Light Hypernuclei Measurements in Au+Au Collisions from STAR

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Outline

- Introduction
- Hypernuclei measurements in STAR BES-II
  - Internal structure
    - Branching ratios, lifetimes
  - Production mechanism
    - Yields, particle ratios, directed flow
- Summary and outlook
Introduction: what and why

- What are hypernuclei?
  - Bound nuclear systems of non-strange and strange baryons

- Why hypernuclei?
  - Probe hyperon-nucleon (Y-N) interaction
  - Strangeness in high density nuclear matter
    - Equation-of-State (EoS) of neutron star

Marian Danysz (right) and Jerzy Pniewski (left) discovered hypernuclei in 1952.
Introduction: how

• Experimentally, we can make measurements related to:

1. Internal structure
   • Lifetime, binding energy, branching ratios etc.

   *Understanding hypernuclei structure can provide insights to the Y-N interaction*

2. Production mechanism
   • Spectra, collectivity etc.

   *The formation of hypernuclei in violent heavy-ion collisions is not well understood*
Introduction: RHIC BES program

- During the BES-II program, STAR utilized the fixed-target (FXT) setup, which extends the energy reach below $\sqrt{s_{NN}} = 7.7$ GeV, down to 3.0 GeV.
Introduction: hypernuclei and STAR BES-II

- Hypernuclei measurements are scarce in heavy-ion collision experiments

- At low beam energies, hypernuclei production is expected to be enhanced due to high baryon density

- Datasets with large statistics taken during BES-II

→ BES-II is a great opportunity to study hypernuclei production

List of BES-II datasets:

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A. Andronic et al. PLB (2011) 697:203–207
Particle identification and hypernuclei reconstruction

- Particle identification from energy loss measurement using TPC
- KF particle package\[^1\] is used for signal reconstruction
- Hypernuclei reconstructed via their weak decay channels:
  \[ \Lambda^3_\text{H} \rightarrow ^3\text{He} + \pi^- \]
  \[ ^4\Lambda_\text{He} \rightarrow ^3\text{He} + p + \pi^- \]
  \[ ^3\Lambda_\text{He} \rightarrow ^3\text{He} + p + \pi^- \]

Hypernuclei signal reconstruction

2-body decay channels: STAR, PRL 128, 202301(2022)

- Combinatorial background estimated via:
  - Rotating pion tracks for 2-body decay channels
  - Event mixing for 3-body decay channels

![Graphs showing 2-body decay channels and 3-body decay channels]
3ΛH branching ratio $R_3$

Relative branching ratio: $R_3 = \frac{B \cdot R \cdot (3ΛH \rightarrow 3He\pi^-)}{B \cdot R \cdot (3ΛH \rightarrow 3He\pi^-) + B \cdot R \cdot (3ΛH \rightarrow dp\pi^-)}$

- Improved precision on $R_3$
- Stronger constraints on absolute B.R.s and hypertriton internal structure models

- Using $\sqrt{s_{NN}} = 3.0$ GeV data:
  - $R_3 = 0.272 \pm 0.030$(stat.) $\pm 0.042$(syst.)
  - Updated world average $R_3$ (0.32 $\pm$ 0.03) is consistent with theoretical models assuming $B_Λ \sim 0.1$ MeV

- Recent calculation shows that $R_3$ may be sensitive to the binding energy ($B_Λ$) of $3ΛH$
  - $B_Λ \rightarrow$ provide constraints to Y-N interaction

F. Hildenbrand et al. PRC 102, 064002 (2020)
Lifetime [ps]

- Lifetimes of light hypernuclei $^3\Lambda H$, $^4\Lambda H$ and $^4\Lambda He$ are shorter than that of free $\Lambda$ (with 1.8$\sigma$, 3.0$\sigma$, 1.1$\sigma$ respectively).
- Consistent with former measurements (within 2.5$\sigma$ for $^3\Lambda H$, $^4\Lambda H$).
- $\tau_{^3\Lambda H}$: consistent with calculation including pion FSI\(^{[1]}\) and calculation with $\Lambda$d 2-body picture\(^{[2]}\) within 1$\sigma$.
- $\tau_{^4\Lambda H}$ and $\tau_{^4\Lambda He}$: consistent with expectations from isospin rule.

Using $\sqrt{s_{NN}} = 3.0$ GeV and 7.2 GeV datasets:

- $^3\Lambda H$: $\tau = 221 \pm 15$ (stat.) $\pm 19$ (syst.) [ps]
- $^4\Lambda H$: $\tau = 218 \pm 6$ (stat.) $\pm 13$ (syst.) [ps]
- $^4\Lambda He$: $\tau = 229 \pm 23$ (stat.) $\pm 20$ (syst.) [ps]

$^3\Lambda H$, $^4\Lambda H$ and $^4\Lambda He$ results with improved precision

→ Provide tighter constraints on models.

\([1]\) A. Gal and H. Garcilazo, PLB 791, 48 (2019)
Hypernuclei production at 3 GeV

• Different trends in the $^4\Lambda$H rapidity distribution in central (0-10%) and mid-central (10-50%) collisions at $\sqrt{s_{NN}} = 3.0$ GeV

• Transport model (JAM) with coalescence approximately reproduces trends of $^4\Lambda$H rapidity distributions seen in data
$^3\Lambda H$ and $^4\Lambda H$ directed flow at 3 GeV

- First measurements of $^3\Lambda H$ and $^4\Lambda H$ directed flow ($v_1$) in 5-40% central Au+Au collisions at 3 GeV
- $v_1$ slopes of $^3\Lambda H$ and $^4\Lambda H$ follow mass number scaling.

→ Imply coalescence process to be the dominant formation mechanism for hypernuclei in heavy-ion collisions

To be submitted to arXiv soon
Energy dependence of hypernuclei production in heavy-ion collisions

- $^3\Lambda^3H$ yield at mid-rapidity increases from 2.76 TeV to 3 GeV
- Driven by increase in baryon density at low energies
- Thermal(GSI), Coalescence(UrQMD), Thermal-FIST and PHQMD reproduce the trend

For Au+Au @ 3 GeV
- Coalescence(JAM) with tuned coalescence parameters can describe data
- PHQMD describes $^4\Lambda^4H$, but slightly overestimates $^3\Lambda^3H$

Provide first constraints for hypernuclei production models in the high-baryon-density region

Y. Nara et al, PRC 61 (1999) 024901 (JAM)
S. Gläßel et al, arXiv: 2106.14839 (PHQMD)
A. Andronic et al, PLB 697 (2011) 203 (Thermal (GSI))

STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360
• Suppression of $^{3}_\Lambda H/^{3}He$ yield ratios compared to that of $\Lambda/p$
  • Observed at both 0-10% and 10-40% centrality in Au+Au collisions at 3 GeV.

• The $^{4}_\Lambda H/^{4}He$ yield ratios are comparable to that of $\Lambda/p$

• Thermal model calculations including excited $^{4}_\Lambda H^*$ feed-down show a similar trend
  • Feed-down from excited state enhances $^{4}_\Lambda H$ production

• Support creation of excited A=4 hypernuclei in heavy-ion collisions
Strangeness population factor $S_A$

- Relative suppression of hypernuclei production compared to light nuclei production

$$S_A = \frac{\frac{\Lambda H}{^3\text{He}}}{\frac{\Lambda}{p}} = \frac{B_A(\Lambda H)(p_T)}{B_A(^3\text{He})(p_T)}$$

  - $B_A$: Coalescence parameters
  - Expect ~1 if no suppression

$S_3 < 1 \rightarrow$ relative suppression of $^3\Lambda$H to $^3$He

$S_4 > S_3 \rightarrow$ enhanced $^4\Lambda$H production due to feed-down from excited state

No obvious kinematic and centrality dependence of $S_A$ is observed at 3 GeV.

$\rightarrow$ Coalescence parameter $B_A$ of $^4\Lambda$H and $^4$He follows similar tendency versus $p_T$, rapidity and centrality.
Energy dependence of $S_3$

- Data shows a hint of an increasing trend from $\sqrt{s_{NN}} = 3.0$ GeV to 2.76 TeV.
- For coalescence models, the energy dependence is sensitive to the source radius ($\Delta r$).
- Thermal-FIST describes the $S_3$ data reasonably well.

References:

- STAR, Science 328 (2010) 58
- ALICE, PLB 754 (2016) 360
- E864, PRC 70 (2004) 024902
- A. Andronic et al, PLB 697 (2011) 203 (Thermal (GSI))
- S. Zhang, PLB 684(2010)224 (Coal.+AMPT)
Summary

Presented measurements on hypernuclei production in the high-baryon-density region with high statistical precision using STAR data

- **Hypernuclei structure**
  - $^3\Lambda H$, $^4\Lambda H$ lifetimes and $R_3$ of $^3\Lambda H$ measured with improved precision
    - Strong constraints on hyperon-nucleon interaction models

- **Hypernuclei production in heavy-ion collisions**
  - $^3\Lambda H$, $^4\Lambda H$ production yields at 3.0, 19.6 and 27 GeV
    - Coalescence models approximately describe the trends of $^4\Lambda H$ rapidity distribution
    - $S_3$ and $S_4$ show weak centrality/kinematic dependence
    - Energy dependence of $^3\Lambda H$, $^4\Lambda H$ yields and $S_3$ compared with models are shown
    - Provide constraints to hypernuclei production models
  - $^3\Lambda H$ and $^4\Lambda H$ collectivity $v_1$
    - $v_1$ slopes follow mass number scaling -> Support coalescence picture
Outlook

1. ITPC and eToF fully installed in 2019 → improve $\eta$ acceptance and PID at large $\eta$
2. High statistics data in STAR BES-II $\sqrt{s_{NN}} = 3.0 - 54.4$ GeV, especially the 2 billion events collected at 3 GeV in 2021 → larger statistics, higher precision

- Precision measurements on hypernuclei properties
- Energy dependence study of hypernuclei yields
- Search for double $\Lambda$ hypernuclei
  - e.g. $^4\Lambda\Lambda$He$\rightarrow^4\Lambda$He$\pi$, $^5\Lambda\Lambda$He$\rightarrow^5\Lambda$He$\pi$

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STAR, PRL 128, 202301(2022)
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Thank you!
Backup slides
### Analysis Details: Reconstruction via 3-body Decay

- **Counts**
  - 0.002
  - 0.004
  - 0.006
  - 0.008
  - 0.012

**Background, estimated via kinematically correlated SE-ME signals contains real signal and contamination correlated backgrounds.**

1. Subtract uncorrelated 0.01

2. Excess around hypertriton peak contains real signal: lower contamination correlated backgrounds.

3. Correct for efficiency of real signal:
   
   \( f_{\Lambda d} \) and \( f_{3^1\Lambda H} \), and reconstructed signal \( f_{Data} \)

### Methodology

- **Signal Reconstruction**
  - Particle packaged is used to improve significance.

- **Purity** estimated via template fit to secondary vertex fit.

- **Star Preliminary**
  - Purity: the fraction of real \( \Lambda + d \) in \( \Lambda \rightarrow p\pi^- \)

### Data

- **Counts**
  - 0.002
  - 0.004
  - 0.006
  - 0.008
  - 0.012

**Data/Fit**

- Estimation of \( ^3\Lambda H \) purity in signals

- Normalized \( \chi^2_{NDF} \) distribution of \( \Lambda + d \) and \( ^3\Lambda H \) template from MC
  - \( f_{\Lambda d} \) and \( f_{3^1\Lambda H} \), and reconstructed signal \( f_{Data} \)

- Purity: the fraction of real \( ^3\Lambda H \) signals \( f_{3^1\Lambda H} \) in signals \( f_{Data} \) from fitting

\[
 f_{Data} = p_0 f_{\Lambda d} + p_1 f_{3^1\Lambda H} 
\]
• Lifetime $\tau$ extracted via $N(t) = N_0 e^{-L/\beta \gamma c \tau}$

• $\Lambda$ lifetime cross check: 267±4 ps, consistent with PDG value (263±2 ps)

• $^3\Lambda H$ and $^4\Lambda H$ lifetimes from 3.0 GeV consistent with 7.2 GeV results
Hyper-to-light nuclei ratios

- Thermal/coalescence models predict approx. exponential dependence of yields/(2J+1) vs A
- $^{4}_\Lambda$H lies a factor of 6 above exponential fit to ($\Lambda$, $^{3}_\Lambda$H, $^{4}_\Lambda$H)
- Non-monotonic behavior in light-to-hyper-nuclei ratio vs A observed
  - Thermal model calculations including excited $^{4}_\Lambda$H* feed-down shows a similar trend

A. Andronic et al, PLB 697 (2011) 203 (Thermal model)

- Non-existence of bound $^{3}_\Lambda$H* (J$^+$=3/2)
- Data support creation of unstable A =4 hypernuclei from heavy-ion collisions