Bulk properties of the system formed in Au+Au collisions at $\sqrt{s_{NN}} = 14.5$ GeV using the STAR detector at RHIC

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Outline

• Introduction & Motivation
• STAR Experiment at RHIC
• Results
  • Identified particle production and freeze out parameters
  • Azimuthal anisotropy of identified hadrons
• Summary
Motivation: RHIC BES Program

Goals of RHIC beam energy scan program

✧ Search for turn-off of QGP signatures
✧ Search for the first-order phase transition
✧ Search for critical point

Freeze out in heavy-ion collisions

Chemical freeze out ($T_{ch}$, $\mu_B$)
✧ Inelastic collisions among particles cease

Kinetic freeze out ($T_{kin}$, $<\beta>$)
✧ Elastic collisions among particles cease

Elliptic flow ($v_2$) of identified hadrons

New data: Au+Au $\sqrt{s_{NN}} = 14.5$ GeV
✧ Corresponding $\mu_B = 260$ MeV fills a gap in $\mu_B$ of about 100 MeV between $\sqrt{s_{NN}} = 11.5$ GeV ($\mu_B = 315$ MeV) and 19.6 GeV ($\mu_B = 205$ MeV).

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STAR Experiment at RHIC

Large Coverage: $0 < \phi < 2\pi, \ |\eta| < 1.0$

Uniform acceptance: transverse momentum ($p_T$) and rapidity ($y$)

Excellent particle identification capabilities (TPC and TOF)

BES-I Dataset

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Minimum Bias Events($10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>62.4</td>
<td>67</td>
</tr>
<tr>
<td>2010</td>
<td>39</td>
<td>130</td>
</tr>
<tr>
<td>2011</td>
<td>27</td>
<td>70</td>
</tr>
<tr>
<td>2011</td>
<td>19.6</td>
<td>36</td>
</tr>
<tr>
<td>2014</td>
<td>14.5</td>
<td>20</td>
</tr>
<tr>
<td>2010</td>
<td>11.5</td>
<td>12</td>
</tr>
<tr>
<td>2010</td>
<td>7.7</td>
<td>4</td>
</tr>
</tbody>
</table>

Particle Identification

Time Projection Chamber (TPC)

\[ z = \log \left( \frac{(dE/dx)_{\text{meas.}}}{(dE/dx)_{\text{theory}}} \right) \]

Time Of Flight (TOF)

\[ m^2 = p^2 \left( \frac{c^2 t^2}{L^2} - 1 \right) \]

\( p = \) momentum
\( t = \) time of flight
\( L = \) path length

\( \sqrt{s_{\text{NN}}} = 14.5 \text{ GeV} \)

Au + Au

H. Bichsel, NIM A. 562 (2006) 154

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Identified particle production and freeze out properties

See also
- Talk of James Brandenburg
  Heavy flavors and Strangeness
  Monday, 11.15-11.35
Transverse Momentum Spectra

**Au + Au $\sqrt{s_{NN}} = 14.5$ GeV**

**Bose-Einstein fit**

- $\pi^+$
  - 40-50%
  - 50-60%
  - 60-70%
  - 70-80%

- $K^+$
  - 3.0x0-5%
  - 2.0x5-10%
  - 1.5x10-20%
  - 1.2x20-30%
  - 30-40%

- $\Sigma^-$
  - 0-5%
  - 5-10% ($x10^{-2}$)
  - 10-20% ($x10^{-3}$)
  - 20-30% ($x10^{-2}$)
  - 30-40% ($x10^{-3}$)
  - 40-60% ($x10^{-3}$)
  - 60-80% ($x10^{-5}$)

- $\Lambda$
  - 0-5%
  - 5-10% ($x10^{-2}$)
  - 10-20% ($x10^{-3}$)
  - 20-30% ($x10^{-3}$)
  - 30-40% ($x10^{-3}$)
  - 40-60% ($x10^{-3}$)
  - 60-80% ($x10^{-5}$)

- $\bar{p}$
  - 3.0x0-5%
  - 2.0x5-10%
  - 1.5x10-20%
  - 1.2x20-30%
  - 30-40%

**Boltzmann fit**

- $\pi^+$
  - 40-50%
  - 50-60%
  - 60-70%
  - 70-80%

- $K^+$
  - 3.0x0-5%
  - 2.0x5-10%
  - 1.5x10-20%
  - 1.2x20-30%
  - 30-40%

- $\Sigma^-$
  - 0-5%
  - 5-10% ($x10^{-2}$)
  - 10-20% ($x10^{-3}$)
  - 20-30% ($x10^{-2}$)
  - 30-40% ($x10^{-3}$)
  - 40-60% ($x10^{-3}$)
  - 60-80% ($x10^{-5}$)

- $\Lambda$
  - 0-5%
  - 5-10% ($x10^{-2}$)
  - 10-20% ($x10^{-3}$)
  - 20-30% ($x10^{-3}$)
  - 30-40% ($x10^{-3}$)
  - 40-60% ($x10^{-3}$)
  - 60-80% ($x10^{-5}$)

- $\bar{p}$
  - 3.0x0-5%
  - 2.0x5-10%
  - 1.5x10-20%
  - 1.2x20-30%
  - 30-40%

**Double Exponential fit**

- $\pi^+$
  - 40-50%
  - 50-60%
  - 60-70%
  - 70-80%

- $K^+$
  - 3.0x0-5%
  - 2.0x5-10%
  - 1.5x10-20%
  - 1.2x20-30%
  - 30-40%

- $\Sigma^-$
  - 0-5%
  - 5-10% ($x10^{-2}$)
  - 10-20% ($x10^{-3}$)
  - 20-30% ($x10^{-2}$)
  - 30-40% ($x10^{-3}$)
  - 40-60% ($x10^{-3}$)
  - 60-80% ($x10^{-5}$)

- $\Lambda$
  - 0-5%
  - 5-10% ($x10^{-2}$)
  - 10-20% ($x10^{-3}$)
  - 20-30% ($x10^{-3}$)
  - 30-40% ($x10^{-3}$)
  - 40-60% ($x10^{-3}$)
  - 60-80% ($x10^{-5}$)

- $\bar{p}$
  - 3.0x0-5%
  - 2.0x5-10%
  - 1.5x10-20%
  - 1.2x20-30%
  - 30-40%
New results for Au+Au, 14.5 GeV

- Particles used in fit: $\pi$, $K$, $p$, $\Lambda$, $\Xi$ and their anti-particles.
- $T_{ch}$ increases as collision energy increases.
- $\mu_B$ decreases with increase in collision energy.
- Centrality dependence is observed for $\mu_B$.


**Blast-Wave Fit**

**New results for Au+Au 14.5 GeV data**

- $<\beta>$ decreases from central to peripheral collisions.
- $T_{kin}$ increases from central to peripheral collisions.
- An anti-correlation observed between $T_{kin}$ and $<\beta>$.

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*STAR, QM 2014, Darmstadt, Germany*
Elliptic flow ($v_2$) of Identified hadrons

See also
- Talk of Liao Song, Session: Correlations and fluctuations
  Tuesday, 14.40-15.00
- Poster by Shusu Shi, Board: 0833 / 351,
  Tuesday, 16.30-18.30
Elliptic Flow ($v_2$)

The observed $v_2$ is corrected for event plane resolution.

- $\eta$-sub event plane method is used for calculation of $v_2$.

$$
\frac{dN}{d\phi} \propto \frac{1}{2\pi} \left[ 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \psi_{rp})) \right]
$$

$$
v_n = \langle \cos[n(\phi - \psi_{rp})] \rangle
$$

Mass ordering of $v_2$ is observed at low $p_T$ for $\pi^+$, $K^+$, $p$ and their antiparticles.

No mass ordering observed for $K_s^0$, $\phi$, $\Lambda$ and $\bar{\Lambda}$.

Difference between $v_2$ of $\Lambda$ and $\bar{\Lambda}$-bar observed.
New measurement for Au+Au, 14.5 GeV data

- Mass ordering of $v_2$ is observed at low $p_T$ for $\pi^+$, $K^+$, $p$ and their antiparticles.
- No mass ordering observed for $K_{s0}$, $\phi$, $\Lambda$ and $\Lambda$-bar.
- Difference between $v_2$ of $\Lambda$ and $\Lambda$-bar observed.
- Finite $\phi$-meson $v_2$ in Au+Au at 14.5 GeV.
\( \Delta v_2 = v_2(X) - v_2(\bar{X}) \) increases with decrease in energy.

\( \Delta v_2 = v_2(X) - v_2(\bar{X}) \) relative to proton \( v_2 \) (at \( p_T = 1.5 \) GeV/c) shows a centrality dependence.

Centrality dependence

- Centrality dependence of $v_2$ is observed.
- Baryon-meson separation of $v_2$ is more prominent for particles compared to anti-particles at transverse kinetic energy $(m_T - m_0) > 1$ GeV/c$^2$

Fit function:

$$f v_2(n) = \frac{an}{1 + e^{-((m_T-m_0)/n-b)/c}} - dn$$

n = 3 for baryons, 2 for mesons
(A) New Measurements:
- Transverse momentum spectra and elliptic flow $v_2$ of identified hadrons in Au+Au collisions at 14.5 GeV were presented.
- The results for Au+Au collisions at 14.5 GeV are consistent with the trends established by the other BES energies.

(B) Observations:

Chemical Freeze-out:
- $T_{ch}$ increases as collision energy increases.
- $\mu_B$ decreases as collision energy increases.
- Centrality dependence of $\mu_B$ is observed.

Kinetic Freeze-out:
- Centrality dependence is observed for $T_{kin}$ and $<\beta>$.
- $T_{kin}$ and $<\beta>$ are anti-correlated.

Elliptic flow $v_2$:
- Low $p_T$ mass ordering of $v_2$ for $\pi^+$, $K^+$, $p$ and their anti-particles is observed for Au+Au at 14.5 GeV.
- Centrality dependence is observed for $v_2(p)$–$v_2(\bar{p})$ when normalized to proton $v_2$ for all BES energies.

Summary

<table>
<thead>
<tr>
<th>Au+Au, 14.5 GeV 0-5% Most Central</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{ch}$ (MeV)</td>
</tr>
<tr>
<td>$\mu_B$ (MeV)</td>
</tr>
<tr>
<td>$T_{kin}$ (MeV)</td>
</tr>
<tr>
<td>$&lt;\beta&gt;$</td>
</tr>
</tbody>
</table>
BackUp
Chemical freeze out:
Inelastic collisions among the particles ceases and particle yields get fixed.

**THERMUS: Statistical thermal model**
Grand Canonical Ensemble: Quantum numbers (B, S, Q) conserved on average

\[ n_i = \frac{Tm_i^2 g_i}{2\pi^2} \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k} \left( e^{\frac{k\mu_i}{T}} \right) K_2 \left( \frac{km_i}{T} \right) \]


**Thermodynamics quantities extracted:**
Chemical freeze out temperature \( T_{ch} \)
Baryon chemical potential \( \mu_B \)
Kinetic freeze out:
Elastic collisions among the particles stop and the momentum distribution gets fixed

Blast-Wave (BW) Model:

\[
\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0 \left( \frac{p_T \sinh \rho(r)}{T_{\text{kin}}} \right) \times K_1 \left( \frac{m_T \cosh \rho(r)}{T_{\text{kin}}} \right)
\]

\( I_0, K_1 \): Modified Bessel functions
\( \rho(r) = \tanh^{-1} b \), \( b \): transverse radial flow velocity,
\( r/R \): relative radial position; \( R \): radius of fireball
\( T_{\text{kin}} \): Kinetic freeze-out temperature

- Hydrodynamic based model
- Assumes local thermalization of particles at a kinetic freeze-out temperature and moving with a common radial flow velocity

Comparison with BES energies