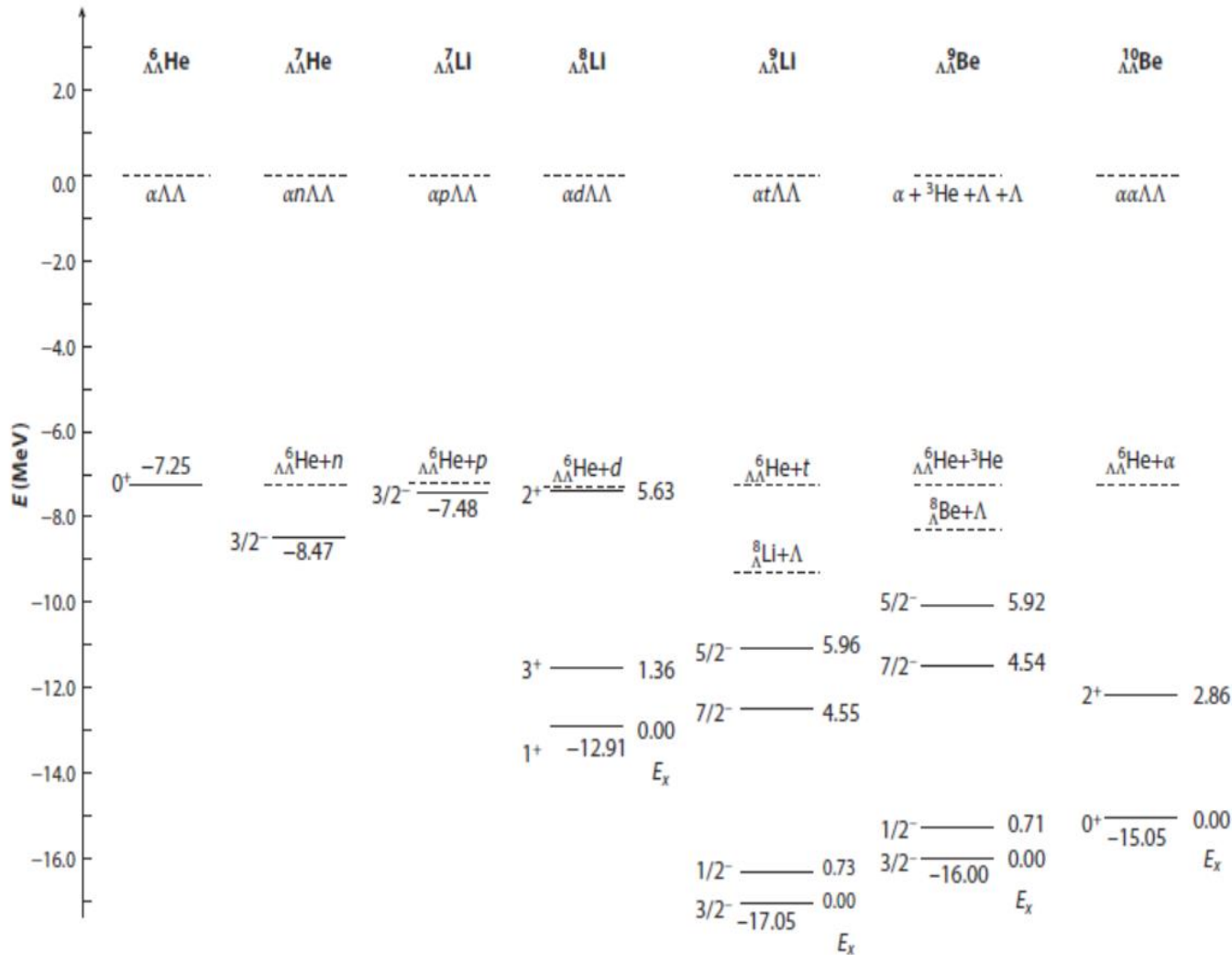
2. 超核结构理论研究

Emiko Hiyama and Kazuma Nakazawa, Annu. Rev. Nucl. Part. Sci. 68, 131-159 (2018)

T. T. Sun, E. Hiyama, H. Sagawa, H.-J. Schulze, and J. Meng, Phys. Rev. C 94, 064319 (2016)

W.-Y. Li, J.-W. Cui, X.-R. Zhou, Phys. Rev. C 97, 034302 (2018)

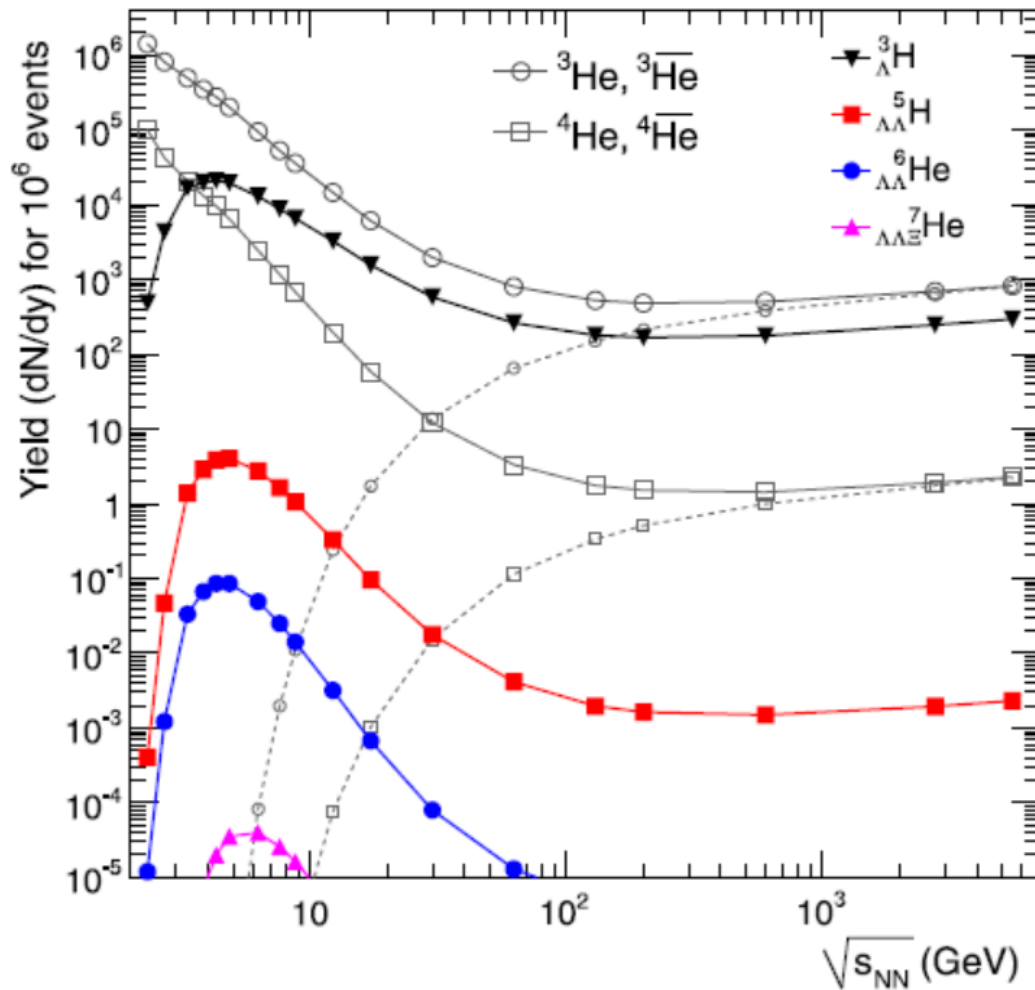
Yu-Ting Rong, Pengwei Zhao, and Shan-Gui Zhou, Phys. Lett. B 807 135533 (2020)



3. 中高能重离子碰撞产生超核理论研究—统计理论

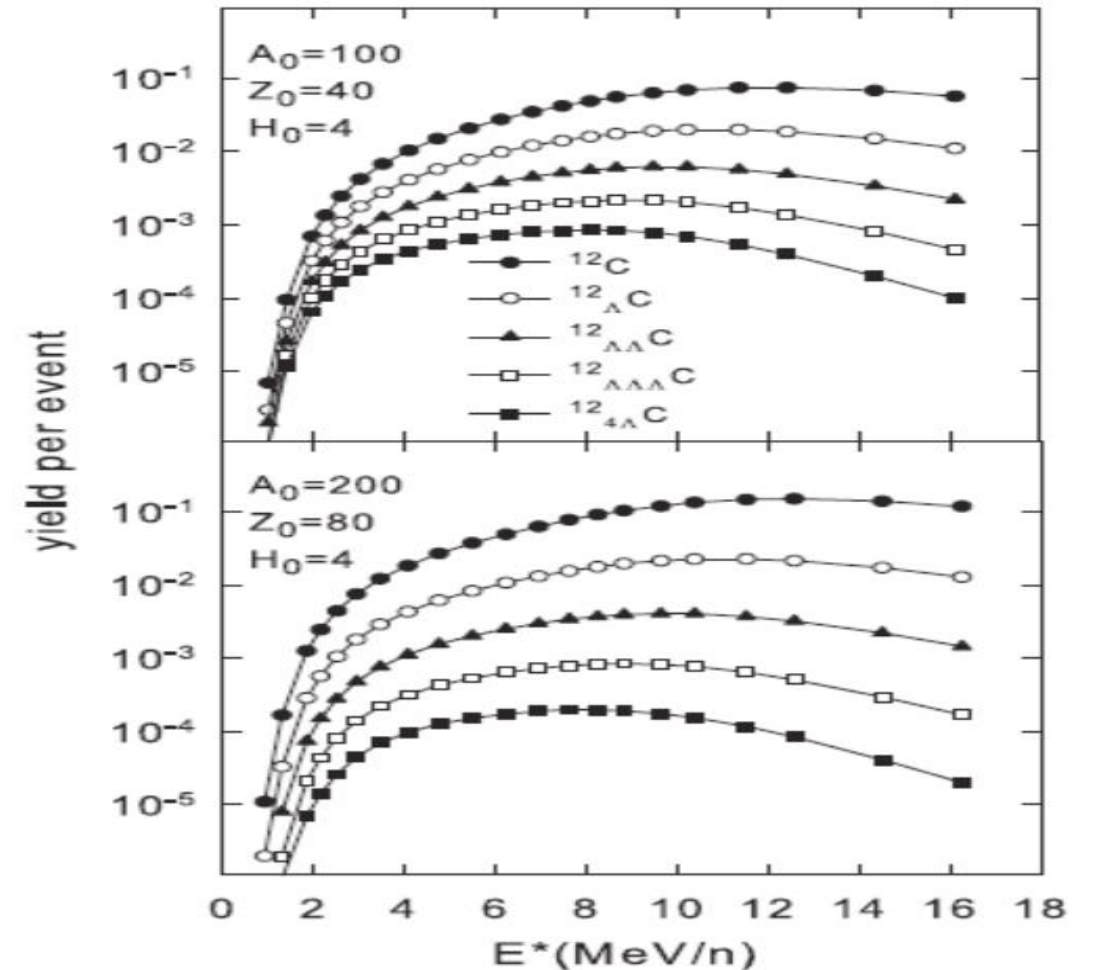
A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker,
Physics Letters B 697 (2011) 203–207

Pb+Pb



N. Buyukcizmeci, R. Ogul, A. S. Botvina, M.
Bleicher, Phys. Scr. 95 075311 (2020)

Statistical multifragmentation model (SMM)



4. 中高能重离子碰撞产生超核理论研究方法

— 输运理论+并合模型

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

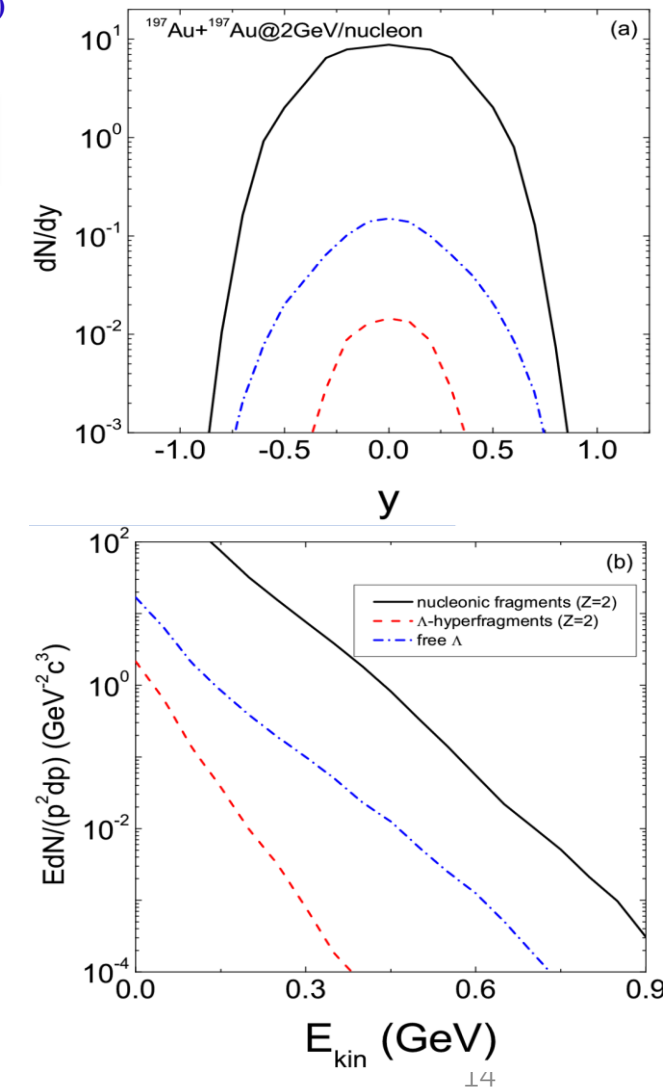
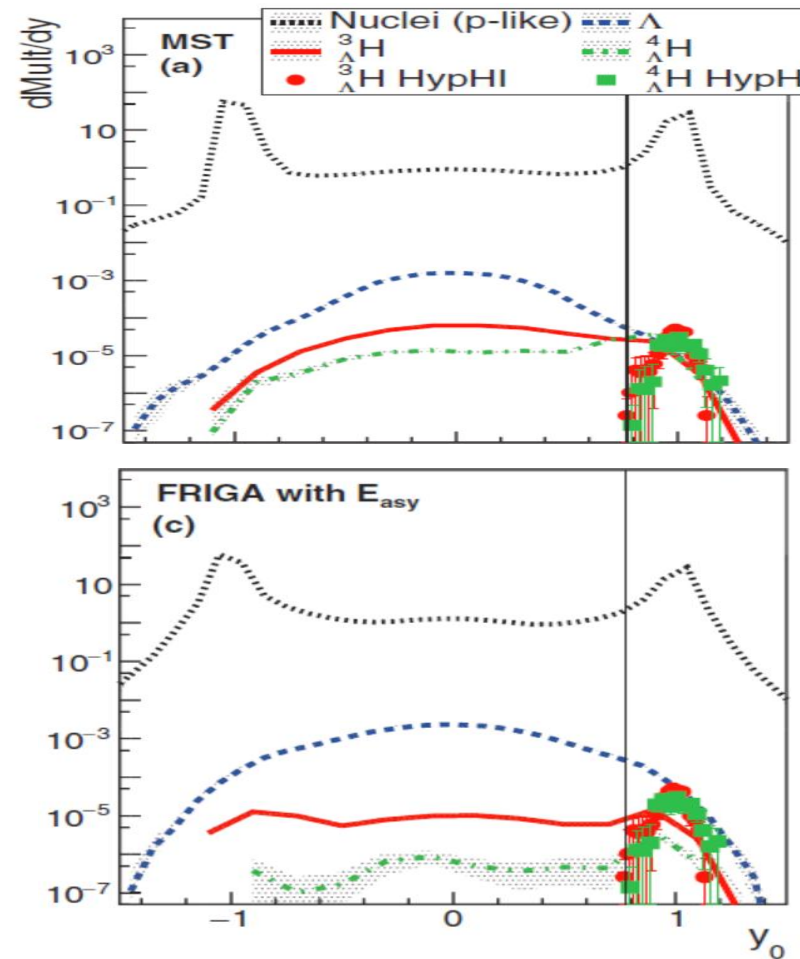
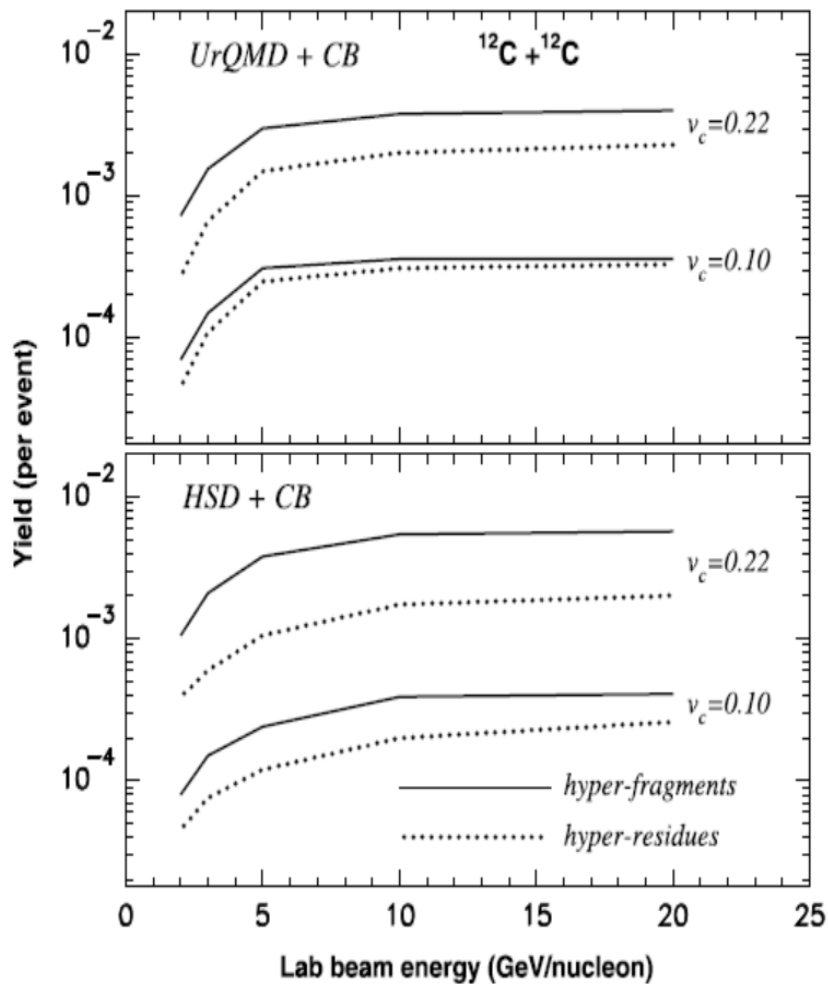
中国科学院近代物理研究所, 兰州 730000
E-mail: fmgzq@impcas.ac.cn

A.S. Botvina, J. Steinheimer, E. Bratkovskaya et al., Physics Letters B 742 (2015)7-14

J. Aichelin, E. Bratkovskaya, A. Le Fèvre et al., Physical Review C 101, 044905 (2020)

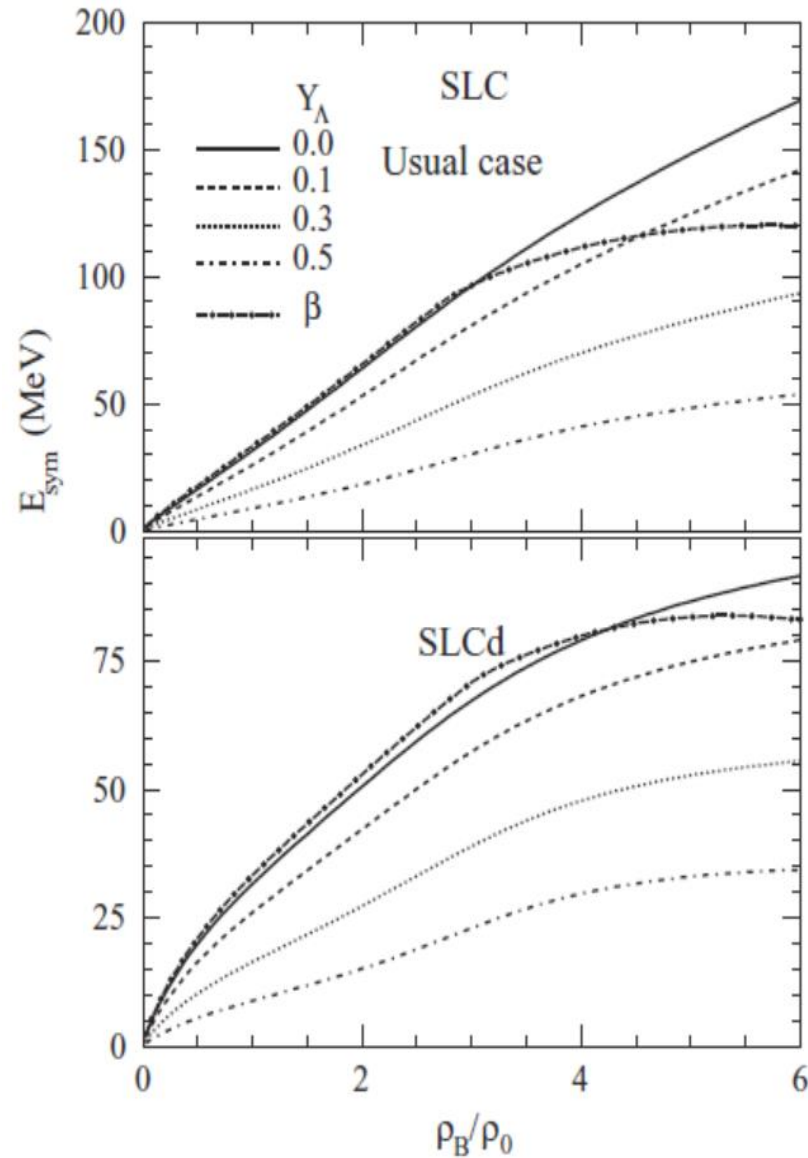
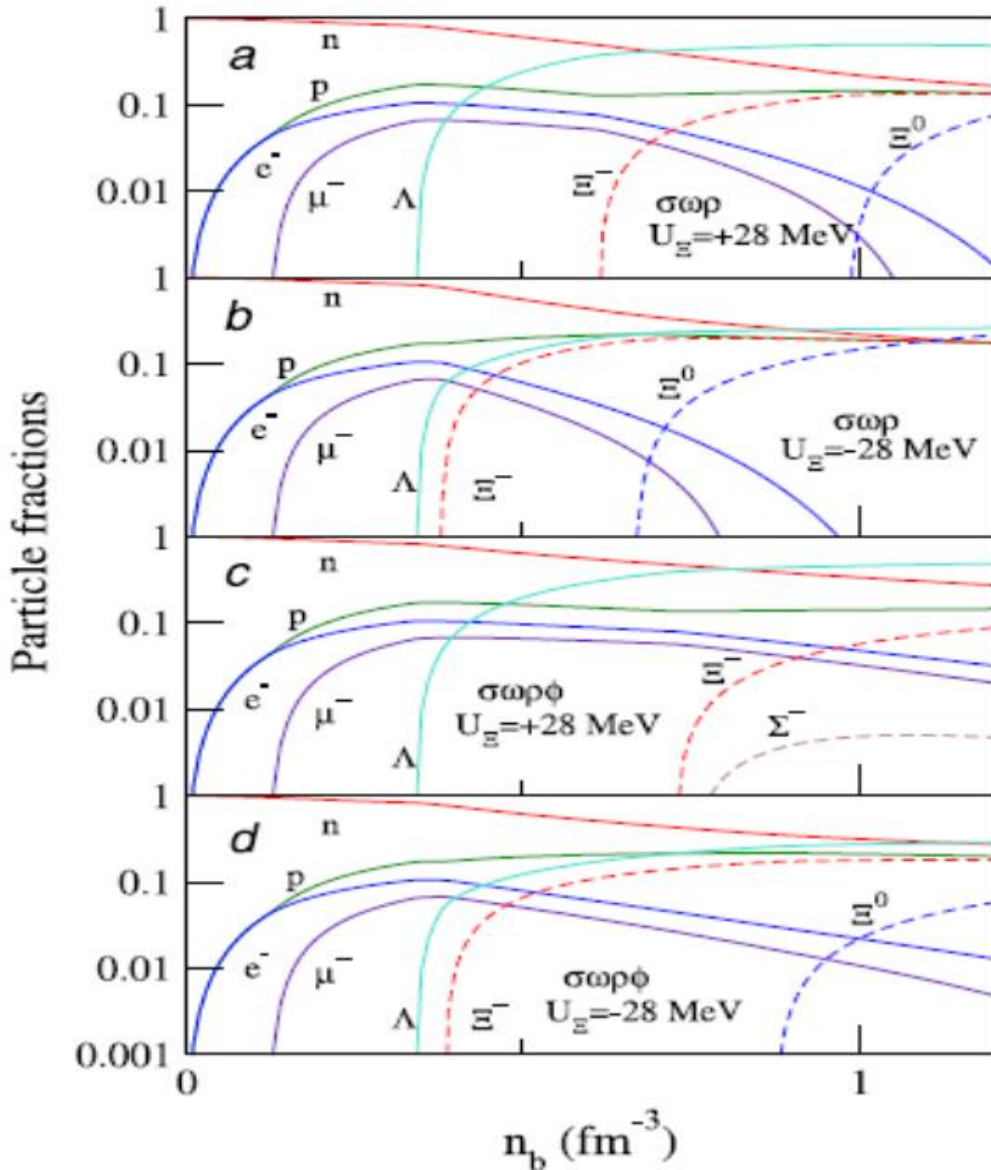
A. Le Fèvre, J. Aichelin, C. Hartnack and Y. Leifels 100, Physical Review C 034904 (2019)

${}^6\text{Li}+{}^{12}\text{C}@2\text{A GeV}$

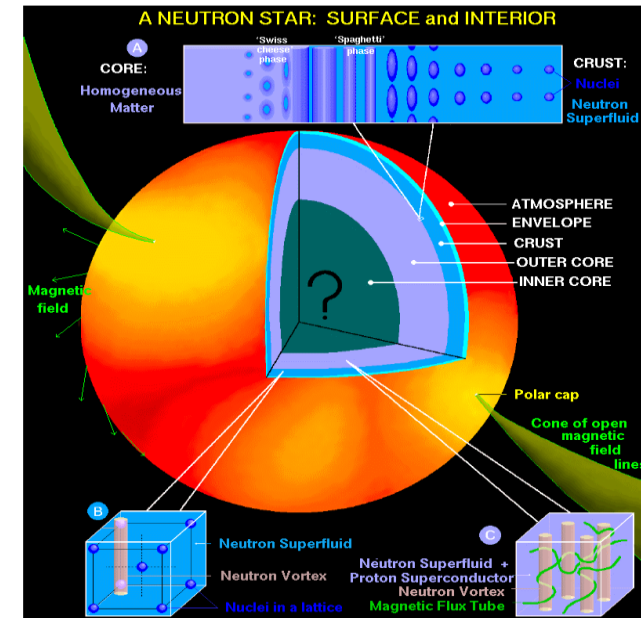


5. 致密物质中超子成分的影响

S. Weissenborn, D. Chatterjee, J. Schaffner-Bielich, Nuclear Physics A 881, 62 (2012)
 W. Z. Jiang, R. Y. Yang, and D. R. Zhang, Phys. Rev. C 87, 064314 (2013).



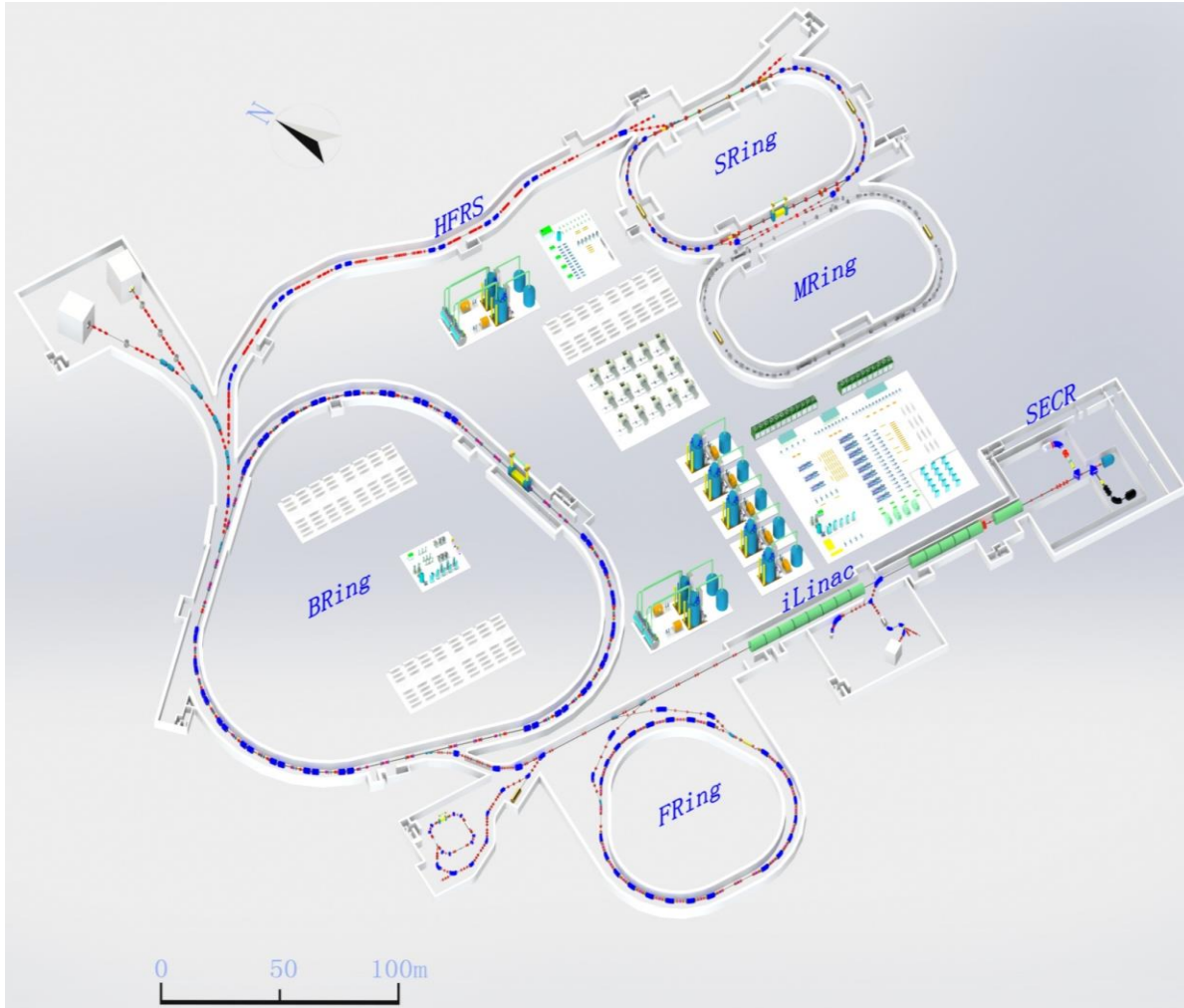
J. M. Lattimer and M. Prakash,
 Science 304, 536 (2004)



惠州强流重离子加速器(2018年12月开建)

HIAF (*High-Intensity Heavy Ion Accelerator Facility*)

Provided by Jian-Cheng Yang



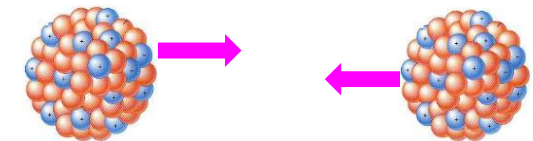
	Ions	Energy	Intensity
SECR	$^{238}\text{U}^{35+}$	14 keV/u	0.05-0.1 pmA
iLinac	$^{238}\text{U}^{35+}$	17 MeV/u	0.028-0.05 pmA
FRing	$^{238}\text{U}^{35+}$	0.35 GeV/u	$\sim 2.0 \times 10^{11}$ ppp
BRing	$^{238}\text{U}^{35+}$	1.0 GeV/u	$\sim 1.0 \times 10^{12}$ ppp
	$^{238}\text{U}^{92+}$	3.8 GeV/u	$\sim 5.0 \times 10^{11}$ ppp
SRing	RIBs: neutron-rich, proton-rich	0.84 GeV/u ($A/q=3$)	$\sim 10^{9-10}$ ppp
	Fully stripped heavy ions H-like, He-like heavy ions	0.8 GeV/u ($^{238}\text{U}^{92+}$)	$\sim 10^{11-12}$ ppp

三、量子分子动力学模型 (LQMD)



Nuclear dynamics from 5 MeV/nucleon – 10 GeV/nucleon for HICs, antiproton (proton, π , K, etc)

- **Dynamics of low-energy heavy-ion collisions** (dynamical interaction potential, barrier distribution, neck dynamics, fusion/caption excitation functions etc)
- **Isospin physics at intermediate energies** (constraining nuclear **symmetry energy** at sub- and supra-saturation densities in HICs and probing isospin splitting of nucleon effective mass from HICs)
- **In-medium properties of hadrons in dense nuclear matter from heavy-ion collisions** (extracting optical potentials, i.e., $\Delta(1232)$, $N^*(1440)$, $N^*(1535)$), hyperons ($\Lambda, \Sigma, \Xi, \Omega$) and mesons ($\pi, K, \eta, \rho, \omega, \phi \dots$), hypernucleus dynamics)
- **Hadron (antiproton, proton, π^\pm , K^\pm) induced reactions** (hypernucleus production, e.g., $\Lambda(\Sigma)X$, $\Lambda\Lambda X$, ΞX , $\bar{\Lambda}X(S=1)$, in-medium modifications of hadrons, cold QGP)



1. Particle production channels in the LQMD model

π and resonances ($\Delta(1232)$, $N^*(1440)$, $N^*(1535)$, ...) production:

$$\begin{aligned}
 NN &\leftrightarrow N\Delta, & NN &\leftrightarrow NN^*, & NN &\leftrightarrow \Delta\Delta, & \Delta &\leftrightarrow N\pi, \\
 N^* &\leftrightarrow N\pi, & NN &\leftrightarrow NN\pi(s\text{-state}), & N^*(1535) &\leftrightarrow N\eta
 \end{aligned}$$

Collisions between resonances, $NN^* \leftrightarrow N\Delta$, $NN^* \leftrightarrow NN^*$

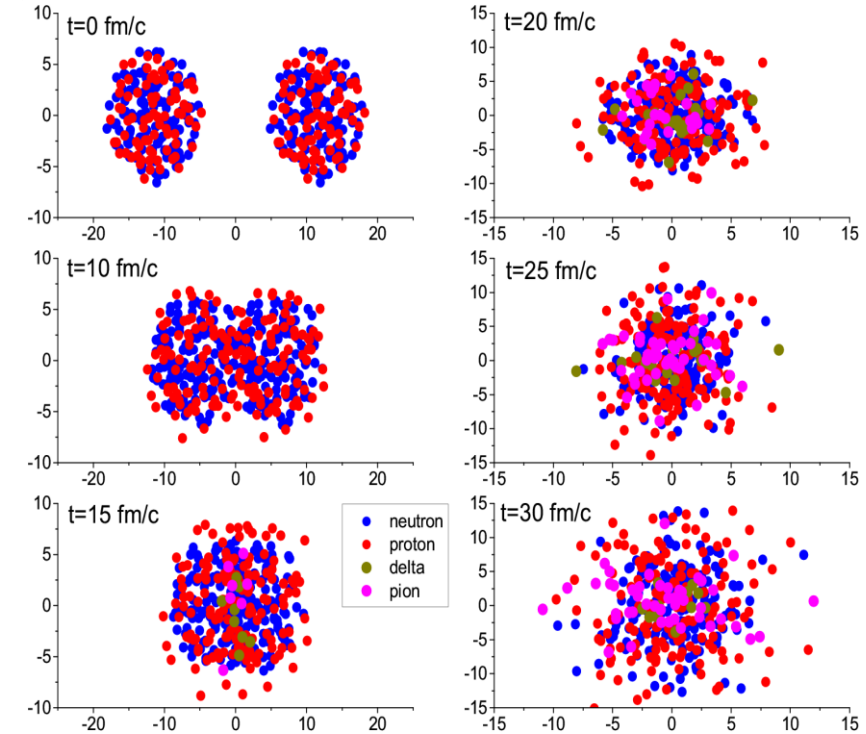
Strangeness channels:

$$\begin{aligned}
 BB &\rightarrow BYK, & BB &\rightarrow BBK\bar{K}, & B\pi(\eta) &\rightarrow YK, & YK &\rightarrow B\pi, \\
 B\pi &\rightarrow NK\bar{K}, & Y\pi &\rightarrow B\bar{K}, & B\bar{K} &\rightarrow Y\pi, & YN &\rightarrow \bar{K}NN, \\
 BB &\rightarrow B\Xi KK, & \bar{K}B &\leftrightarrow K\Xi, & YY &\leftrightarrow N\Xi, & \bar{K}Y &\leftrightarrow \pi\Xi.
 \end{aligned}$$

Reaction channels with antiproton:

$$\bar{p}N \rightarrow \bar{N}N, \quad \bar{N}N \rightarrow \bar{N}N, \quad \bar{N}N \rightarrow \bar{B}B, \quad \bar{N}N \rightarrow \bar{Y}Y$$

$$\bar{N}N \rightarrow \text{annihilation}(\pi, \eta, \rho, \omega, K, \bar{K}, K^*, \bar{K}^*, \phi)$$



Statistical model with SU(3)

symmetry for annihilation

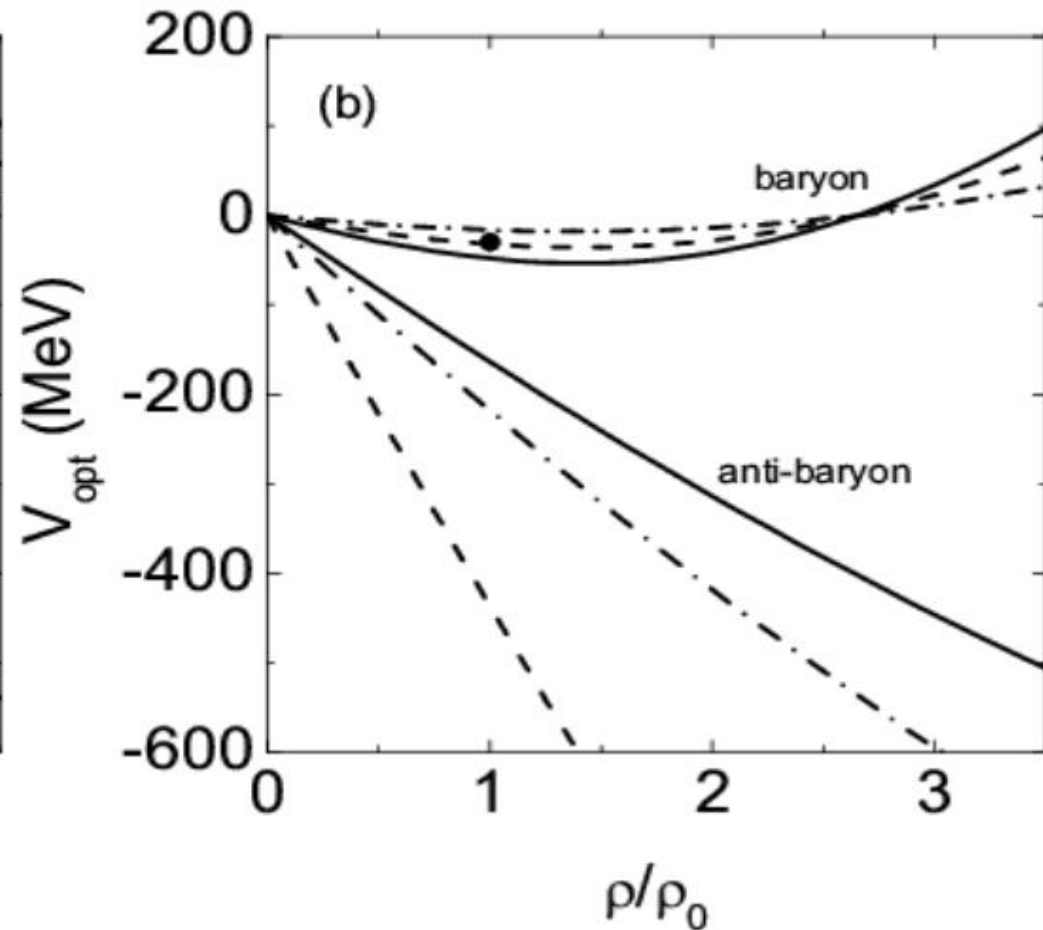
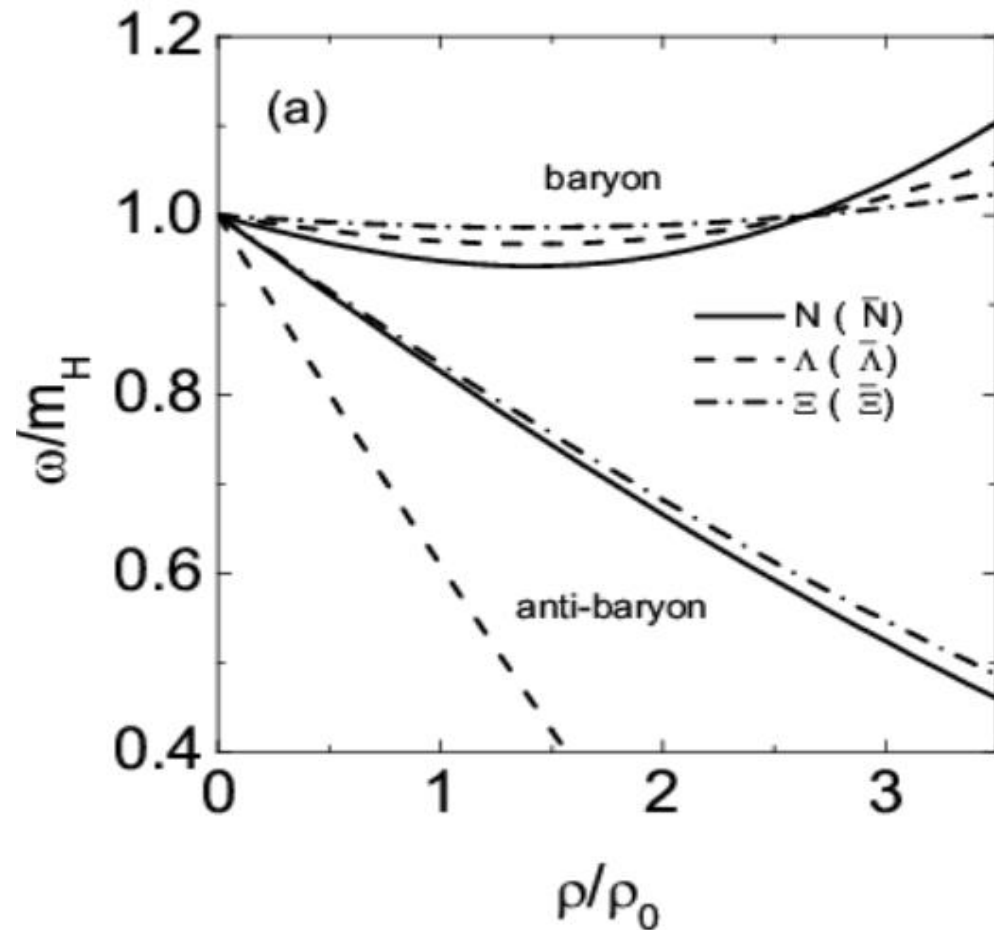
(E.S. Golubeva et al., Nucl. Phys. A 537, 393 (1992))

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

2. Mean-field potentials for hyperons and antiprotons in nuclear medium

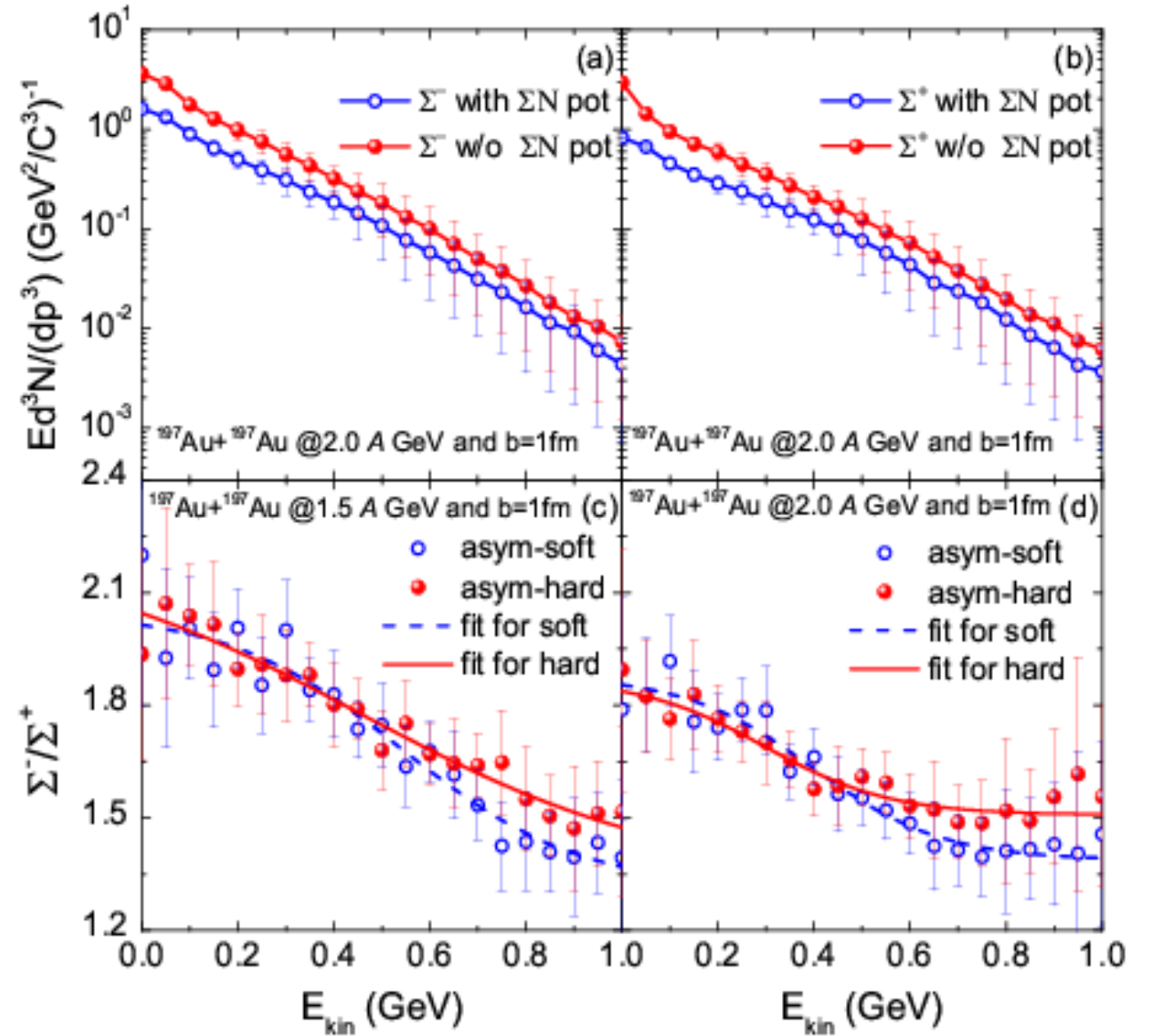
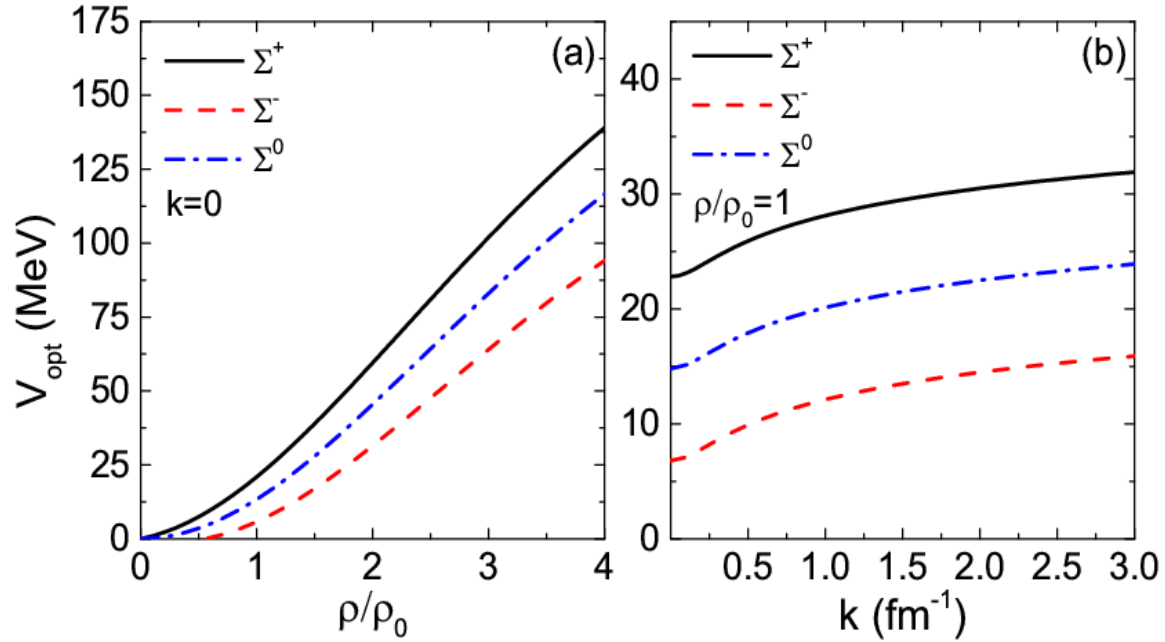
A factor ξ is introduced in evaluating self-energies of the antinucleon, e.g., $\xi=0.25$ for $V_{\bar{N}N} = -160$ MeV at $\rho = \rho_0$

$$H_M = \sum_{i=1}^{N_M} (V_i^{\text{Coul}} + \omega(\mathbf{p}_i, \rho_i)) \quad \omega(\mathbf{p}_i, \rho_i) = \sqrt{(m_H + \Sigma_S^H)^2 + \mathbf{p}_i^2} + \Sigma_V^H \quad V_{\text{opt}}(\mathbf{p}, \rho) = \omega(\mathbf{p}, \rho) - \sqrt{\mathbf{p}^2 + m^2}$$



Ding-Chang Zhang, Hui-Gan Cheng and Zhao-Qing Feng.
Chinese Physics Letters 38 (2021) 092501. (arXiv:
 2107.00277, editor's suggestion)

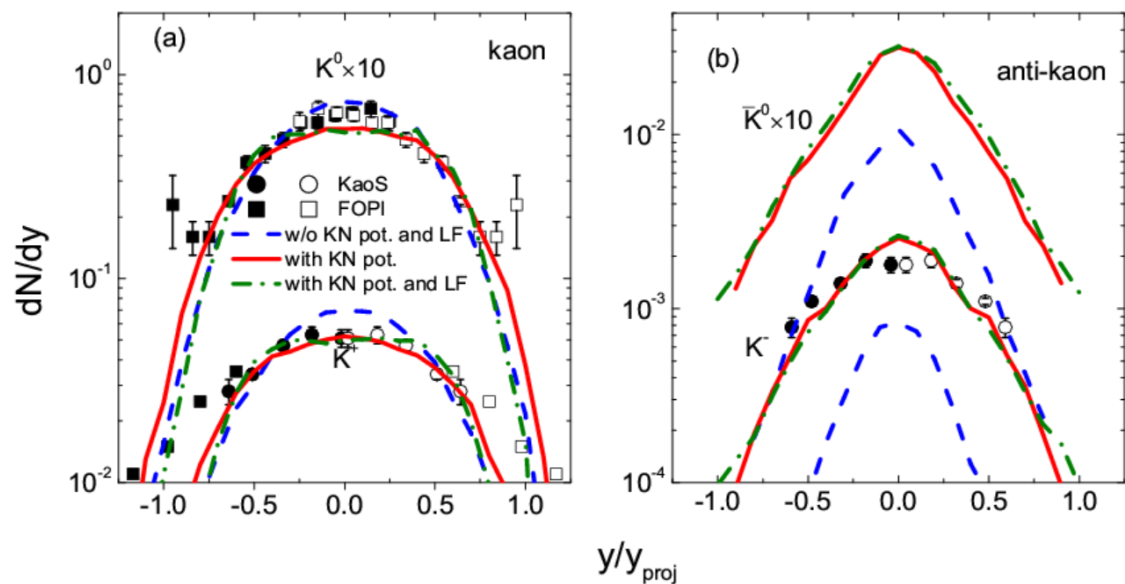
$$V_{\text{opt}}^{\Sigma}(p_i, \rho_i) = V_0(\rho_i/\rho_0)^{\gamma_s} + V_1(\rho_n - \rho_p)t_{\Sigma}\rho_i^{\gamma_s-1}/\rho_0^{\gamma_s} \\ + C_{\text{mom}}\rho_i \ln(\epsilon p_i^2 + 1)$$



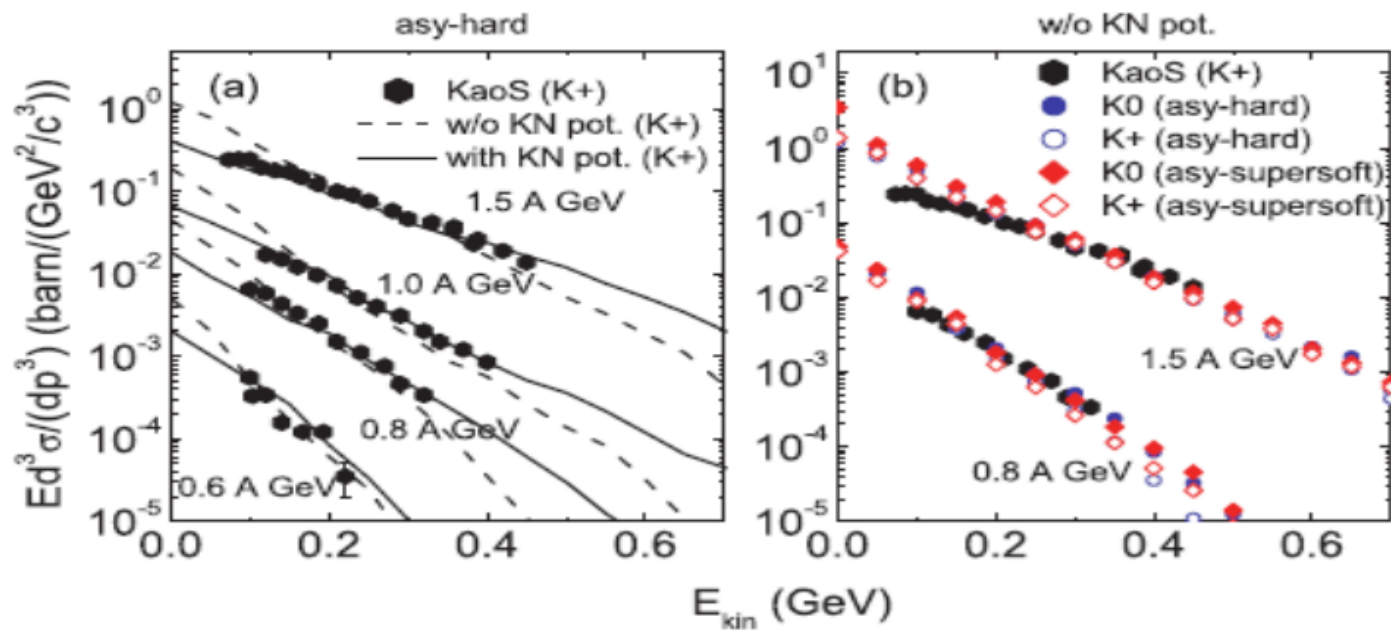
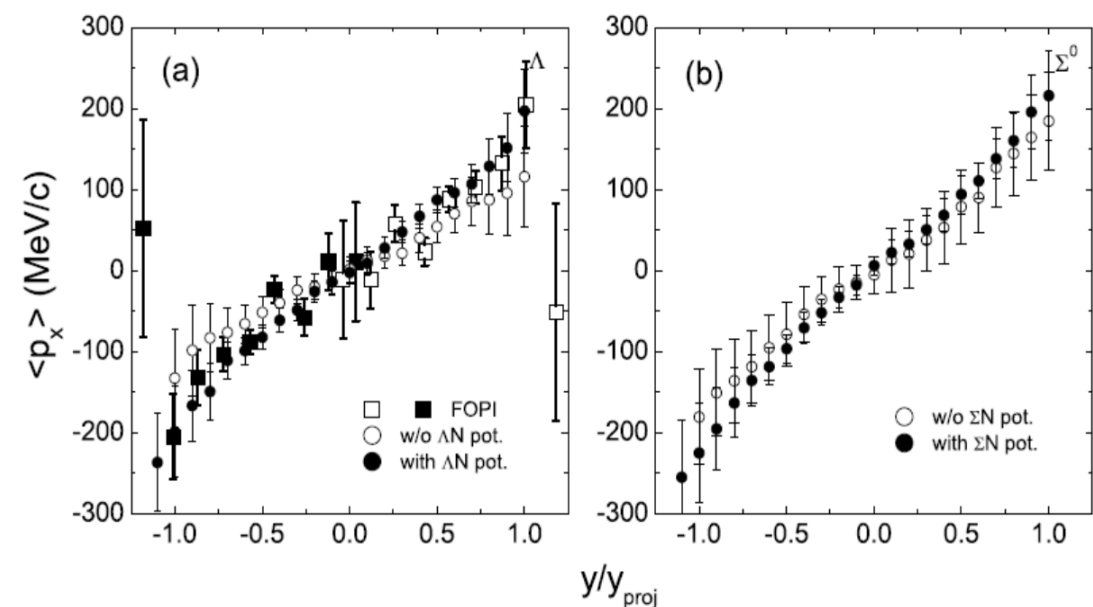
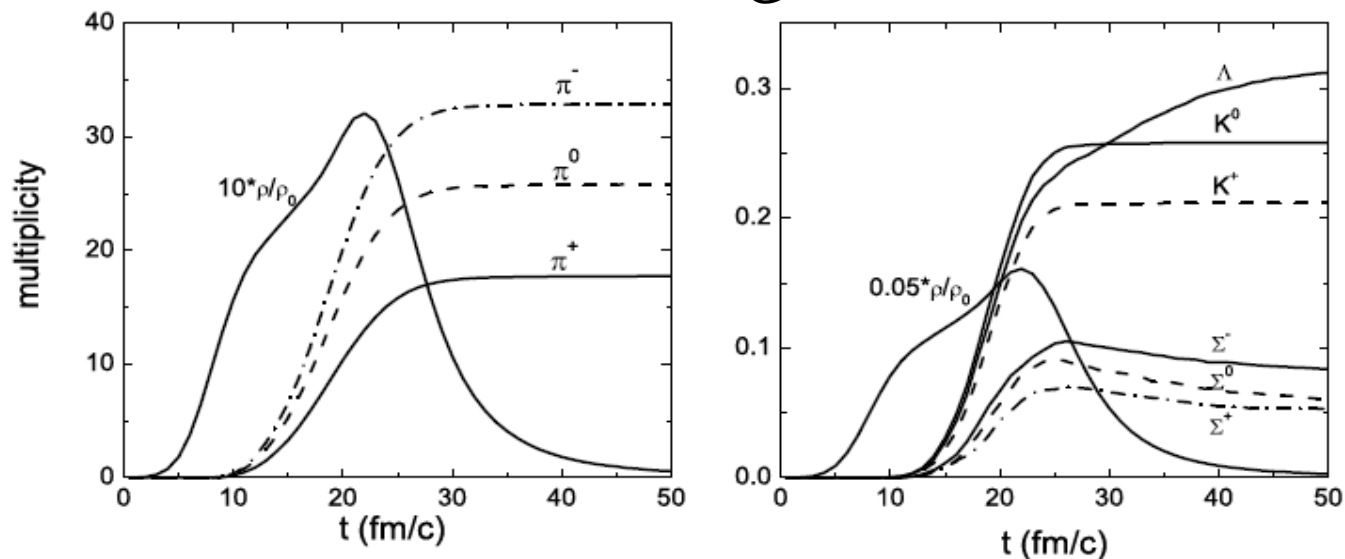
3. Strangeness production in heavy-ion collisions

Phys. Rev. C 82 (2010) 057901; Phys. Rev. C 87, 064605 (2013); Nuclear PhysicsA919(2013)32–45

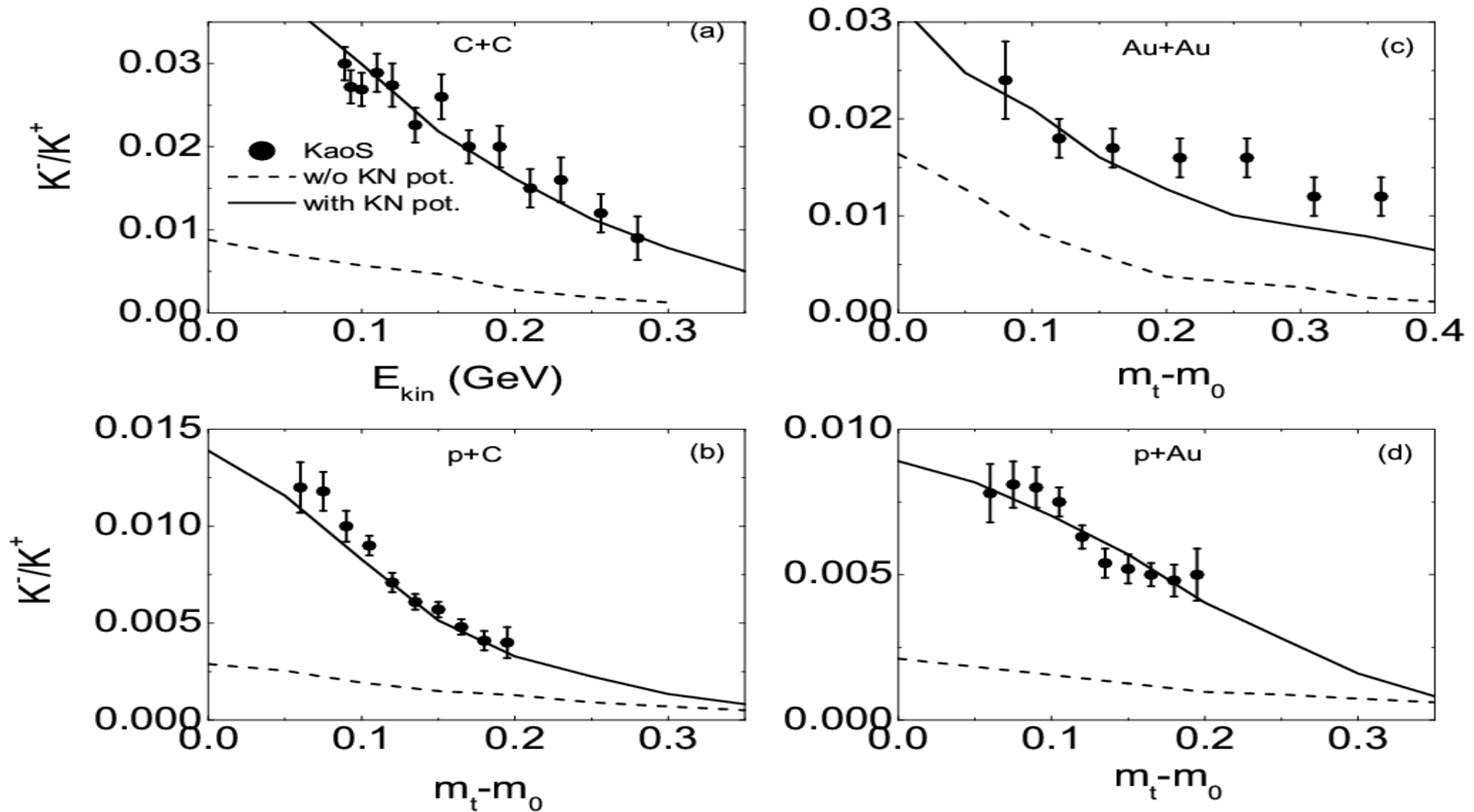
$^{58}\text{Ni}+^{58}\text{Ni}@1.93\text{A GeV}$



$^{197}\text{Au}+^{197}\text{Au}@1.5\text{A GeV}$



The K^-/K^+ ratio in collisions of $^{12}\text{C} + ^{12}\text{C}$ at 1.84 GeV and protons on ^{12}C and ^{197}Au with 2.5 GeV



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

四、中高能重离子碰撞原子核碎裂反应和超核形成



Physics Reports 510 (2012) 119–200



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



Physics Reports 512 (2012) 1–124



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



Strangeness production close to the threshold in proton–nucleus and heavy-ion collisions

Christoph Hartnack^a, Helmut Oeschler^{b,*}, Yvonne Leifels^c, Elena L. Bratkovskaya^{d,e}, Jörg Aichelin^a



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Progress in Particle and Nuclear Physics 56 (2006) 1–103

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Review

Kaon production in heavy ion reactions at intermediate energies

Christian Fuchs*

*Institut für Theoretische Physik der Universität Tübingen, Auf der Morgenstelle 14,
D-72076 Tübingen, Germany*

Transport-theoretical description of nuclear reactions

O. Buss, T. Gaitanos, K. Gallmeister, H. van Hees, M. Kaskulov, O. Lalakulich, A.B. Larionov¹, T. Leitner, J. Weil, U. Mosel*

Institut für Theoretische Physik, Universität Giessen, Germany



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Review

Strangeness dynamics in relativistic nucleus–nucleus collisions

E.L. Bratkovskaya^a, M. Bleicher^a, W. Cassing^{b,*}, M. van Leeuwen^{c,d}, M. Reiter^a, S. Soff^a, H. Stöcker^a, H. Weber^a

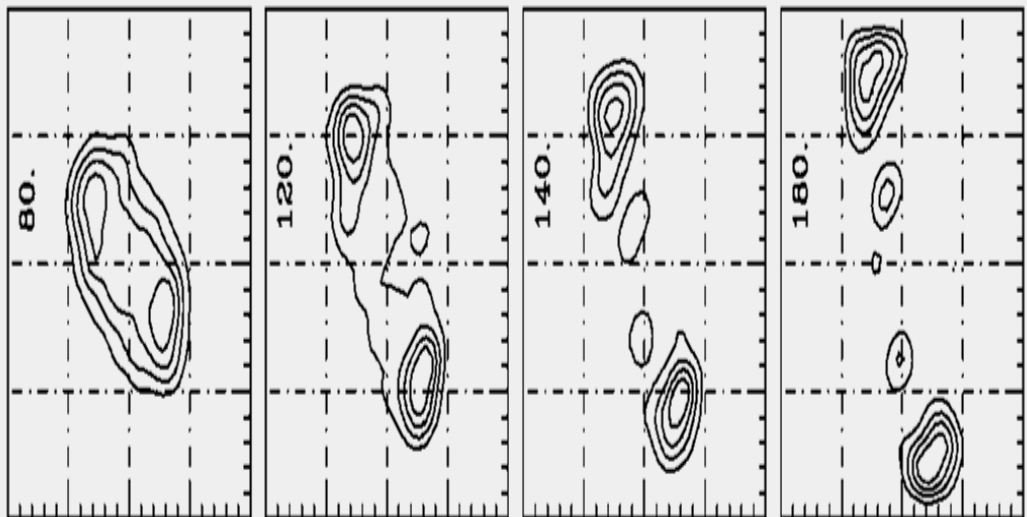
1. 费米能区(10A-100A MeV)重离子碰撞中的同位旋效应

Experiments:

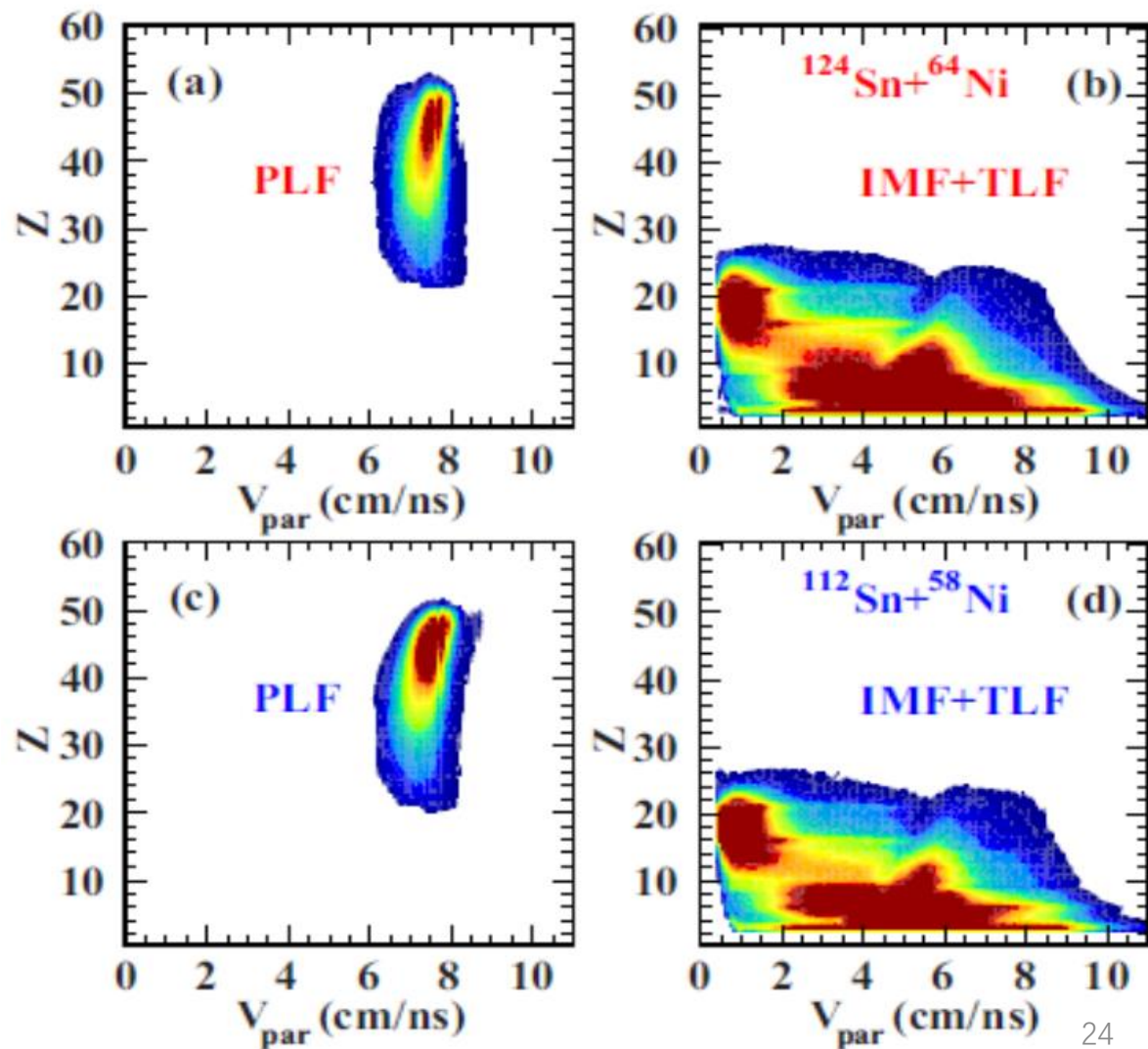
INDRA (GANIL), CHIMERA (LNS), NSCL (MSU)

SSC (HIRFL) ...

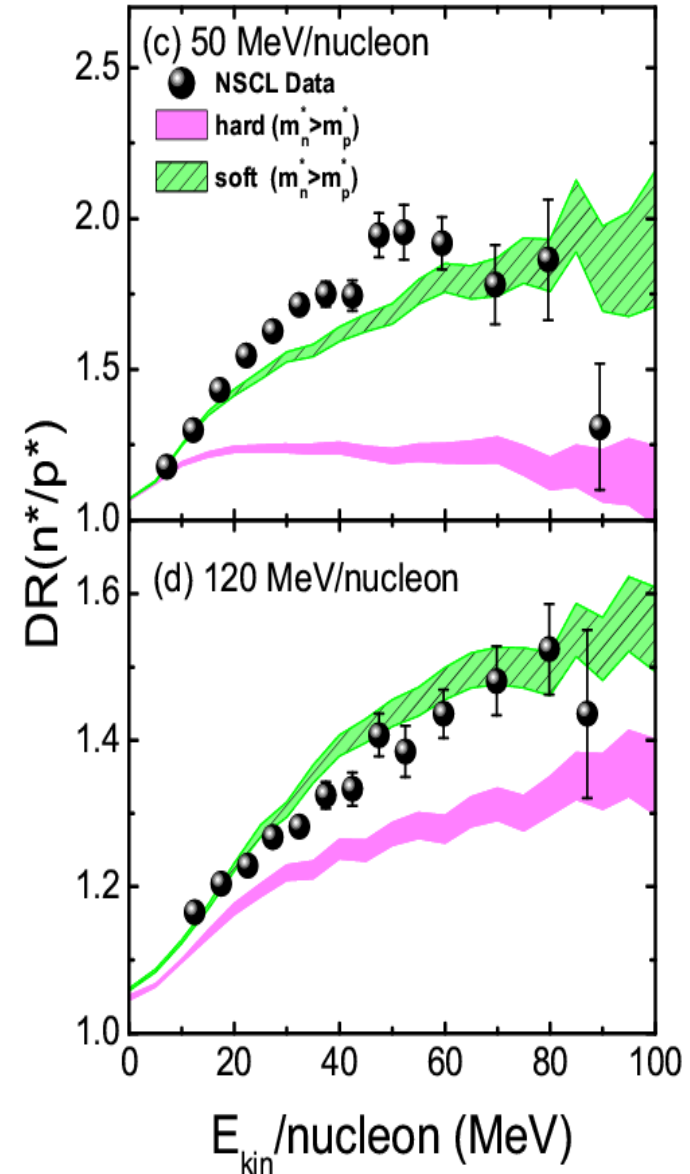
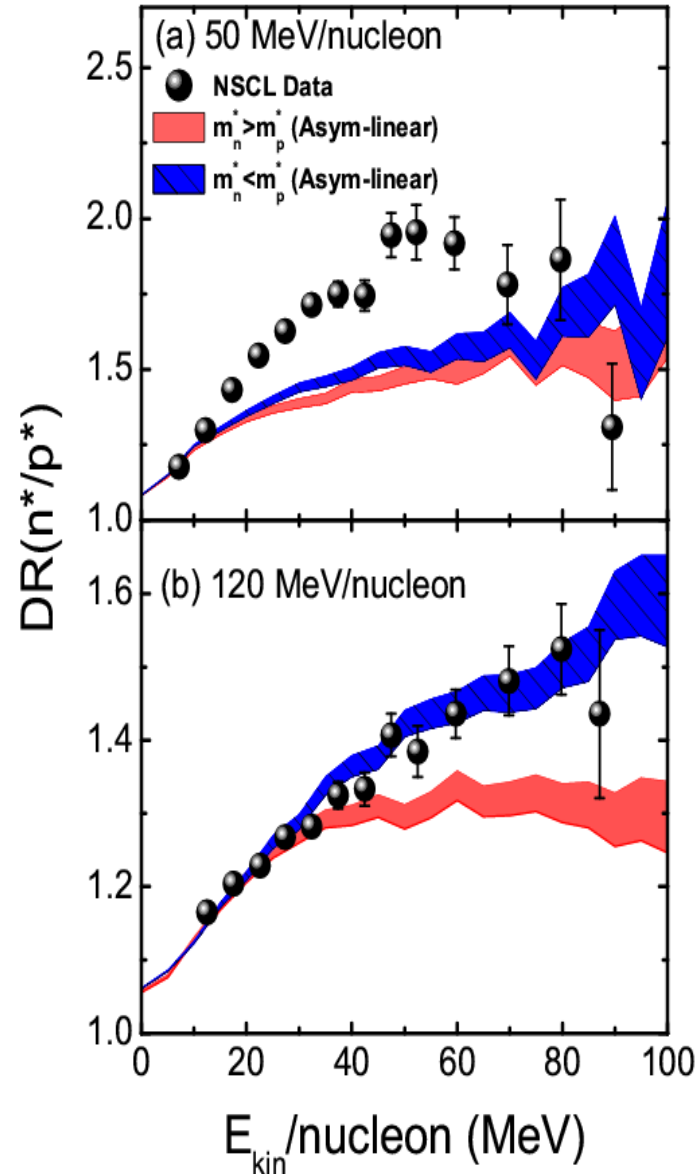
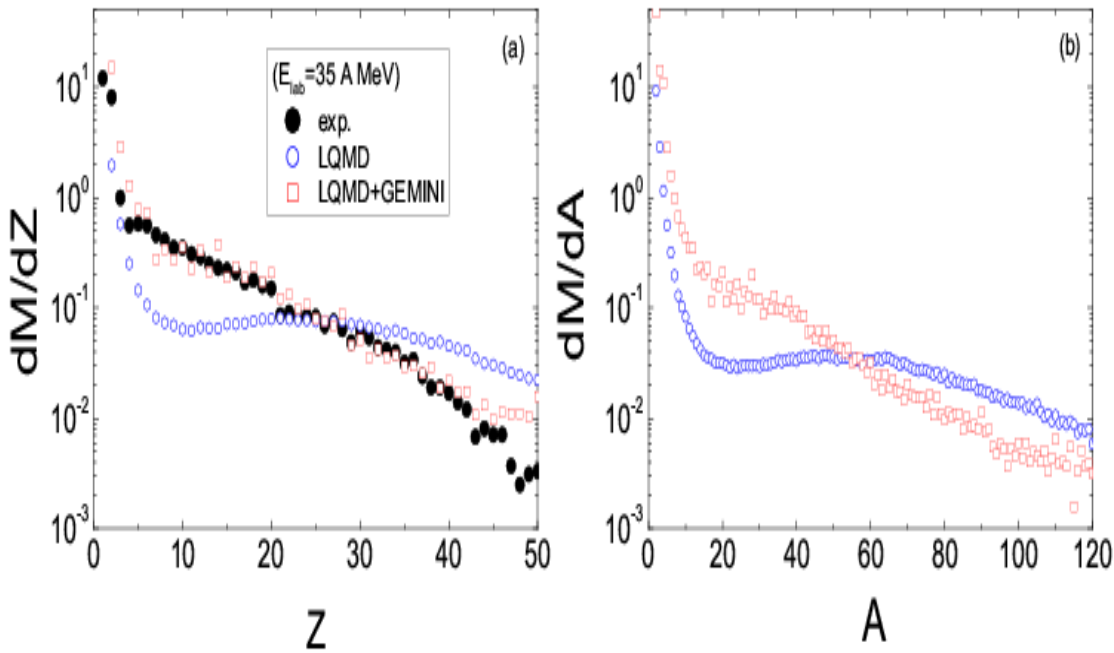
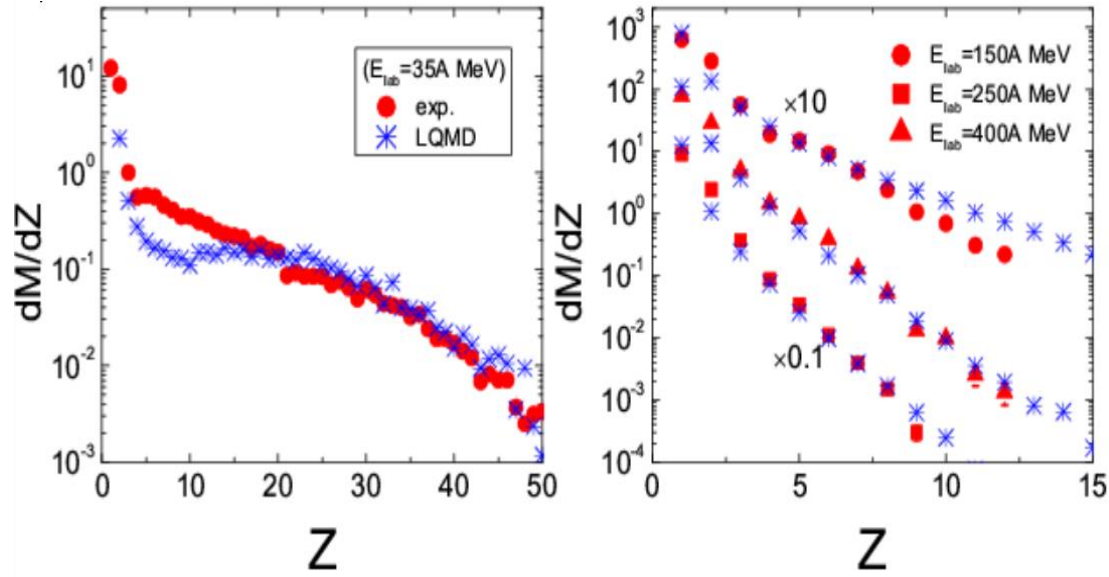
密度演化等高图



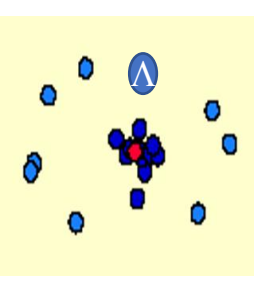
P. Russotto *et al.*, PRC 91, 014610 (2015)



$^{197}\text{Au}+^{197}\text{Au}$ 碰撞中碎裂分布 (Phys. Rev. C 82, 044615 (2010); 94, 014609 (2016), Chin. Phys. C 41 (2017) 104104)



2. 超核碎片构造和动力学分析



1) Classical coalescence approach in phase space for nuclides of $Z > 2$ combined with the GEMINI decay code (minimum spanning tree (MST) procedure)

$$|r_i - r_j| \leq 3 \text{ fm}, |r_i - r_Y| \leq 4.5 \text{ fm}, |p_i - p_j| \leq 0.3 \text{ GeV}/c$$

C. Samanta et al, J. Phys. G: Nucl. Part. Phys. 32 (2006) 363

Binding energy: $E_B(Z_i, N_i) = \sum_j \sqrt{p_j^2 + m_j^2} - m_j$

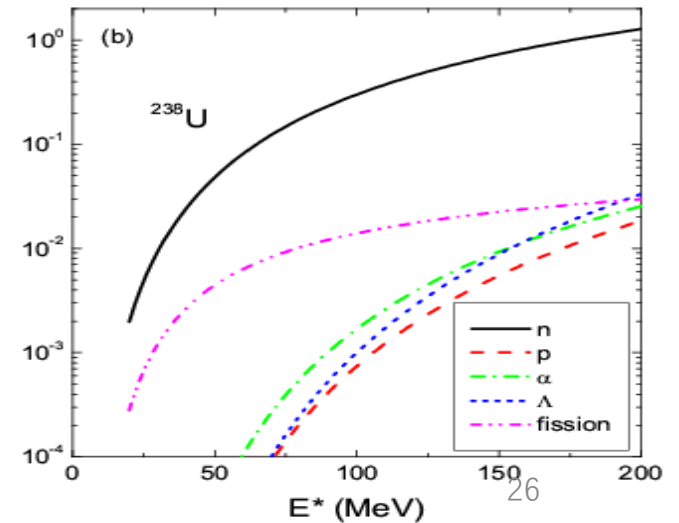
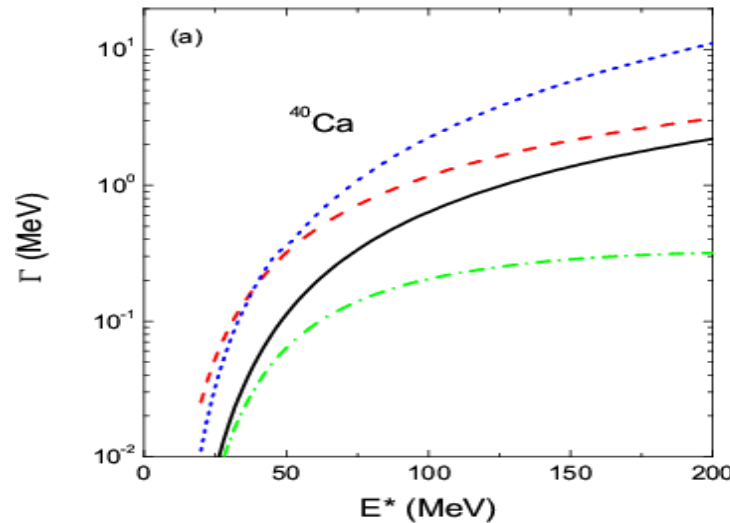
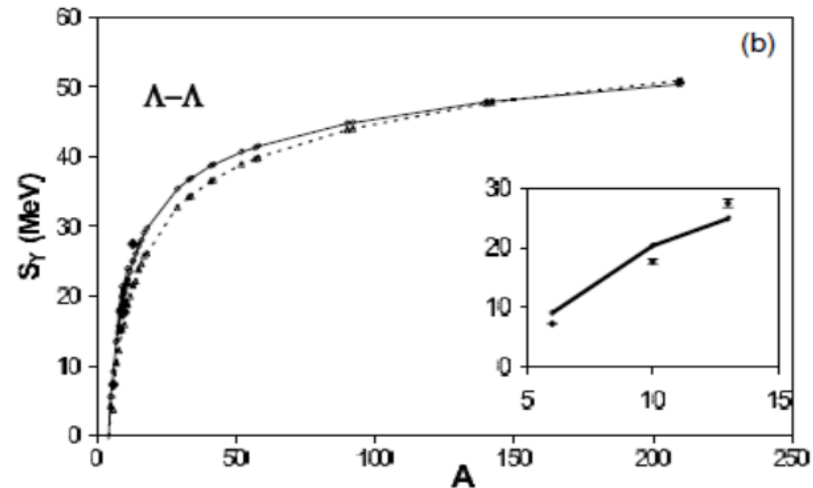
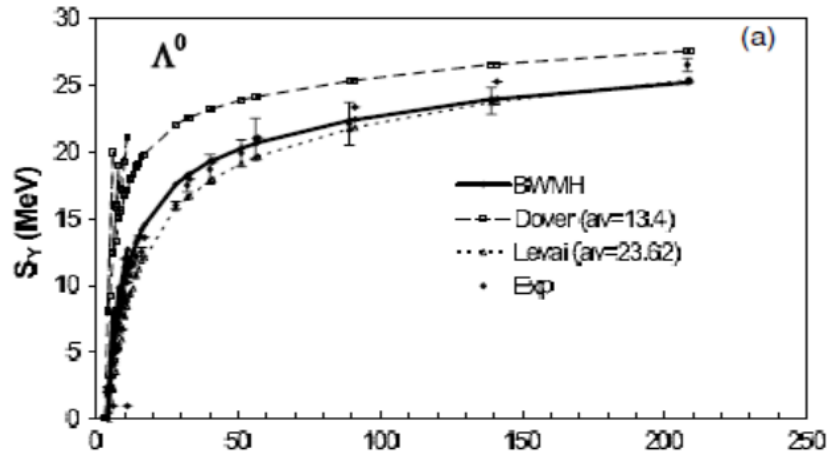
Excitation energy $E^*(Z_\nu, N_\nu, nY)$

$$= E_B(Z_\nu, N_\nu, nY) - E_{LD}(Z_\nu, N_\nu, nY)$$

The decay of excited hypernucleus is described by the GEMINI code!

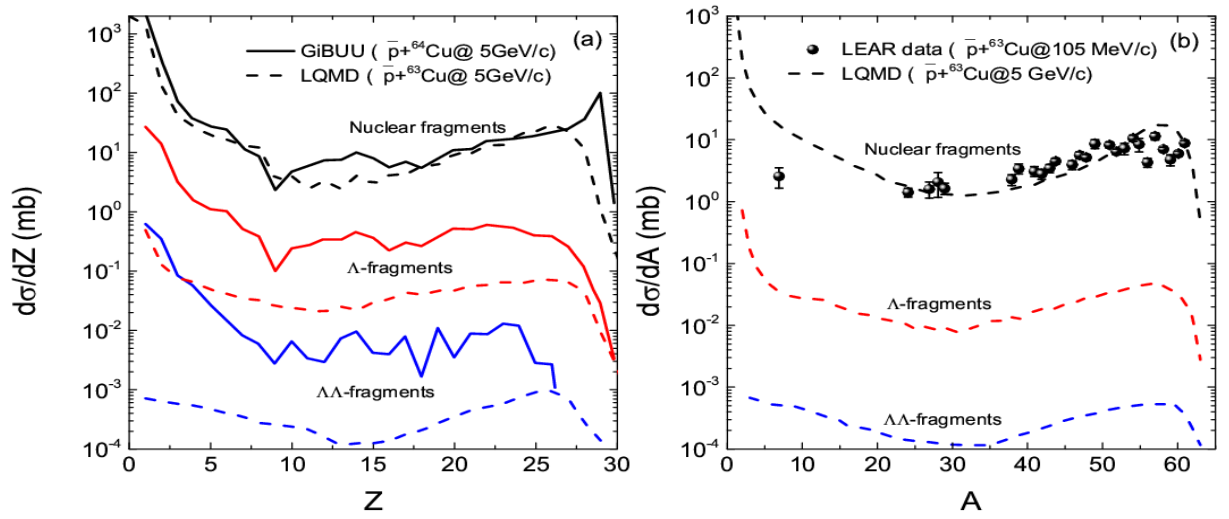
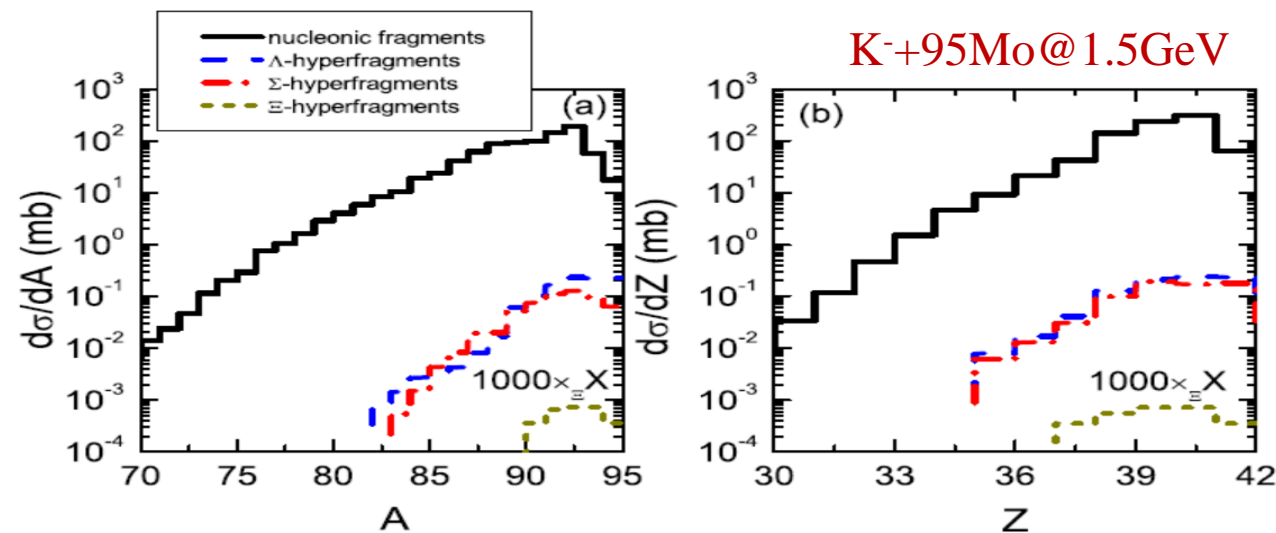
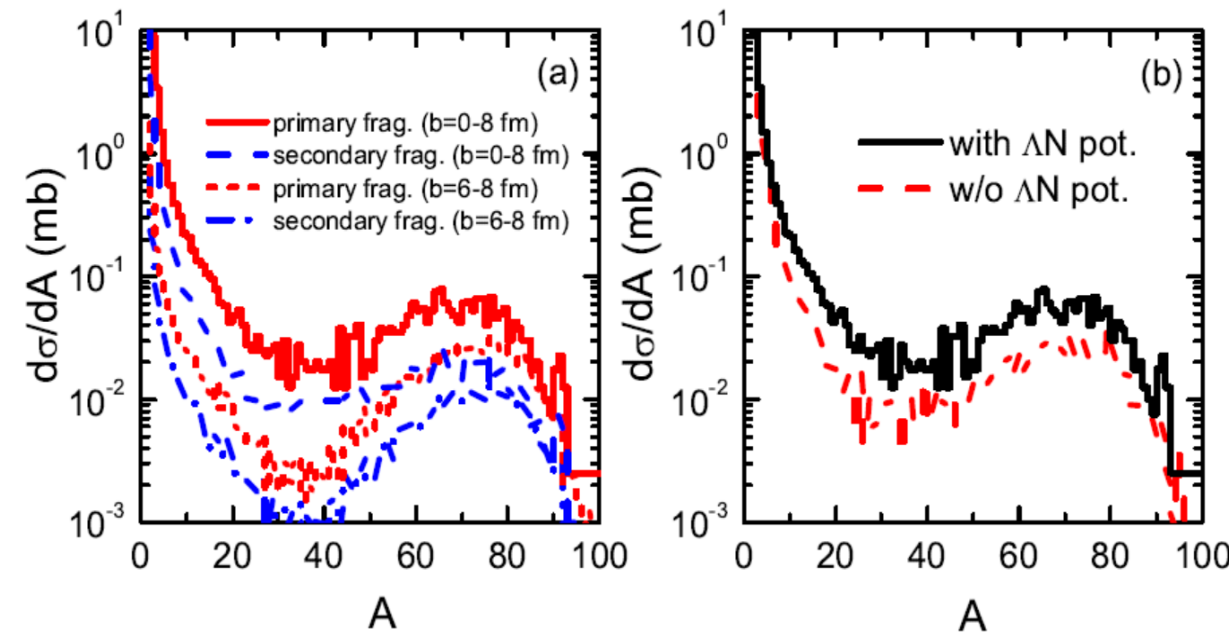
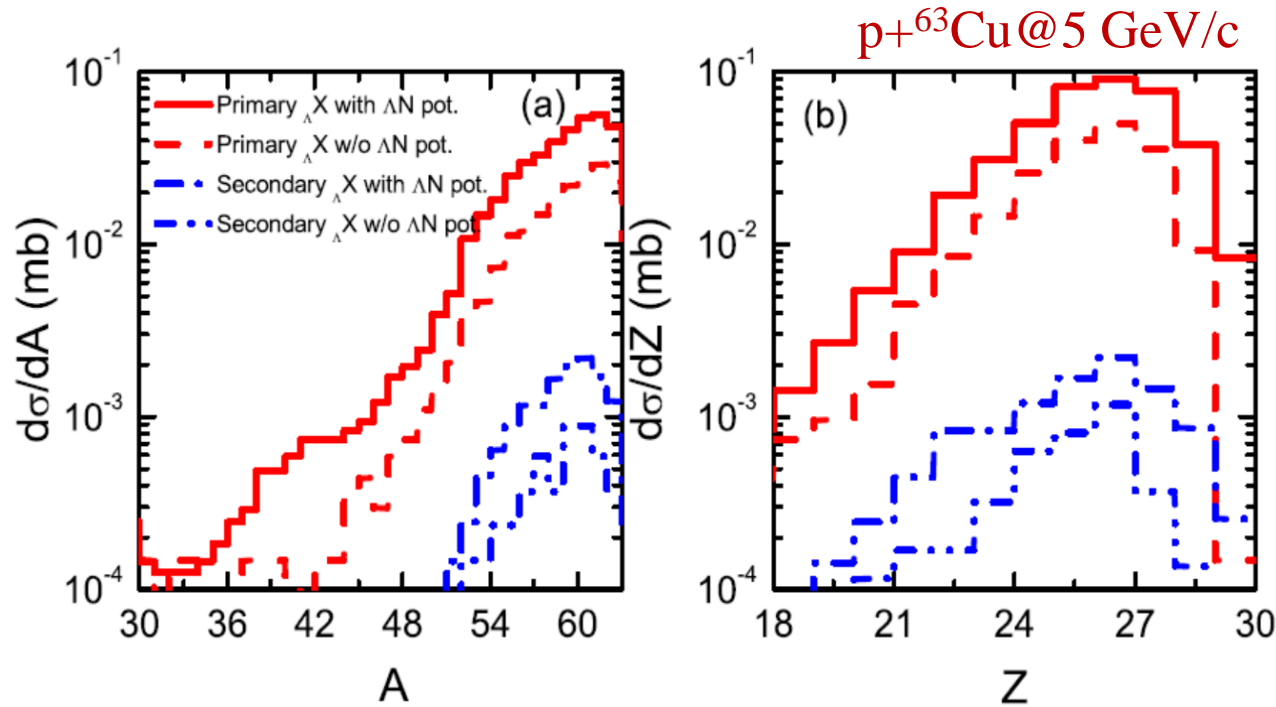
$$+ \frac{1}{2} \sum_{j,k,k \neq j} \int f_j(\mathbf{r}, \mathbf{p}, t) f_k(\mathbf{r}', \mathbf{p}', t) \times v(\mathbf{r}, \mathbf{r}', \mathbf{p}, \mathbf{p}') d\mathbf{r} d\mathbf{r}' d\mathbf{p} d\mathbf{p}'$$

$$+ \frac{1}{6} \sum_{j,k,l} \sum_{k \neq j, k \neq l, j \neq l} \int f_j(\mathbf{r}, \mathbf{p}, t) f_k(\mathbf{r}', \mathbf{p}', t) \times f_l(\mathbf{r}'', \mathbf{p}'', t) v(\mathbf{r}, \mathbf{r}', \mathbf{r}'', \mathbf{p}, \mathbf{p}', \mathbf{p}'') \times d\mathbf{r} d\mathbf{r}' d\mathbf{r}'' d\mathbf{p} d\mathbf{p}' d\mathbf{p}''$$



Influence of the statistical decay and hyperon-nucleon potential on the hyperfragment production induced by proton, K- and antiproton (Physical Review C 101, 064601 (2020); 101, 014605 (2020); 101, 064601 (2020))

$^{124}\text{Sn}+^{124}\text{Sn}@2A \text{ GeV/nucleon}$

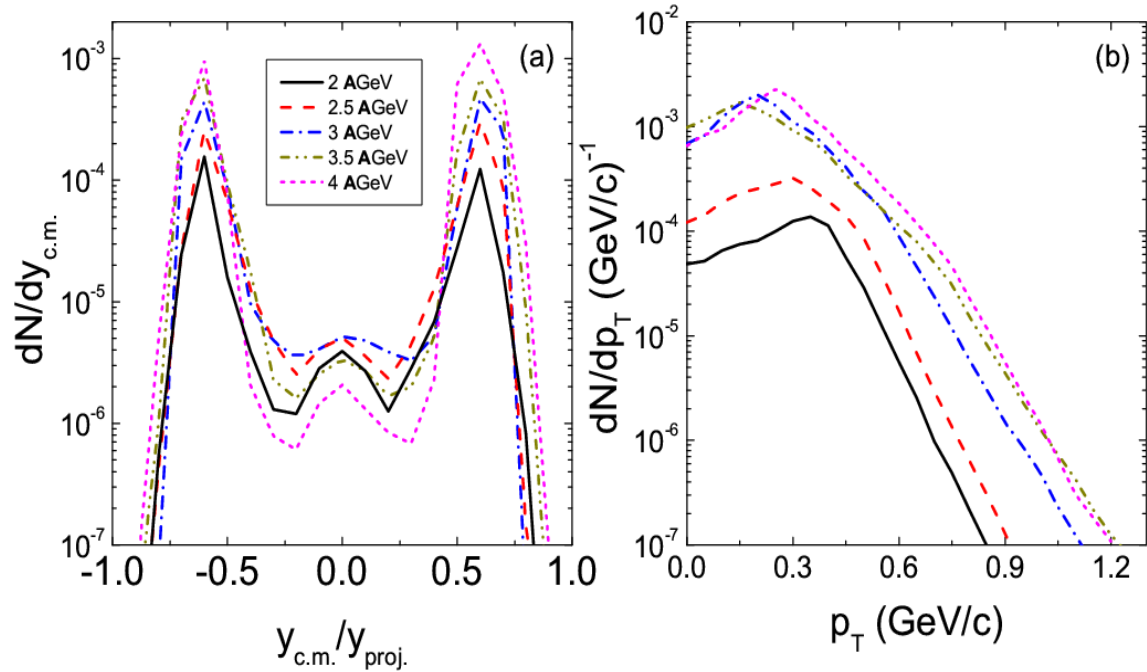


2) Wigner density approach for $Z \leq 2$

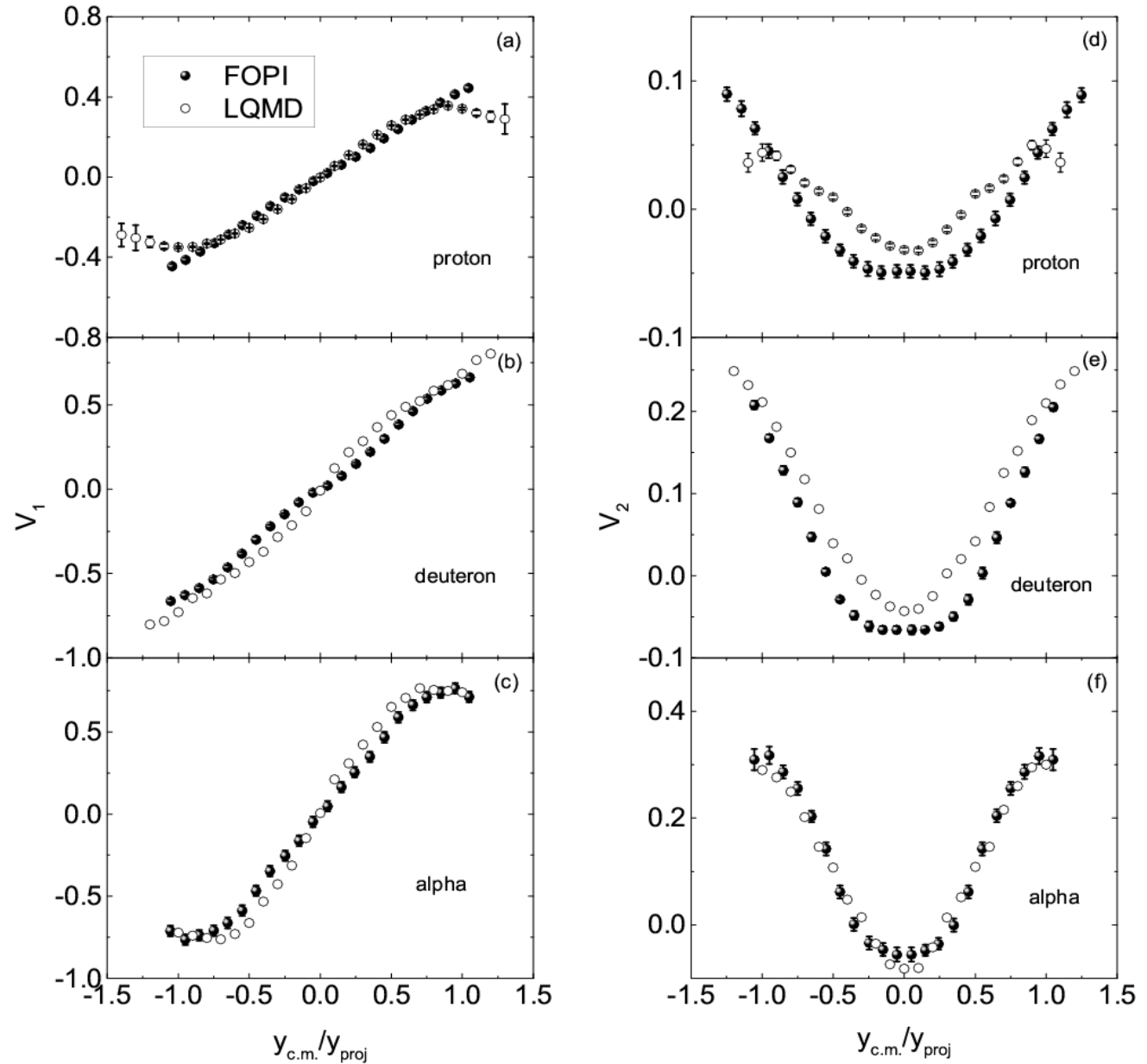
R. Mattiello et al., Phys. Rev. C 55, 1443 (1997)

$$\frac{dN_M}{d^3P} = G_M \binom{A}{M} \binom{M}{Z} \frac{1}{A^M} \int \prod_{i=1}^Z f_p(\mathbf{r}_i, \mathbf{p}_i) \prod_{i=Z+1}^M f_n(\mathbf{r}_i, \mathbf{p}_i) \times \rho^W(\mathbf{r}_{k_1}, \mathbf{p}_{k_1}, \dots, \mathbf{r}_{k_{M-1}}, \mathbf{p}_{k_{M-1}}) \delta(\mathbf{P} - (\mathbf{p}_1 + \dots + \mathbf{p}_M)) d\mathbf{r}_1 d\mathbf{p}_1 \dots d\mathbf{r}_M d\mathbf{p}_M$$

${}^3_{\Lambda}\text{H}$ via ${}^{197}\text{Au}+{}^{197}\text{Au}$



Cal: Eur. Phys. J. A, 57 (2021) 18; FOPI data, Nucl. Phys. A 876, 1 (2012)

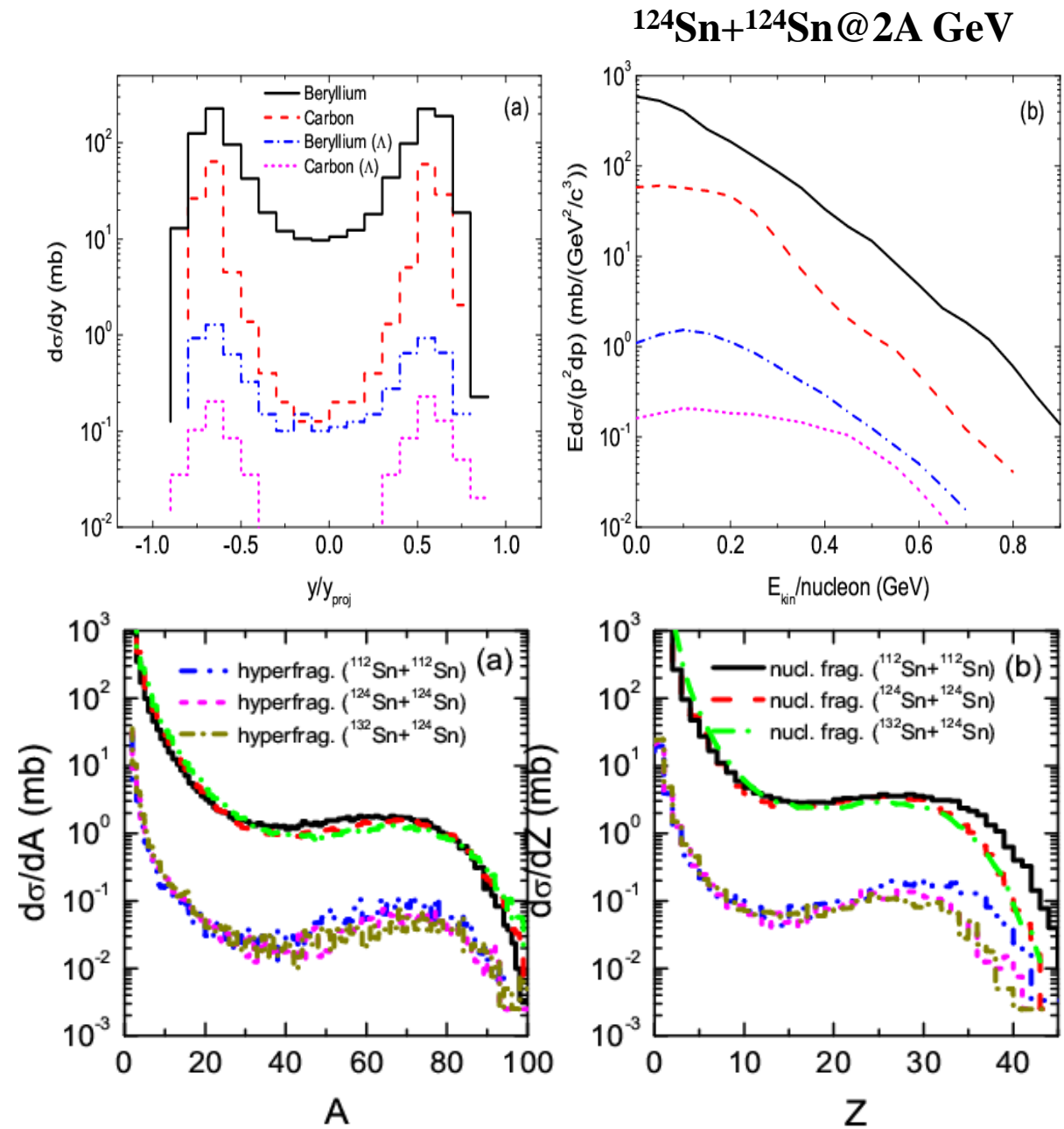
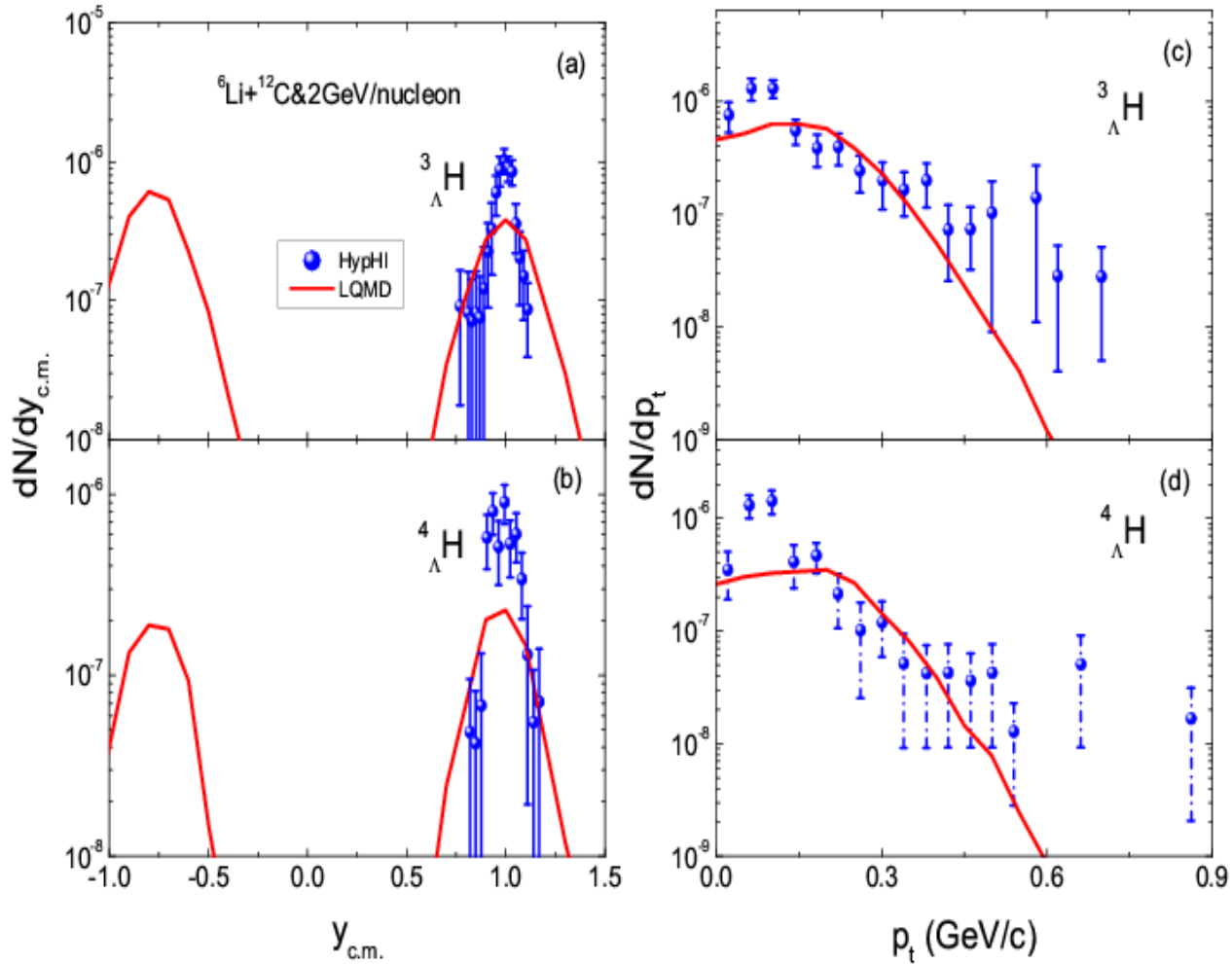


Hypernuclear dynamics in HICs

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

Data: C. Rappold et al., (HypHI collaboration)

Phys. Lett. B 747, 129 (2015).



Multi-strangeness hypernucleide production

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

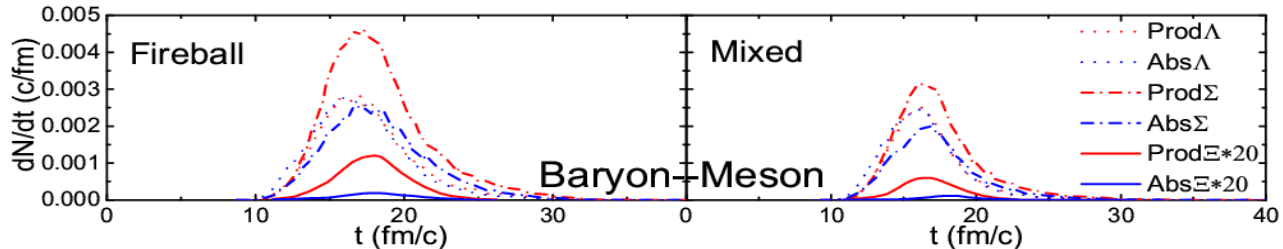
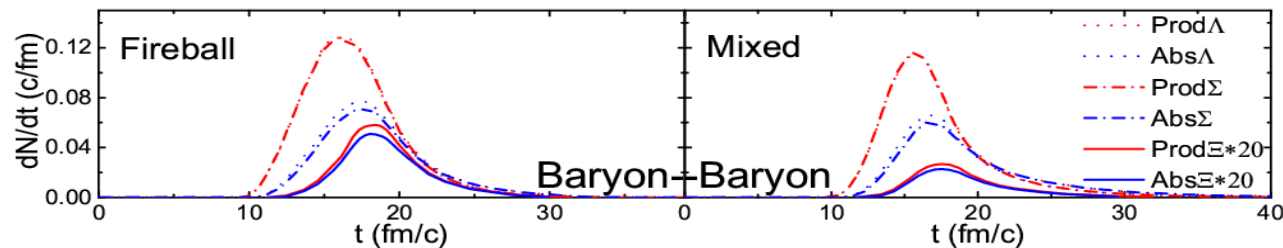
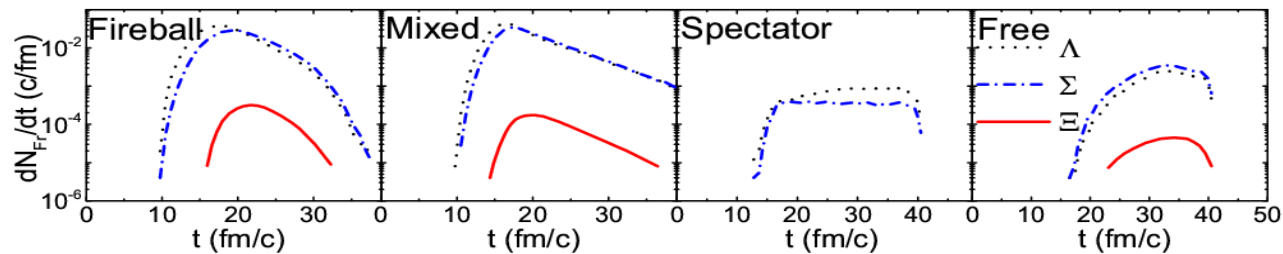
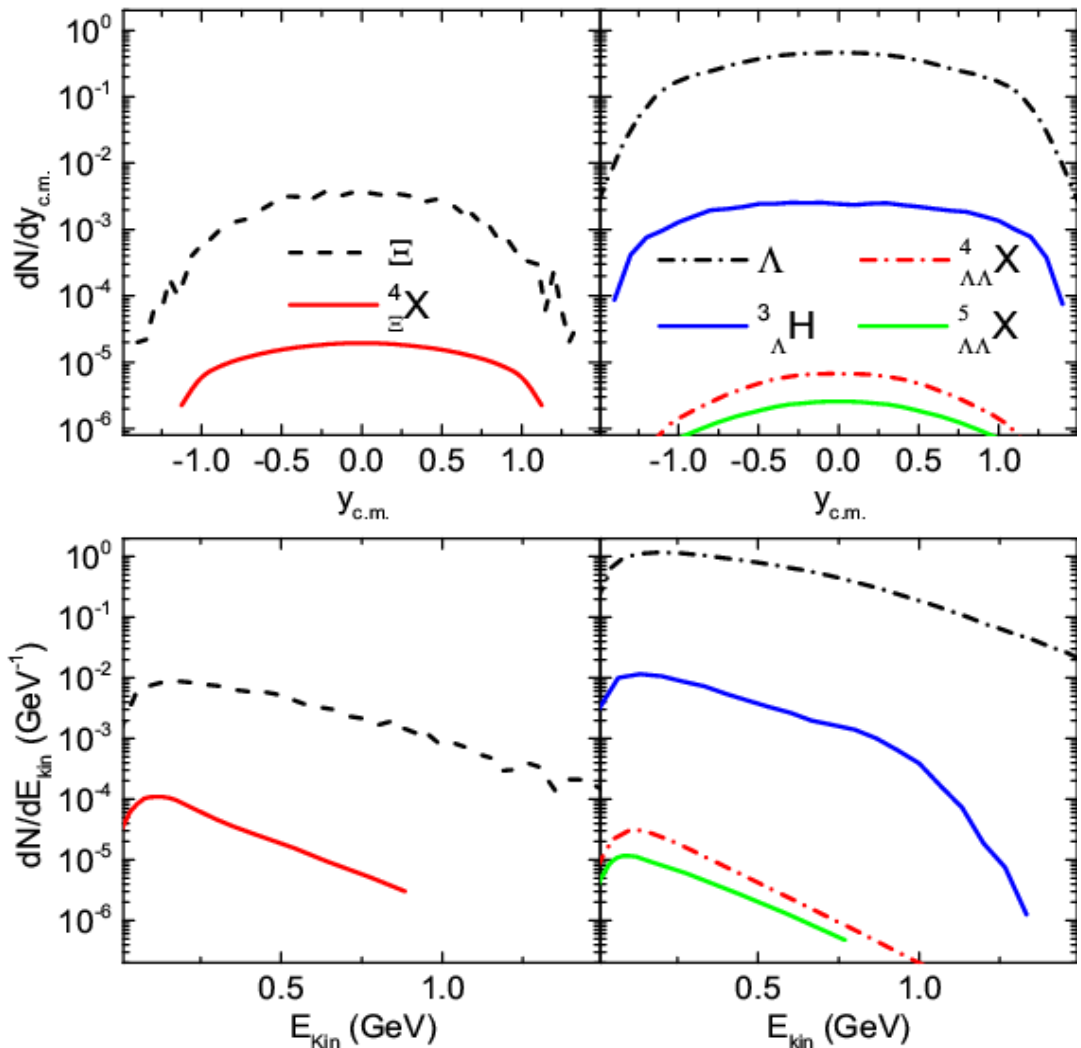
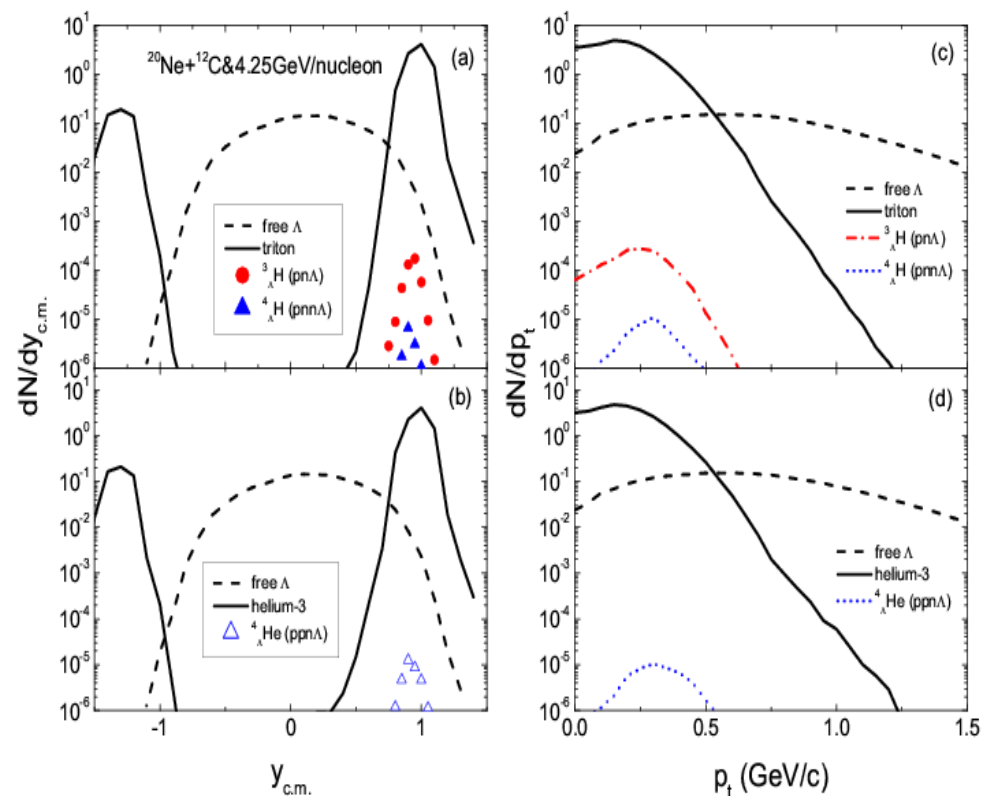


TABLE I. Comparison between cross sections of double lamda hypernuclei calculated with $r_0 = 3.5$ fm for Λ in ${}^{197}\text{Au} + {}^{197}\text{Au}$ and ${}^{40}\text{Ca} + {}^{40}\text{Ca}$ collisions at $3A$ GeV

Hypernuclei	Cross sections (mb)	
	${}^{197}\text{Au} + {}^{197}\text{Au}$	${}^{40}\text{Ca} + {}^{40}\text{Ca}$
${}^4_{\Lambda\Lambda}H$	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}	$\sim 10^{-6}$

五、总结

- 中高能重离子碰撞中奇异粒子主要是在碰撞高重子密区域产生，可以提取高密区域对称能信息
- 碰撞区域产生的超子被“旁观者”（旁观核子）俘获后形成超核，轻质量超核可以在类弹、类靶和中心快度区域产生，重质量超核只能在类弹(靶)区域产生
- 重离子碰撞可以产生极端丰中子/丰质子超核、多奇异性超核。入射能量4.25GeV/核子 $^{20}\text{Ne}+^{12}\text{C}$ 反应可以在HIAF上做超核研究测试实验
- 问题：核子-核子碰撞中涉及超子的三体和四体碰撞直接产生的超核(轻质量、高动量、奇异性，如 $nn\Lambda$, $nn\Lambda\Lambda$, ${}_{\Lambda}^5\text{H}$, ${}_{\Lambda}^6\text{H}$)还没有考虑！



谢谢大家！