Bulk Properties in Au+Au Collisions at $\sqrt{s_{NN}} = 9.2$ GeV in
STAR Experiment at RHIC

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Abstract

One of the primary goals of high-energy heavy-ion collisions is to establish the QCD phase
diagram and search for possible phase boundaries. The planned RHIC energy scan program will
explore this exciting physics topic using heavy-ion collisions at various center of mass energies.
The first test run with Au+Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV took place in early 2008. We
present the results on identified particle ratios, azimuthal anisotropy parameters ($v_1$ and $v_2$) and
HBT at midrapidity using data from this run. These results are compared to data for both lower
and higher center of mass energies at the AGS, SPS and RHIC. These new data demonstrate the
capabilities of the STAR detector for exploring the QCD phase diagram.

1. Introduction:

Searches for the Quantum Chromodynamics (QCD) critical point and for the location of the
phase boundaries in the QCD phase diagram have been of great interest in high-energy heavy-
ion collisions, both theoretically and experimentally. The QCD phase diagram is usually plotted
as temperature ($T$) vs. baryonic chemical potential ($\mu_B$). A critical point in the QCD phase
diagram is the location where first order phase transition ends. Phase boundaries in the diagram
distinguish the hadronic phase from the Quark Gluon Plasma (QGP) phase. Lattice calculations
suggest that near $\mu_B \sim 0$, a smooth crossover occurs between these two phases. To search for the
QCD critical point and to explore the phase diagram, we need to vary the $\mu_B$ and temperature.
These can be varied by altering the center of mass energy and are deduced from the spectra and
ratios of produced particles. There is a proposal at RHIC to start a new program called “Critical
Point Search”, in which $\sqrt{s_{NN}}$ will be varied in order to explore the QCD phase diagram. In
addition to the critical point search, the STAR experiment would like to locate the $\sqrt{s_{NN}}$ where
many interesting observations at top RHIC energies, such as number of constituent quarks (NCQ)
scaling of $v_2$ [1], high transverse momentum ($p_T$) hadron suppression in A+A collisions relative
to p+p collisions [2] and the ridge formation [3], will “disappear” or “switch off”. As a first step
of this program, a test run was conducted at RHIC in 2008 by colliding Au ions at $\sqrt{s_{NN}} = 9.2$
GeV. This short test run yielded ~3000 good events and the results presented in this paper are
based on these data. These number of events were obtained by selecting the $z$-position of the
event vertex within 75 cm of the nominal collision point.
Figure 1: Left panel: (a) $\pi^-/\pi^+$ and (b) $p/p$, plotted as a function of $\sqrt{s_{NN}}$. Right panel: (a) $K^-/K^+$ and (b) $K/\pi$, plotted as a function of $\sqrt{s_{NN}}$. Results from 0–10% central Au+Au collisions at 9.2 GeV (solid stars) are compared with those from AGS [4], SPS [5] and RHIC [6] (open symbols). Errors are statistical and systematic added in quadrature. See text for details.

Figure 2: Left panel: Charged hadrons $v_1$ vs. $\eta$ from 0–60% Au+Au collisions at 9.2 GeV (errors shown are statistical). See text for details. Right panel: Energy dependence of $v_2$ near mid-rapidity ($-1 < \eta < 1$). Errors are statistical only. See text for details.
2. Results

2.1. Energy dependence of particle ratios

Figure 1 shows the particle ratios, $\pi^-/\pi^+$, $\bar{p}/p$, $K^-/K^+$, and $K/\pi$, plotted as a function of $\sqrt{s_{NN}}$. Results from 0–10% central Au+Au collisions at 9.2 GeV (solid stars) at midrapidity ($|y| < 0.5$) are compared with those from AGS [4], SPS [5] and RHIC [6] (open symbols). We observe that the ratios at 9.2 GeV are consistent with the $\sqrt{s_{NN}}$ dependence trend. The ratio $\pi^-/\pi^+$ (Fig. 1a left panel) for 9.2 GeV is close to one, suggesting that $\pi^-$ and $\pi^+$ are produced from similar sources at this energy. However, this ratio is greater than one at lower energies, indicating that pions are dominantly produced from resonance decays (such as $\Delta$). The ratio $\bar{p}/p$ (Fig. 1b left panel) at 9.2 GeV is much less than one, indicating large net proton ($p - \bar{p}$) due to a large baryon stopping and hence large value of $\mu_B$ at this energy. This ratio increases with increasing center of mass energy, approaching a value close to one at higher energies. This suggests that $p$ and $\bar{p}$ are dominantly produced by pair production at higher energies. The STAR proton results presented here are not corrected for feed down contributions. The ratio $K^+/K^{+}$ (Fig. 1a right panel) for 9.2 GeV is close to 0.4, which indicates that $\sim 60\%$ of $K^+$ are produced via associated production with $\Lambda$. As the center of mass energy increases, this ratio approaches the value of one, suggesting the dominance of pair production. Strangeness production in heavy-ion collision experiments can be studied from the kaon to pion ratio (Fig. 1b right panel). A “horn-like” distribution is observed for the $K^+/\pi^+$ ratio around $\sqrt{s_{NN}} \sim 7.7$ GeV at the SPS [5]. It can be seen that 9.2 GeV result agrees with the corresponding results from SPS data. This is of great interest to both theorists and experimentalists in order to understand the relevant degrees of freedom.

2.2. Azimuthal anisotropy measurements

The azimuthal anisotropy parameters - directed flow ($v_1$) and elliptic flow ($v_2$), in ultra-relativistic heavy ion collisions are believed to be sensitive to the equation of state. Figure 2 (left panel) shows the charged hadrons $v_1$ as a function of pseudorapidity ($\eta$) for 0–60% central Au+Au collisions at 9.2 GeV. The results are compared to $v_1$ for 30–60% central Au+Au collisions at 62.4 and 200 GeV [7]. Also shown for comparison are $v_1$ for charged pions for 0–60% central Pb+Pb collisions at 8.8 GeV [8]. The $v_1$ for 9.2 GeV shows similar behaviour to that of the other center of mass energies at midrapidity. The difference seen at forward rapidities ($|\eta| > 2$) is due to the contributions of spectator protons and nuclear fragments. When $v_1$ is divided by the beam rapidities (2.3, 4.2 and 5.4 for $\sqrt{s_{NN}} = 9.2$ GeV, 62.4 GeV and 200 GeV, respectively), the difference disappears and $v_1$ for all $\sqrt{s_{NN}}$ lie on a common trend. Figure 2 (right panel) shows the $v_2$ as a function of $\sqrt{s_{NN}}$ for charged hadrons. Results from minimum bias collisions at 9.2 GeV (solid star symbol) at midrapidity are compared with those from STAR [9] at higher energy, E877 [10], NA49 [8], PHENIX [11] and PHOBOS [12] (open circles). The 9.2 GeV $v_2$ result follows the established $\sqrt{s_{NN}}$ trend.

2.3. Pion interferometry measurements

The pion interferometry measurements are performed for 0–30% central Au+Au collisions at 9.2 GeV. Table 1 shows various parameters obtained from these measurements. The ratio $R_{out}/R_{side}$ is observed to be close to one and is consistent with the established $\sqrt{s_{NN}}$ dependence trends.
Table 1: The HBT parameters for 0–30% central events and $k_T = [150, 250] \text{ MeV}/c$.

| $\lambda$ | $R_{\text{out}}$ (fm) | $R_{\text{side}}$ (fm) | $R_{\text{long}}$ (fm) |
|----------|------------------------|------------------------|------------------------|
| $0.6 \pm 0.1$ | $4.8 \pm 0.8$ | $4.4 \pm 0.5$ | $5.1 \pm 0.8$ |

3. Summary and Outlook

We have presented results on identified particle ratios and azimuthal anisotropy measurements for Au+Au collisions at 9.2 GeV. This is the lowest center of mass energy at RHIC so far. The ratios of various particles for 9.2 GeV at midrapidity are consistent with the previously established $\sqrt{s_{NN}}$ dependence trends. The $\pi^-/\pi^+$ ratio for 9.2 GeV is close to one, $\bar{p}/p$ ratio is much less than one, and $K^−/K^+$ ratio is close to 0.4. The azimuthal anisotropy measurements and $\pi$ interferometry results for 9.2 GeV follow the established $\sqrt{s_{NN}}$ dependence trends. The results presented here are only from the few thousand good events and qualitative improvements on the previous results at the SPS will be made with higher statistics. Being a collider experiment, the STAR detector has many advantages over a fixed target experiment in terms of acceptance ($\eta$, $p_T$) and particle density per unit area at a fixed $\sqrt{s_{NN}}$. In addition to this, the particle identification in STAR is very good and will be further improved by the inclusion of Time Of Flight (TOF). Based on the results presented here for Au+Au collisions at 9.2 GeV and capabilities of STAR, it is clear that the RHIC collider and the STAR experiment are ready for the future “Critical Point Search” program.

References

[1] B. I. Abelev, et al. (STAR Collaboration), Phys. Rev. Lett. 99 (2007) 112301; Phys. Rev. C 77 (2008) 54901.
[2] B. I. Abelev, et al. (STAR Collaboration), Phys. Lett. B 655 (2007) 104; J. Adams, et al. (STAR Collaboration), Phys. Lett. B 637 (2006) 161; B. I. Abelev, et al. (STAR Collaboration), Phys. Rev. Lett. 97 (2006) 152301; J. Adams, et al. (STAR Collaboration), Phys. Lett. B 616 (2005) 8.
[3] J. Putschke (for the STAR Collaboration), J. Phys. G. Nucl. Part. Phys. 34 (2007) 5679; M. Daugherity (for the STAR Collaboration), J. Phys. G. Nucl. Part. Phys. 35 (2008) 104090.
[4] L. Ahle et al., (E866 Collaboration and E917 Collaboration), Phys. Lett. B 490 (2000) 53; L. Ahle et al., (E866 Collaboration and E917 Collaboration) Phys. Lett. B 476 (2000) 1; J.L. Klay et al., (E895 Collaboration), Phys. Rev. Lett. 88 (2002) 102301; J. Barrette, et al., (E877 Collaboration), Phys. Rev. C 62 (2000) 024901; Y. Akiba, et al., (E802 Collaboration), Nucl. Phys. A 610 (1996) 139c; L. Ahle, et al., (E802 Collaboration), Phys. Rev. C 60 (1999) 064901; L. Ahle, et al., (E802 Collaboration), Phys. Rev. C 57 (1998) 466.
[5] S. V. Afanasiev et al. (NA49 Collaboration), Phys. Rev. C 69 (2004) 054902; T. Anticic et al. (NA49 Collaboration), Phys. Rev. C 69 (2004) 024902.
[6] B.I. Abelev et al. (STAR Collaboration), Phys. Rev. C 79 (2009) 34909; D. Cebra (for the STAR Collaboration) arXiv:0903.4702 [nucl-ex].
[7] B. I. Abelev et al (STAR Collaboration), Phys. Rev. Lett. 101 (2008) 252301.
[8] C. Alt et al., (NA49 Collaboration), Phys. Rev. C 68 (2003) 034903.
[9] B. I. Abelev et al., (STAR Collaboration), Phys. Rev. C 75 (2007) 054906; J. Barrette et al., (E877 Collaboration), Phys. Rev. C 55 (1997) 1420.
[11] A. Adare, et al., (PHENIX Collaboration), Phys. Rev. Lett. 98 (2007) 162301.
[12] B. Alver et al., (PHOBOS Collaboration), Phys. Rev. Lett. 98 (2007) 242302; B. B. Back et al., (PHOBOS Collaboration), Phys. Rev. C 72 (2005) 051901.