Centrality dependence of freeze-out parameters from the beam energy scan at STAR

Sabita Das\textsuperscript{a,b} (for the STAR Collaboration)
\textsuperscript{a} Brookhaven National Laboratory, Upton, NY, 11973-5000, USA
\textsuperscript{b} Institute of Physics, Bhubaneswar, 751005, INDIA

Abstract
The STAR experiment at RHIC has a unique capability of measuring identified hadrons over a wide range of pseudorapidity ($\eta$), transverse momentum ($p_T$), and azimuthal angle ($\phi$) acceptance. The data collected ($\sqrt{s_{NN}} = 7.7, 11.5, \text{and} 39$ GeV) in its beam energy scan (BES) program provide a chance to investigate the final hadronic state freeze-out conditions of ultrarelativistic Au+Au collisions. The particle ratios are used to compare to a statistical model calculation using both grand canonical and strangeness canonical ensembles to extract the chemical freeze-out parameters. The $p_T$ distributions are fitted to calculations using a blast-wave model to obtain the kinetic freeze-out parameters. We discuss the centrality dependence of the extracted chemical and kinetic freeze-out parameters at these lower energies.

1. Introduction
One of the early goals of heavy-ion collisions at Relativistic Heavy Ion Collider (RHIC) is to establish the existence of a new state of matter which is called quark-gluon plasma (QGP) \cite{1}. According to lattice quantum chromodynamics calculations (QCD), the theory of strong interactions, QGP occurs when a sufficiently high temperature and high energy density ($\approx 1$ GeV/fm$^3$) is reached. The partonic system is transformed into hadronic matter as the system cools to lower temperatures. The phase diagram of QCD is in general characterized by two quantities, the temperature ($T$) and the baryon chemical potential ($\mu_B$) or the (net) baryon density ($n_B$). The phase diagram should contain information about the phase boundary that separates the QGP and hadronic phases \cite{2}. Lattice QCD finds a rapid, but smooth crossover transition from hadron gas to QGP at vanishing baryon chemical potential and large temperature $T$, while various models predict a strong, first-order phase transition at large $\mu_B$. If this is the case, then there should be a critical point at intermediate values in the ($T, \mu_B$) plane where the transition changes from a smooth crossover to a first order \cite{3}. The BES program at RHIC is carried out using several center-of-mass energies of colliding nuclei, to explore the above aspects of this QCD phase diagram.

The constituents of the hot and dense medium produced during a heavy-ion collision interact with each other by inelastic and elastic collisions and it evolves into a state of free particles. This process of hadron decoupling is called freeze-out. Two kinds of freeze-out are found: chemical freeze-out ($T_{ch}$) when inelastic collisions cease and the particle yields become fixed; thermal (kinetic) freeze-out ($T_{kin}$) when elastic collisions cease and particle transverse momenta ($p_T$) spectra

\footnote{\texttt{sabita@rcf.rhic.bnl.gov}}

Preprint submitted to Nuclear Physics A March 12, 2013
We present a study of the centrality dependence of hadronic freeze-out parameters in Au+Au collisions at mid-rapidity for $\sqrt{s_{NN}} = 7.7, 11.5,$ and $39$ GeV measured by the STAR experiment. To extract chemical freeze-out parameters we use a statistical thermal model (THERMUS) [5] where we fit experimental particle ratios using a grand canonical ensemble (GCE) approach with the inclusion of a strangeness saturation factor ($\gamma_S$) and also with strangeness canonical ensemble (SCE) where strangeness quantum number is conserved exactly. In this study we have used mid-rapidity particle ratios that include the pions ($\pi^+$, $\pi^-$), kaons ($K^+$, $K^-$), protons ($p$, $\bar{p}$), $K_0^S$, Lambdas ($\Lambda$, $\bar{\Lambda}$) and Cascades ($\Xi^-$, $\Xi^+$) [6, 7]. The chemical freeze-out parameters extracted are $T_{ch}$, $\mu_B$, $\mu_S$ and $\gamma_S$. The kinetic freeze-out parameters are determined from the blast-wave model (BW) [8] fits to the $p_T$ spectra of $\pi$, $K$, and $p$ [6]. The main kinetic freeze-out parameters extracted are $T_{kin}$ and average flow velocity ($\langle \beta \rangle$).

2. Results

2.1. Kinetic freeze-out

At the kinetic freeze-out, elastic collisions among the particles stop and the spectral shape of the particles get fixed. Kinetic freeze-out parameters are obtained using blast-wave model by doing the simultaneous fits of $\pi$, $K$, and $p$ transverse momentum spectra. The BW model describes the spectral shapes assuming a locally thermalized source with a common transverse flow velocity field. It has been successfully used to describe $p_T$ spectra with three parameters - $T_{kin}$, $\langle \beta \rangle$, and the exponent in the flow velocity profile $n$ at 62.4 and 200 GeV [4, 9]. Figure 1(a) shows the simultaneous blast-wave fit of $\pi$, $K$, $p$ and the corresponding antiparticles for 0 – 5% centrality in Au+Au collisions at $\sqrt{s_{NN}} = 11.5$ GeV. The variation of $T_{kin}$ as a function of $\langle \beta \rangle$ at $\sqrt{s_{NN}} = 7.7, 11.5, 39, 62.4$ and 200 GeV is shown in Fig 1(b). The 62.4 and 200 GeV results are taken from the Ref.[4]. The $T_{kin}$ decreases from peripheral to central collisions. It also decreases with increasing collision energy. The $\langle \beta \rangle$ increases with increase of energy as well as collision centrality. So, higher value of $T_{kin}$ corresponds to lower value of $\langle \beta \rangle$ and vice-versa. The errors shown are the quadratic sum of statistical and systematic errors.
2.2. Chemical freeze-out

At the chemical freeze-out, inelastic collisions among the particles stop and hadron yields get fixed. A statistical thermal model (THERMUS) was used to fit mid-rapidity particle ratios including yields of $\pi, K, p, K^0_S, \Lambda$ and $\Xi$ measured in Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5,$ and $39$ GeV. Although the particle ratios are obtained at $y=0$, the measurements of yields for $\pi, K, p$ are for $|y| < 0.1$ and those for $K^0_S, \Lambda, \Xi$ are for $|y| < 0.5$. The errors on particle ratios including yields of $\pi, K, p, K^0_S, \Lambda$, and $\Xi$, are the quadratic sum of statistical and systematic uncertainties. Pion yields have been corrected for feed-down from $K^0_S$ weak decays. Proton yields have not been corrected for feed-down contributions. The $\Lambda$ yields have been corrected for the feed-down contributions from $\Xi$ and $\Xi^0$ weak decays [7]. In the framework of this model, the particle yield ratios can be described by a set of parameters such as $T_{ch}, \mu_B, \mu_S$ and $\gamma_S$. The errors on freeze-out parameters are obtained from THERMUS model. Considering grand canonical formulation of this model we have studied the centrality and energy dependence of the freeze-out parameters.

Figure 2 shows the statistical model fits to experimental particle ratios for $0 - 5\%$ centrality in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV. The data and model matches very well, except for $\bar{\Lambda}/\Lambda$. Figure 3(a) shows the $T_{ch}$ increases with increase of collision energy. Figure 3(b) shows $\mu_B$ decreases...
with increasing collision energy. From peripheral to central collisions, $\mu_B$ increases at lower energies. We observe a centrality dependence of chemical freeze-out curve ($T_{ch}$ vs. $\mu_B$) at BES energies which was not observed at higher energies like Au+Au 200 GeV [10]. Figure 3 (c) shows that the $\gamma_S$ increases from peripheral to central collisions for all energies. In contrast to GCE where all quantum numbers are conserved on an average, THERMUS model also allows for a strangeness canonical ensemble where only the strangeness quantum number is required to be conserved exactly whereas baryon and charge quantum numbers are conserved on an average. Figure 4 (a) and (b) indicate that in peripheral collisions, $T_{ch}$ and $\mu_B$ follow a different behavior in GCE and SCE at $\sqrt{s_{NN}} = 7.7$ GeV. We observe a higher $\chi^2$/ndf in SCE in comparison to GCE at peripheral collisions. Further systematic investigations are ongoing towards a more quantitative analysis for all the BES energies.

3. Summary

The new measurement at BES energies 7.7, 11.5, and 39 GeV at RHIC extends the $\mu_B$ range from 20 to 400 MeV in the QCD phase diagram. Kinetic freeze-out parameters are obtained using the measured particle spectra and a BW model. For all the beam energies studied, the central collisions are characterized by a lower $T_{kin}$ and larger $\langle \beta \rangle$ while the peripheral collisions are found to have a higher $T_{kin}$ and smaller $\langle \beta \rangle$. Chemical freeze-out parameters are obtained using the measured particle ratios and a THERMUS model. We have observed a centrality dependence of the chemical freeze-out parameters at the lower energies. We have observed different behavior of chemical freeze-out parameters ($T_{ch}$, $\mu_B$) for peripheral collisions in GCE and SCE.

References

[1] J. Adams et al. (STAR Collaboration), Nucl. Phys. A757, 102 (2005).  
[2] P. Braun-Munzinger et al. arXiv:1101.3167, 2011; B. Mohanty. Nucl. Phys. A 830, 899C (2009).  
[3] S. Gupta et al., Science 332, 1525 (2011); E. S. Bowman and J. I. Kapusta, Phys. Rev. C 79, 015202 (2009).  
[4] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79, 034909 (2009).  
[5] J. Cleymans et al., Computer Physics Communications, 180, 84 (2009).  
[6] L. Kumar (STAR collaboration), arXiv:1201.3203 (2012), J. Phys. G: Nucl. Part. Phys. 38, 124145 (2011).  
[7] X. Zhu (STAR Collaboration), Acta Phys. Polon. B Proc. Supp. 5 (2012) 213-218.  
[8] E. Schnedermann et al., Phys. Rev. C 48, 2462 (1993).
[9] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 81, 024911 (2010).
[10] M. M. Aggarwal et al. (STAR Collaboration), Phys. Rev. C 83, 024901 (2011).