Strange Hadron Production in Au+Au Collisions at RHIC Beam Energy Scan

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Outline

• Introduction

• STAR Fixed Target (FXT)

• Results of strange hadron production
  • $p_T$ spectra
  • Rapidity distribution
  • Yield ratio
  • Kinetic freeze-out properties

• Summary
Introduction

• RHIC BES covers a wide region of baryon density
  - Look for the onset of de-confinement, phase boundary, and location of possible critical point

• STAR FXT mode $\sqrt{s_{NN}} = (3.0 - 7.7) \text{ GeV}$
  - High baryon chemical potential $\mu_B$ ($\sim 400 \text{ MeV up to } \sim 750 \text{ MeV}$) allows us to study the properties of high baryon density matter
  - Strangeness can be used to study medium properties at low collision energies
FXT setup at STAR

- Target was installed at the edge of TPC
- 260M events for Au+Au FXT at $\sqrt{s_{NN}} = 3$ GeV (year 2018)
- Good mid-rapidity coverage

Conventions:
beam-going direction is the positive direction
In C.M. frame, $y_{target} = -1.045$ for the 3 GeV collisions

Beam pipe
Au-Target = 0.25mm thickness
1% interaction probability

Target was installed at the edge of TPC
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Particle identification and reconstruction

- TPC (dE/dx) and TOF (β) for pion, kaon and proton identification
- Reconstruct the short-lived particle $\Xi^-$, $\phi$, $\Lambda$, $K^0_S$ via a hadronic decay channel
  - $\phi \to K^+K^-$, $\Xi^- \to \Lambda(p\pi^-) + \pi^-$,
  - $K^0_S \to \pi^+\pi^-$
- KF Particle package is used to improve the signal significance
- The combinatorial background is reconstructed by the rotation method

Efficiency corrected $p_T$ spectra

- Tracking efficiency and detector acceptance are estimated with GEANT simulations embedded into real events

- $\Lambda$ and $K_S^0$ invariant yields in 0-10% centrality for various rapidity regions

- Low $p_T$ extrapolation: Blast-Wave function

$$\frac{d^2N}{2\pi p_T dp_T dy} = A \int_0^R r dr m_T \times I_0 \left( \frac{p_T \sinh \rho(r)}{T_{kin}} \right) K_1 \left( \frac{m_T p \cosh \rho(r)}{T_{kin}} \right)$$

$T_{kin}$: the kinetic freeze-out temperature

$\langle \beta_T \rangle$: average transverse radial flow velocity

$n$: the exponent of flow velocity profile, $n=1$

$I_0$ and $K_1$ are from Bjorken Hydrodynamic assumption

- Alternative fit functions are used in order to estimate the systematic uncertainty in dN/dy
Centrality and rapidity dependence of yields

- Rapidity dependent yields obtained from integrating data and Blast-wave function (or $m_T$ exponential function) fits of spectra for the unmeasured region
  - $y_{cm}$ range will be extended by eTOF & iTPC upgrade

- UrQMD reproduces the yields of $\Lambda$ except in the 40-60% centrality bin, but overestimates Kaons, $\Xi^-$ and underestimates $\phi$ mesons
Enhanced production of $\Lambda$ at mid-rapidity compared to target rapidity
UrQMD model underpredicts those ratios but can describe the trend of the data
Comparison with hypernuclei to light nuclei ratios help us gain insight into hypernuclei and light nuclei production mechanisms

See talk from Yuanjing Ji, Jun 14, 2022, 11:30 AM
Strangeness production vs $\langle N_{\text{Part}} \rangle$

- Universal centrality dependence of strangeness production
  - Increase with centrality
  - Strangeness yield ($K^-$, $K^0_S$, $\phi$, $\Lambda$) $\propto \langle N_{\text{Part}} \rangle^\alpha$, $\alpha = 1.42 \pm 0.04$

- $\Xi^-$ seems to deviate from the scaling trend
  - $\Xi^-$ is different from other hadrons due to its multi-strange-quark content and sub-threshold production

- Proton has a different trend

\[ K^0_S \sqrt{s_{\text{NN}}} \sim 2.55 \text{ GeV} \]
\[ \Lambda \sqrt{s_{\text{NN}}} \sim 2.55 \text{ GeV} \]
\[ \phi \sqrt{s_{\text{NN}}} \sim 2.89 \text{ GeV} \]
\[ \Xi \sqrt{s_{\text{NN}}} \sim 3.25 \text{ GeV} \]
• STAR FXT dN/dy consistent with the $\Lambda, K_S^0$ trends demonstrated by published data

• First sub-threshold $\Xi^-$ measurement in Au+Au collisions

• Expect more results at low energies from additional high statistics BES II data sets
Particle ratios vs $\sqrt{s_{NN}}$

- Local strangeness conservation is required!
  - $\rightarrow$ GCE to CE transition!

- Default UrQMD failed to describe the measurement at low energies

- Transport models with high-mass resonance decay to $\phi$ and $\Xi^{-}$ (modified UrQMD and SMASH) can reasonably describe data at low energies

UrQMD$^1$: the public version
UrQMD$^2$: the modified version

$r_c$: correlation length, radius of the volume inside which the production of particles with open strangeness is canonically conserved

Data compilation:
Kinetic freeze-out properties

- Kinetic freeze-out temperature ($T_{\text{kin}}$) of $\Lambda$ is systematically higher than that of $K_S^0$ at 3 GeV
- $T_{\text{kin}}$ of $\Lambda$ and $K_S^0$ at 3 GeV is lower than $\pi, K, p$ at higher energy collisions
  ➞ Similar observations for protons and deuterons, implying different EOS at freeze-out
Summary

• Presented measurements on strangeness production in 3 GeV Au+Au collisions
  - Precise centrality & rapidity dependence of yields
  - $\phi/K^-$ and $\phi/\Xi^-$ show a strong effect of canonical suppression
  - $\Lambda$ and $K_S^0$ spectra indicate lower kinetic freeze-out temperature than $\pi, K, p$ at higher energy collisions

• At 3 GeV, the measured $\nu_2$ for all particles are negative and the NCQ scaling breaks, especially for positive charged particles

• The suppression of $C_4/C_2$ is consistent with fluctuations driven by baryon number conservation which indicates a hadronic interaction dominated region in the top 5% central Au+Au collisions at 3 GeV

• The freeze-out parameter ($T_{kin}$) of deuteron is systematically higher than that of proton at 3 GeV, which is different from higher energies

All results from 3 GeV Au+Au collisions: particle production mechanism dominated by hadronic interactions
Successful Operation of STAR in Years 2020-21

Run 20 and 21 completed successfully: enhanced collision rates due to Low Energy RHIC Electron Cooling (LEReC) system, smooth & desired performance of BES-II upgrades (iTPC, eTOF, EPD)

RHIC Beam Energy Scan II completed, p+p √s = 510 run with fully installed forward upgrade is ongoing

https://online.star.bnl.gov/aggregator/livedisplay/

Watch Live Collisions At STAR:
- 7 energies between 7.7 - 27 GeV (collider mode)
- 12 energies between 3.0 - 13.7 GeV (FXT mode)

Early completion of BES-II data taking allowed O+O & d+Au runs in 2021

Year 2021
- Au+Au √s = 7.7 GeV

Achieved

Projected

Goal

### Outlook

- Strange hadron yields together with π, K, p will be used for chemical equilibrium models to determine $T_{chem}$ and $\mu_B$
- High statistics data in STAR BES II $\sqrt{s_{NN}} = 3 - 27$ GeV, iTPC+eTOF
  - Extract freeze-out parameters
  - Analyze baryon correlation functions
  - Analyze hyper-nuclei production and collectivity
  - And more …

- See poster from Sameer Aslam, Jun 14, 2022, 5:10 PM