Identified Hadron Production from the RHIC Beam Energy Scan Program

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Outline:
- Motivation
- Identified hadron yields and average $m_T$
- Particle ratios
- Freeze-out parameters
- Nuclear modification factor $R_{AA}$ (from PHENIX)
- Summary
Motivation-I

QCD Phase Diagram (Hadrons-Partons):

- Experimental study: Heavy-ion collisions at varying beam energies

Goal of RHIC BES program:
- Search for the phase boundary
- Search for the possible QCD Critical Point

We will discuss the bulk properties of the matter through the measurements of particle yields, average $p_T$, particle ratios and freeze-out parameters ($T_{ch}$, $\mu_B$, $T_{kin}$ and $<\beta>$)

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Jet Quenching:

- Large suppression of high $p_T$ meson production in central Au+Au collisions
- No suppression in d+Au experiment
- Similar suppression in $\pi$, $\eta$ and $\phi$: suppression is at partonic level
- No suppression for direct photons: final state effect

Motivation-II

$$R_{AA} = \frac{dN_{AA}/d\eta d^2p_T}{T_{AB} d\sigma_{NN}/d\eta d^2p_T}$$

$$T_{AB} = N_{binary}/\sigma_{inelastic}$$

$N_{binary}$: Number of binary collisions

What is the energy dependence of $R_{AA}$ for the BES data??

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Au+Au Collisions: 7.7, 11.5 and 39 GeV
|y| < 0.1 
$p_T > 0.1$ GeV/c 
Centrality: 0-80%

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Good events (proposed) Million MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>~5(5 ) - 2010</td>
</tr>
<tr>
<td>7.7</td>
<td>~11 (5) - 2010</td>
</tr>
<tr>
<td>11.5</td>
<td>~17 (15) - 2011</td>
</tr>
<tr>
<td>19.6</td>
<td>~130 (150) - 2011</td>
</tr>
<tr>
<td>27</td>
<td>~170 (25 ) - 2010</td>
</tr>
<tr>
<td>39</td>
<td>~170 (25 ) - 2010</td>
</tr>
</tbody>
</table>
STAR: \( \pi^{+/−}, K^{+/−} \) and \( p/\bar{p} \) Identification

\[ \sqrt{s_{NN}} = 39 \text{ GeV Au + Au Collisions} \]

**TPC**

- \( dE/dx \) (MeV/cm)

**TPC+ToF**

- 1/\( \beta \)

**Mathematical Expressions**

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

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

- \( p = \) momentum, \( t = \) time-of-flight
- \( c = \) velocity of light, \( L = \) path length

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

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STAR: Large and Uniform Acceptance

- Similar acceptance at midrapidity - Crucial for all analyses
Results: Identified hadrons measurements from STAR
We measure ~ 70-80% of $\pi$, K and p within our $p_T$ acceptance at mid-rapidity. Similar measurements are carried out for 7.7 and 11.5 GeV collisions.
Results consistent with the published energy dependence

\[ <m_T> - m \text{ remains constant for BES energies (7.7, 11.5, and 39 GeV)} \]

References for other energies:

- **E802(AGS)**: PRC 58 (1998) 3523, PRC 60 (1999) 044904
- **E877(AGS)**: PRC 62 (2000) 024901
- **E895(AGS)**: PRC 68 (2003) 054903

\[ m_T = \sqrt{p_T^2 + m^2} \]

 أجساداً بحرنديم أن نظام الترموديناميك:

\[ T \sim <m_T> - m \]

ال��ية ~ dN/dy

\[ \propto \log(\sqrt{s_{NN}}) \]
Centrality Dependence of Yields & $<p_T>$

- $dN/dy/0.5N_{\text{part}}$ ~ constant for $\pi$ as function of centrality at 7.7 GeV. For other energies and kaons, it increases with centrality.

- $<p_T>$ increases with centrality – collectivity increases with centrality.

- $<p_T>$ for $\pi$ seems to be similar from 39 GeV to 200 GeV.

- $<p_T>$ increases with mass of the particle.

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Anti-Particle to Particle Ratios

Midrapidity and central collisions

- Results consistent with the published energy dependence
- $\pi^-/\pi^+$ ratio $\sim 1.1$ at $7.7$ GeV: resonance decay ($\Delta$)
- $K^-/K^+ \sim 0.4$–$0.5$: associated production at $7.7$-$11.5$ GeV
- $\bar{p}/p < 1$ at $7.7$-$11.5$ GeV: large baryon stopping

Correlation between $K^-/K^+$ and $\bar{p}/p$:
- Follows power law behavior
- Shows how the kaon production is related to net-baryon density.

J. Cleymans et al. ZPC 57, 135 (1993)
The maximum net-baryon density at freeze-out: $\sqrt{s_{NN}} \sim 8$ GeV

- $K/\pi$ ratio indicates the strangeness enhancement
- $K^+/\pi^+$ vs. $\sqrt{s_{NN}}$ seems to be best explained using HRG+Hagedorn model
- $K/\pi$ at BES energies are consistent with published energy dependence

Weak decay contribution for $\pi$ are estimated from HIJING. Error due to this effect included in final errors.


Energy Dependence of Freeze-out Parameters

Spectra and ratios used to obtain freeze-out parameters: $\mu_B$, $T_{ch}$, $T_{kin}$, and $\langle \beta \rangle$

central collisions

- Baryon chemical potential decreases with energy
- Chemical freeze-out temperature increases with energy at low energies and becomes almost similar at higher energies
- Kinetic freeze-out temperature decreases with energy after $\sqrt{s_{NN}} \sim 7.7$ GeV
- Average flow velocity increases with energy

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Results: Nuclear modification factor $R_{AA}$ from PHENIX
Central collisions: Strong suppression for $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV

Peripheral collisions: 62.4 and 200 GeV are suppressed but not 39 GeV

$p+p$ reference at 39 GeV taken from E0706
taking care of rapidity acceptance difference

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Centrality and Energy Dependence of $R_{AA}$

- For central collisions:
  \[ R_{AA} (39) > R_{AA} (62.4) > R_{AA} (200) \]

- For peripheral collisions:
  \[ R_{AA} (62.4) \sim R_{AA} (200); \ R_{AA} (39) \geq 1 \]
Bulk Properties:
- dN/dy increases with \( \sqrt{s_{NN}} \) and consistent with published energy dependence trend. Inverse slopes of spectra follow: \( \pi < K < p \)

Baryon Density:
- Reflected in energy dependence of \( K/\pi \) ratio
- \( K^-/K^+ \) correlation with \( \bar{p}/p \)

Freeze-out Conditions:
- New measurements extend the \( \mu_B \) range covered by RHIC data from 20-350 MeV in the phase diagram
- Collectivity increases with beam energy, centrality and mass
- R_{AA} < 1 is also observed for central Au+Au collisions at \( \sqrt{s_{NN}} = 39 \) GeV
- For 0-10% centrality and \( p_T \): 4-6 GeV/c: 
  \( R_{AA} (39) > R_{AA} (62.4) > R_{AA} (200) \)

- More results coming from \( \sqrt{s_{NN}} = 19.6 \) and 27 GeV collisions

Thank You
Back-up
Models: K/π

Statistical Model

- Entropy/T^3 as function of collision energy - increases for mesons, and decreases for baryons
- Thus, a rapid change is expected at the crossing of the two curves, as the hadronic gas undergoes a transition from a baryon-dominated to a meson-dominated gas, T=140 MeV, μ_B=410 MeV, energy ~ 8.2 GeV

Statistical Hadronization Model

- Strong interactions saturate particle production matrix elements
- Below 7.6 GeV system in chemical non-equilibrium, above over saturation of chemical composition

Thermal Model

- Includes many higher resonances (m > 2 GeV) and σ-meson which is neglected in most of the models

Hadron Resonance Gas + Hagedorn Model

- Assumes a bag of hadron gas. Includes all hadrons up to masses 2 GeV as given in PDG
- Unknown hadron resonances are included through Hagedorn formula
- Assumes that the strangeness in the baryon sector decays to strange baryons and does not contribute to kaon production

Hadronic non-equilibrium Kinetic Model

- Surplus of strange particles are produced in secondary reactions of hadrons generated in nuclear collisions.
- Amount of kaons depend on the lifetime of the whole system
Freeze-out Conditions

Chemical Freeze-out:

\[ n_i(T, \mu_i) \sim \exp \left( \frac{\mu_i - m_i}{T} \right) \]

\[ \frac{N_i}{N_j} \sim \exp \left( \frac{\mu_{i, ch.} - \mu_{j, ch.}}{T_{ch.}} - \frac{m_i - m_j}{T_{ch.}} \right) \]

Kinetic Freeze-out:

\[ \chi^2/\text{ndf} \sim O(1) \]

\[ \frac{dN}{p_T dp_T} \propto \int_0^R rdrm_r \frac{p_T \sinh \rho(r)}{T_{\text{kin}}} \times K_i \left( \frac{m_i \cosh \rho(r)}{T_{\text{kin}}} \right) \]

\[ \chi^2/\text{ndf} \sim O(1) \]