Beam Energy Dependence of Strange Hadron Production from STAR at RHIC

Xiaoping Zhang (Tsinghua University)

For the STAR Collaboration

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Outline

- Motivation for strangeness production measurement in STAR Beam Energy Scan (BES)
- Strangeness (K$^\pm$, K$_S^0$, $\phi$, $\Lambda$, $\Xi$, $\Omega$) production at mid-rapidity
  - $p_T$ spectra
  - Particle yields and ratios
  - Mean transverse kinetic energy: $<m_T> - m_0$
  - Central-to-peripheral nuclear modification factor: $R_{CP}$
  - Baryon enhancement: $\Omega/\phi$
- Summary
Motivation: study QCD phase diagram

- Beam Energy Scan at RHIC
  - Look for onset of de-confinement, phase boundary and critical point
  - Systematic study of Au+Au collisions at 7.7, 11.5, 19.6, 27, 39, 62.4 GeV

- Key observables on de-confinement
  1. Strangeness enhancement
  2. Baryon/meson ratio
  3. Nuclear modification factor
     - Partonic energy loss & recombination

STAR, arXiv:1007.2613; NA49, PRC78, 034918
Collisions: Au+Au
Collisions centrality from uncorrected $dN_{\text{ch}}/d\eta$ in $|\eta| < 0.5$

| $\sqrt{s_{NN}}$ (GeV) | Good MB events in Million |
|----------------------|---------------------------|
| 7.7                  | ~ 4 M                     |
| 11.5                 | ~ 12 M                    |
| 19.6                 | ~ 36 M                    |
| 27                   | ~ 70 M                    |
| 39                   | ~ 130 M                   |
| 62.4                 | ~ 67 M                    |
Particle identification and reconstruction

- dE/dx+TOF: $\pi$, $K$, $p$ and $\phi \rightarrow K^+ + K^-$ (invariant mass)
- Weak decay particles ($K^0_S$, $\Lambda$, $\Xi$, $\Omega$), secondary vertex + invariant mass
Extensive strange particle spectra

- $\Lambda(\bar{\Lambda})$ spectra are weak decay feed-down corrected
- $\sim 20\%$ for $\Lambda$; $\sim 25\%$ for $\bar{\Lambda}$
The NA57 and NA49 yields have been scaled by the corresponding number of wounded nucleons, **STAR results closer to NA49**

- **Lambda** yields show dip at 39 GeV. Why? the baryon stopping at mid-rapidity may decrease with increasing energy

- **Central collisions**

- **Mid-rapidity**

  - NA49, PRC78,034918. 7% or 10% most central. (|y|<0.4 or 0.5)

  - NA57, PLB595,68; JPG32, 427 0-4.5% most central, |y|<0.5, stat. err. only

  - STAR, PRL86,89,92,98; PRC83 0-5% most central, |y|<0.5
The image contains graphs showing the centrality dependence of $\bar{B}/B$ ratios: peripheral > central. This effect is more prominent at lower energies. Baryon stopping and absorption are also discussed. There is also a mention of the loss of low $p_T$ $\bar{\Lambda}$ in central collisions.
Excitation function of $\bar{B}/B$ ratios

- STAR BES data lie in a trend with NA49 data
- $\bar{B}/B$ ratios increase with number of strange quarks at low energies
- $\bar{\Omega}^+/\Omega^- > \bar{\Xi}^+/\Xi^- > \bar{\Lambda}/\Lambda$: pair production v.s. baryon transport & associated production

Left: Solid red: STAR BES; Solid blue: STAR published; Open blue: NA49

Statistical + systematical error
Particle ratios

- Central, mid-rapidity
- Particle ratios consistent with NA49, consistent with the picture of a maximum net-baryon density around $\sqrt{s_{NN}} \sim 8$ GeV at freeze-out
- Associate production channels like $N + N \rightarrow N + \Lambda + K^+$ may be important for $K^+$ production, N is nucleon

J. Randrup et al., PRC 74, 047901 (2006)

![Graphs of Particle Ratios](image-url)
Particle ratios

- Clear $K^-$, $\Lambda$, $\Xi^+$ yield enhancement compared to pions with increasing collision energy
- Similar behavior for hidden strangeness $\phi(s\bar{s})$
- New scaling for $\phi/\pi$ v.s. $\sim$ total collision energy, system size insensitive, initial production seems important for $\phi$

Statistical + systematical error
New scaling on yields

φ mesons follow total participant nucleons energy scaling

K⁻ yield is lower than expected from the scaling in low beam energies

φ(s¯s): hidden strangeness

K⁻ (¯u s): open strangeness

Absorption of K⁻? no significant centrality dependence

Strangeness quark pairs (s¯s) correlation scenario, “K⁻ is suppressed compared to φ meson at small phase space”, qualitatively consistent

Redlich et al: Phys. Lett. B 603, 146 (2004)
Beam energy dependence of $<m_T>-m_0$

- For heavy strange hadrons $\phi$, $\Lambda$, $\Xi$, $<m_T>-m_0$ show increasing trend with energy, mass matters
- $\Lambda$, $\Xi$: Solid red, STAR BES, 0-5% most central, statistical error only
- Solid blue, STAR published, most central, PRL 89, 092301; PRL 92, 182301. Open, NA49, most central, from NA49, PRC 78, 034918
- $\phi$ meson, statistical error

From L. Van Hove
Nuclear modification factors $R_{CP}$

- No $K_S^0$ suppression in Au+Au 7.7 and 11.5 GeV
- Cronin effect takes over partonic rescatterings @ lower energies
- Intermediate $p_T$, particle $R_{CP}$ difference becomes smaller @ 7.7 and 11.5 GeV

$R_{CP}(p_T) = \frac{[d^2\sigma/(N_{bin}dp_Tdp_Tdy)]_{central}}{[d^2\sigma/(N_{bin}dp_Tdp_Tdy)]_{peripheral}}$

$\phi$ meson $R_{CP}$: 0-10%/40%-60%

- $38.8$ GeV
- $27.4$ GeV
\( \Omega/\phi \) ratio

- **\( \Omega \) and \( \phi \) \( p_T \) distribution is sensitive to strange quark thermalization and recombination.** Intermediate \( p_T \) \( \Omega \) yield enhancement is explained by mainly thermal \( s \) quark recombination @ Au+Au 200 GeV

- **Intermediate \( p_T \) \( \Omega/\phi \) ratios: clear separation between \( \geq 19.6 \) and 11.5 GeV** (probability of same ratios in \( p_T \) 0.8—3.6 GeV/c: 11.5 & 19.6 GeV: \( 8.6 \times 10^{-5} \); 19.6 & 27 GeV: 0.50; preliminary systematical error included)

- **Change of \( \Omega \) production mechanism?** parton recombination fails at 11.5 GeV?
Summary

- Measurements of strange hadron production in $\sqrt{s_{\text{NN}}} = 7.7 - 39$ GeV
- Particle yields and ratios are consistent with the picture of a maximum net-baryon density around $\sqrt{s_{\text{NN}}} \sim 8$ GeV at freeze-out, baryon transport to mid-rapidity is important
- Clear $K^-$, $\phi$, $\Lambda$, $\Xi^+$ yield enhancement compared to pions with increasing collision energy
- The evolution of $K^-$ and $\phi$ meson yields v.s. system size and collision energies is qualitatively consistent with strange quark pair ($s\bar{s}$) correlation scenario
- Intermediate $p_T$ $\Omega/\phi$ ratios and nuclear modification factors show clear separation between 200 — 19.6 GeV and below 11.5 GeV, phase transition?
Backup
Different strangeness production scenarios

- Canonical statistical model: “$\phi$ is more suppressed than $K^-$ at small phase space”

- Strangeness quark pairs ($s\bar{s}$) correlation, radius $R_C$: $2.2 - 4.2$ fm
  “$K^-$ is more suppressed than $\phi$ at small phase space”

HADES: Phys. Rev. C 80, 025209 (2009)   E917: Phys. Rev. C 69, 054901 (2004)
NA49: Phys. Rev. C 78, 044907 (2008)   STAR 62.4, 130 & 200 GeV: Phys. Rev. C 79, 064903 (2009)
Thermal model-PBM: Nucl. Phys. A 772, 167 (2006)
Redlich model: Phys. Lett. B 603, 146 (2004)

Statistical + systematical error
Au+Au 19.6 GeV spectra

$K^0_S$ spectra, Au+Au 19.6 GeV

$\Lambda$ spectra, Au+Au 19.6 GeV

$\Xi$ spectra, Au+Au 19.6 GeV

$\Omega$ spectra, Au+Au 19.6 GeV

$K^0_S$ spectra, Au+Au 19.6 GeV

$\Lambda$ spectra, Au+Au 19.6 GeV

$\Xi$ spectra, Au+Au 19.6 GeV

$\Omega$ spectra, Au+Au 19.6 GeV

$\Xi$ spectra, Au+Au 19.6 GeV

$\Omega$ spectra, Au+Au 19.6 GeV
Au+Au 27 GeV spectra

K^0_s spectra, Au+Au 27 GeV

Λ spectra, Au+Au 27 GeV

Ξ^- spectra, Au+Au 27 GeV

Ω^- spectra, Au+Au 27 GeV

K^0_s spectrum, STAR Preliminary

Λ spectrum, STAR Preliminary

Ξ^- spectrum, STAR Preliminary

Ω^- spectrum, STAR Preliminary

Φ spectrum, Au+Au 27 GeV

Λ̄ spectrum, Au+Au 27 GeV

Ξ^+ spectrum, Au+Au 27 GeV

Ω^+ spectrum, Au+Au 27 GeV

STAR Preliminary
Mean transverse kinetic energy

- Statistical error only!
- $\langle m_T \rangle - m_0$ increases as the increase of centrality
- $\bar{\Lambda}$: abnormal increase of $\langle m_T \rangle - m_0$ versus centrality at Au+Au 7.7 GeV
Centrality dependence of $\bar{B}/B$ ratios: peripheral > central

This effect is more prominent at lower energies, more baryon transport to mid-rapidity, absorption?
Strange baryon/meson ratios

- Mid-\(p_T\) ratios get higher at lower energy
  More baryon stopping?

- Centrality dependence for Au+Au 39 GeV
  Breaks at lower energies?
Strange baryon/meson ratios

- Mid-$p_T$ ratios get lower at lower energies
- Ratios still rise from low to mid-$p_T$ at lower energies
Multi-strange hadrons?

**partonic**

**hadronic**

J/ψ, Ω, φ

π, K, p

time

Multi-strange hadrons

➢ Small hadronic cross sections, freeze-out early

STAR, Nucl. Phys. A 757 (2005) 102