Strangeness and LF at intermediate baryon density
(RHIC BES + SPS)

Xianglei Zhu
Tsinghua University
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Strangeness in Quark Matter (SQM 2019)
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QCD phase diagram


• **RHIC BES & SPS**
  Cover the intermediate baryon density region
  Look for **onset of de-confinement, phase boundary** and critical point
NA61/SHINE

- Fixed target experiment at SPS
- Large acceptance: full forward hemisphere down to $p_T=0$
- Performed 2D scan in collision energy and system size

S. Puławski, Mon
STAR BES

- Collider experiment at RHIC
- full azimuthal coverage at mid-rapidity

- BES-I (completed)
  \[ \text{Au+Au}\sqrt{s_{NN}} = 62.4 - 7.7 \text{ GeV} \]

- BES-II (on-going)
  \[ \text{Au+Au}\sqrt{s_{NN}} = 19.6 - 7.7 \text{ GeV} \]

- Fixed-target (on-going)
  \[ \text{Au+Au}\sqrt{s_{NN}} = 7.7 - 3.0 \text{ GeV} \]
  \( \mu_B \) up to 721 MeV
Particle yields (STAR BES-I)

- dN/dy at mid-y for all species vs centrality and energy
- Yield per participating pair increases towards central and higher energies in general
- Exceptions:
  - $p$ and $\Lambda$ yields decrease towards higher energy
  - $\bar{p}$ and $\bar{\Lambda}$ has weak centrality dependence
Particle yields in central collisions (STAR BES-I)

- STAR BES-I data consistent with published data in general
- Rich structure in these excitation functions
- $p$ and $\Lambda$ yields reach minimum at 39 GeV: interplay of baryon transport and pair production

STAR, PRC96, 044904
STAR, arXiv:1906.03732
Average transverse mass (STAR BES-I)

- A step-like structure can be seen in the energy dependence first-order phase transition?
- $\Lambda$ and $\bar{\Lambda}$ show split at lower energies might be due to baryon-antibaryon annihilations at high baryon density

STAR, PRC96, 044904
STAR, arXiv:1906.03732
Qualitatively similar energy dependence is seen in $p+p$, $Be+Be$ and $Pb+Pb$ collisions.

Magnitude of $T$ in $Be+Be$ slightly higher than in $p+p$.

$Ar+Sc$ results between $p+p/Be+Be$ and $Pb+Pb$. 
Directed flow (STAR BES-I)

- Sign change of proton $dv_1/dy$, softening of EOS, first-order phase transition
- Double sign change seen in net-proton, net-$\Lambda$, not seen in net-kaon
- Need theory to explain

STAR, PRL112, 162301 (2014)
STAR, PRL120, 062301 (2018)
Directed flow (NA61/SHINE)

- At 30A GeV/c, close to mid-rapidity, slope of pion $v_1$ is negative for all centralities; slope of proton $v_1$ changes sign at centrality of about 50%
- At 13A GeV/c, no evidence for the collapse of proton $v_1$
**K^+/π^+ ratio (NA61/SHINE)**

- Plateau like structure visible in p+p
- Be+Be close to p+p
- Ar+Sc is higher than p+p but form of energy dependence is similar to p+p (no horn)
Strange hadron to pion ratio (STAR BES-I)

- 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

J. Randrup et al., PRC 74, 047901 (2006)
Anti-hadron to hadron ratio (STAR BES-I)

Centrality dependence of $\bar{B}/B$ ratios: peripheral $>$ central

This effect is more prominent at lower energies.

baryon stopping and/or anti-baryon absorption

Loss of low $p_T$ $\bar{\Lambda}$ in central collisions
Anti-hadron to hadron ratio (STAR BES-I)

- STAR BES data lie in a trend with NA49 data
- $\bar{B}/B$ ratios increase with number of strange quarks at low energies:
  $\bar{\Omega}^+ / \Omega^- > \bar{\Xi}^+ / \Xi^- > \bar{\Lambda}/\Lambda > \bar{p}/p$
Anti-hyperon to hyperon ratio

\[ n_i = \frac{g_i}{(2\pi^2)} \gamma_S^{S_i} m_i^2 T K_2(m_i/T) \exp(\mu_i/T) \]

\[ \frac{\bar{\Lambda}}{\Lambda} = \exp\left(-\frac{2\mu_B}{T} + \frac{2\mu_S}{T}\right) \]

\[ \ln\left(\frac{\bar{\Lambda}}{\Lambda}\right) = -\frac{2\mu_B}{T} + \frac{2\mu_S}{T} \]

\[ \frac{\bar{\Xi}^+}{\Xi^-} = \exp\left(-\frac{2\mu_B}{T} + \frac{4\mu_S}{T}\right) \]

\[ \ln\left(\frac{\bar{\Xi}^+}{\Xi^-}\right) = -\frac{2\mu_B}{T} + \frac{4\mu_S}{T} \]

\[ \frac{\bar{\Omega}^+}{\Omega^-} = \exp\left(-\frac{2\mu_B}{T} + \frac{6\mu_S}{T}\right) \]

\[ \ln\left(\frac{\bar{\Omega}^+}{\Omega^-}\right) = -\frac{2\mu_B}{T} + \frac{6\mu_S}{T} \]

- T is the temperature.
- \(\mu_B\) is the baryon chemical potential.
- \(\mu_S\) is the strangeness chemical potential.

**$\mu_S/T_{ch}$ and $\mu_B/T_{ch}$**

Anti-hyperon to hyperon ratios are fit well with statistical thermal model.

Chemical freeze-out parameters, $\mu_S/T_{ch}$ and $\mu_B/T_{ch}$, are extracted.

STAR, arXiv:1906.03732

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STAR, central Au+Au

- $\mu_B/T_{ch}$, thermal fit
- $\mu_S/T_{ch}$, thermal fit
- $\mu_B/T_{ch}$
- $\mu_S/T_{ch}$

$\sqrt{s_{NN}}$ (GeV) vs. $\mu_B/T_{ch}$ and $\mu_S/T_{ch}$.
Strangeness, LQCD and freeze-out in HIC

freeze-out $T$ by comparing $\mu_S/\mu_B$ from LQCD and expt.


From Swagato Mukherjee
not reproduced by hadron gas with only PDG states

reproduced when additional Quark Model (QM) predicted strange baryons are taken into account

indirect evidence for so-far undiscovered strange baryons at RHIC?
Chemical freeze-out parameters: $T_{\text{ch}}$ vs. $\mu_B$

**STAR, Phys. Rev. C 96, 044904, 2017**

- **Particles used:** $\pi, K, p, \Lambda, \Xi$
- **Ensemble used:** Grand canonical (GCE)
- **Fit parameters:** $T_{\text{ch}}, \mu_B, \mu_s$ and $\gamma_s$


Andronic: NPA 834 (2010) 237
Cleymans: PRC 73 (2006) 034905
Nuclear modification factors $R_{CP}$

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

- No $K_S^0$ suppression in Au+Au 7.7 and 11.5 GeV
- Cronin effect and other effects (radial flow) compete with partonic energy loss
- Intermediate $p_T$, particle $R_{CP}$ difference becomes smaller @ 7.7 and 11.5 GeV
Nuclear modification factors $R_{CP}$

- No suppression for lower energies
- Cronin effect and other effects (radial flow) compete with partonic energy loss

STAR, PRL121, 032301, 2018
$\sqrt{s_{NN}} < 19.6$ GeV, at intermediate $p_T$, the separation of central (0-5%) and peripheral (40-60%) collisions in $\bar{\Lambda} / K^0_S$ becomes less significant.
Intermediate $p_T$ $\Omega/\phi$ ratios:
Indication of separation between $\geq 19.6$ and $11.5$ GeV

$\Omega/\phi$ ratios: $40\%-60\%$ peripheral $< 0$-$10\%$ central for $19.6$, $27$ and $39$ GeV
The STAR fixed-target program

1.3M events from half hour test run, top 30% central trigger, Au+Au $\sqrt{s_{NN}}=4.5$ GeV

3.4M events from two hour test run, top 30% central trigger, Al+Au $\sqrt{s_{NN}}=4.9$ GeV
Hadron spectra and dN/dy in Au+Au $\sqrt{s_{NN}}=4.5$ GeV

- Amplitude and width of rapidity densities are consistent with AGS experiments
- $m_T - m_0$ and $y$ range will be extended by eTOF and iTPC upgrades

Y. Wu, QM2018 Top 5%
Directed flow in Au+Au $\sqrt{s_{NN}}=4.5$ GeV

Baryon $v_1$ slope is consistent with E895 at 4.3 GeV
$K_S^0$ and $\Lambda$ spectra/yield from $\text{Al} + \text{Au} \sqrt{s_{NN}} = 4.9$ GeV

M.-U. Ashraf, ATHIC2018

Top 5%
Summary & outlook

- STAR BES-I and NA61/SHINE have measured systematically the production of strangeness and LF at intermediate baryon density
- Step/horn structures are now investigated at different system sizes
- Double sign change seen in directed flow of net-baryons, but not in net-kaons
- QGP signatures appear to turn off at lower collision energies, but need more statistics to confirm
- The ongoing STAR BES-II with detector upgrade (iTPC, eTOF, EPD) and larger luminosity allow precise measurement of the matter properties at intermediate baryon density ($\mu_B$ up to 721 MeV)
- More results from SPS NA61/SHINE 2D scan are expected to fully explore the onset of deconfinement, onset of fireball…