Net-proton measurements at RHIC and the QCD phase diagram

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Abstract. Two measurements related to the proton and anti-proton production near midrapidity in $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4$ and 200 GeV Au+Au collisions using the STAR detector at the Relativistic Heavy Ion Collider (RHIC) are discussed. At intermediate impact parameters the slope parameter of the directed flow versus rapidity ($dv_1/dy$) for the net-protons shows a non-monotonic variation as a function of the beam energy. This non-monotonic variation is characterized by the presence of a minimum in $dv_1/dy$ between $\sqrt{s_{NN}} = 11.5$ and 19.6 GeV and a change in the sign of $dv_1/dy$ twice between $\sqrt{s_{NN}} = 7.7$ and 39 GeV. At small impact parameters the product of the moments of net-proton distribution, kurtosis $\times$ variance ($\kappa \sigma^2$) and skewness $\times$ standard deviation ($S\sigma$) are observed to be significantly below the corresponding measurements at large impact parameter collisions for $\sqrt{s_{NN}} = 19.6$ and 27 GeV. The $\kappa \sigma^2$ and $S\sigma$ values at these beam energies deviate from the expectations from Poisson statistics and that from a Hadron Resonance Gas model. Both these measurements have implications towards the understanding of the QCD phase structures, the first order phase transition and the critical point in the high baryonic chemical potential region of the phase diagram.

Keywords. QCD phase diagram, Critical Point, First Order Phase Transition, Heavy-Ion Collisions, Quark Gluon Plasma, Net-proton

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1. Introduction

The formation of a hot and dense medium of deconfined quarks and gluons (QGP) has been established in high energy heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) facility at Brookhaven National Laboratory and the Large Hadron Collider (LHC) facility at CERN \cite{1}. The transition from QGP to a hadron gas has been shown to be a cross over \cite{2}. The focus of research in this field has now shifted towards two aspects, (a) characterizing the transport properties of QGP and (b) establishing the QCD phase structures at high baryonic chemical potential ($\mu_B$) region of the QCD phase diagram.

A rigorous phenomenological analysis of the precision data from relativistic heavy-ion collisions and theoretical advances over 14 years has led to quantitative estimates for some of the transport properties of a strongly interacting de-confined state of quarks and gluons. The estimated shear viscosity to entropy density ratio ($\eta/s$) is found to reflect the inviscid liquid property of the QGP and has a value between $1-2)/4\pi$ \cite{3,4}. That
reflecting the stopping power or the opacity of QGP has been estimated by obtaining the square of the momentum transferred by the parton to the QGP per unity length ($\hat{q}$) and is found to lie between 2-10 GeV$^2$/fm \cite{5,6}. On the other hand a dedicated program called the Beam Energy Scan (BES) to establish the phase diagram of QCD was launched at RHIC in the year 2010 to unravel the QCD phase structure at large $\mu_B$. A range of $\mu_B$ from 20 MeV to 400 MeV of the phase diagram was covered by varying the $\sqrt{s_{NN}}$ from 200 to 7.7 GeV. The rich phase structure in the high $\mu_B$ region can be seen from the conjectured QCD phase diagram shown in Fig. 1\cite{7}. The two distinct features of the phase diagram at large $\mu_B$ are the first order phase boundary and the critical point (CP). In this paper we concentrate on the status of the experimental search for these two phase structures through the measurement of proton and antiproton production in heavy-ion collisions. Specifically we discuss the observable related to the azimuthal and multiplicity distributions for net-proton (the difference in number of protons and anti-protons) in Au+Au collisions at midrapidity for $\sqrt{s_{NN}} = 7.7$, 11.5, 19.6, 27, 39, 62.4 and 200 GeV. We find the results to be very intriguing, which must to be further quantified by having a high event statistics second phase of BES program in near future at RHIC.

In the next section we discuss the two observables related to the search for the first order phase transition and the critical point. In section 3 we present the experimental results on the directed flow measurements of net-protons, an observable for first order phase transition. In section 4 we discuss the measurements related to the product of higher moments of net-proton multiplicity distribution, observable for critical point search. Finally in section 5 we summarize the findings.

2. Observables

The experimental results presented here are from the data recorded in the STAR detector at RHIC in the year 2010 and 2011.

2.1 Directed flow

The patterns of azimuthal anisotropy in particle production, often termed as flow, in heavy-ion collisions can be obtained by studying the Fourier expansion of the azimuthal

Figure 1. Conjectured QCD phase diagram \cite{7}.
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angle ($\phi$) distribution of produced particles with respect to the reaction plane angle ($\Psi_R$) \[8\]. Where the reaction plane is defined as the plane subtended by the impact parameter direction and the beam direction. The various (order $n$) coefficients in this expansion are defined as:

$$v_n = \langle \cos[n(\phi - \Psi_R)] \rangle.$$  

(1)

The angular brackets in the definition denote an average over many particles and events. Directed flow is quantified by the first coefficient ($v_1$). On the other hand the elliptic flow is given by the second coefficient ($v_2$).

The $v_1$, which is sensitive to early collision dynamics, is proposed as a signature of first order phase transition based on a hydrodynamic calculation \[9–11\]. These calculations whose equation of state incorporates a first-order phase transition from hadronic matter to QGP predict a non-monotonic variation of the slope of directed flow of baryons (and net-baryons) around midrapidity as a function of beam energy, also has a prominent minimum, and a double sign change in the $v_1$ slope, which is not seen in the same hydrodynamic model without a first-order phase transition.

The $v_1$ results discussed in this paper are for the most abundantly measured baryons, antiproton and proton, detected using their energy loss in STAR Time Projection Chamber and by the time-of-flight information from the Time Of Flight detector \[12\]. Protons and antiprotons have a transverse momentum between 0.4 and 2.0 GeV/c and pseudorapidity ($\eta$) between $\pm$ 1 unit. The first order event plane for $\sqrt{s_{NN}} < 62.4$ GeV is constructed using the information from the two Beam Beam Counters at $3.3 < \mid \eta \mid < 5.0$. That for $\sqrt{s_{NN}} = 62.4$ and 200 GeV uses the information from STAR ZDC-SMD detectors. All results discussed here are corrected for event plane resolution and proton track reconstruction efficiency.

2.2 Higher moments

Non-monotonic variations of observables related to the moments of the distributions of conserved quantities such as net-baryon, net-charge, and net-strangeness \[13\] number with $\sqrt{s_{NN}}$ are believed to be good signatures of a CP. The moments are related to the correlation length ($\xi$) of the system \[14\]. Finite size and time effects in heavy-ion collisions put constraints on the significance of the desired signals. A theoretical calculation suggests a non-equilibrium $\xi \approx 2-3$ fm for heavy-ion collisions \[15\]. Hence, it is proposed to study the higher moments (like skewness, $S = \langle (\delta N)^3 \rangle / \sigma^3$ and kurtosis, $\kappa = [\langle (\delta N)^4 \rangle / \sigma^4] - 3$ with $\delta N = N - \langle N \rangle$) of distributions of conserved quantities due to a stronger dependence on $\xi$ \[14\]. Further, products of the moments can be related to susceptibilities associated with the conserved numbers. The product $\kappa \sigma^2$ of the net-baryon number distribution is related to the ratio of fourth order ($\chi^{(4)}_B$) to second order ($\chi^{(2)}_B$) baryon number susceptibilities \[15 \, 17\]. The ratio $\chi^{(4)}_B / \chi^{(2)}_B$ is expected to deviate from unity near the CP. It has different values for the hadronic and partonic phases \[17\].

The higher moments of the net-proton multiplicity ($N_p - N_{\bar{p}} = \Delta N_p$) distributions from Au+Au collisions discussed in this paper are for protons and anti-protons detected at midrapidity ($|y| < 0.5$) in the range $0.4 < p_T < 0.8$ GeV/c. A good purity of the proton sample (better than 98%) for all beam energies is obtained in the momentum range studied. All results presented are corrected for proton reconstruction efficiency.
Figure 2. (Color online) Directed flow slope ($dv_1/dy$) near mid-rapidity as a function of beam energy ($\sqrt{s_{NN}}$) for intermediate-centrality (10-40%) Au+Au collisions [12]. Panels (a), (b) and (c) shows the STAR experiment measurement for antiprotons, protons, and net-protons, respectively, along with corresponding calculations from the UrQMD model obtained with the same cuts and fit conditions. The systematic uncertainties on the measurements are shown as shaded bars. The dashed curves are a smooth fit to guide the eye.
3. Search for the first order phase transition

Figure 2 shows the slope of directed flow versus rapidity ($dv_1/dy$) near midrapidity as a function of $\sqrt{s_{NN}}$ for antiprotons (panel (a)), protons (panel (b)) and net-proton (panel (c)) [12]. The results are for 10-40% Au+Au collision centrality. The antiproton $dv_1/dy$ has negative values and shows a monotonic increase with $\sqrt{s_{NN}}$. The proton $dv_1/dy$ has positive values for $\sqrt{s_{NN}} = 7.7$ GeV and negative values for rest of the energies studied. The proton $dv_1/dy$ dependence on $\sqrt{s_{NN}}$ is non-monotonic with a minimum around $\sqrt{s_{NN}} = 11.5$ and 19.6 GeV. The energy dependence of proton $dv_1/dy$ involves an interplay between the directed flow of protons associated with baryon number transported from the initial beam rapidity to the vicinity of mid-rapidity, and the directed flow of protons from particle-antiparticle pairs produced near mid-rapidity. The importance of the pair production mechanism increases strongly with beam energy. It is important to distinguish between the two mechanisms before further conclusions can be drawn. The net-proton $dv_1/dy$ is expected to provide the contribution from protons associated with baryon number transport. Assuming antiproton directed flow as a proxy for the directed flow of pair produced protons, the proposed net-proton slope can be constructed from

$$[v_1(y)]_p = r(y)[v_1(y)]_p + [1 - r(y)] [v_1(y)]_{\text{net-p}},$$

where $r(y)$ is the observed rapidity dependence of the ratio of antiprotons to protons at each beam energy [12]. The net-proton slope is shown as a function of $\sqrt{s_{NN}}$ in Fig. 2(c). The data shows a non-monotonic dependence on $\sqrt{s_{NN}}$ with a minimum around $\sqrt{s_{NN}} = 11.5$ and 19.6 GeV. The values of slope changes sign twice, goes from positive at 7.7 GeV to negative at $\sqrt{s_{NN}} = 11.5 - 27$ GeV, then again becomes positive for $\sqrt{s_{NN}} > 39$ GeV.

The corresponding UrQMD results [18, 19], which does not include any first order phase transition effects, in all the three cases of slope of antiproton, proton and net-proton shows a monotonic variation with $\sqrt{s_{NN}}$. The slope values also does not agree with the measurements.

A possible interpretation of the changing sign of the $v_1$ slope is that it reflects a change in equation-of-state. At a given energy where the system undertakes a first order quark–hadron phase transition, one expect the formation of a mixed-phase for which the pressure gradient is small. The softest pressure will naturally produces the observed minimum in $v_1$ slope parameter [9,11]. The alternate proposal is that at higher energies pair production is dominant at mid-rapidity and transported baryons have relatively small influence. As there is no preferred direction for pair produced hadrons, so the slope parameter becomes close to zero. While at lower beam energies the observed baryons are strongly influenced by the transported baryons so they are aligned with them hence the slope parameter is positive. The most intriguing is the dependence in the intermediate energies, a mean field model study shows that the energy dependent baryon potential plays an important role in this region [20].

In the search for the signature of a first-order phase transition in the high $\mu_B$ region of the QCD phase diagram, the findings from $dv_1/dy$ from the RHIC beam energy scan program are very compelling and strongly motivates further measurements. To better understand the possible role and relevance of stopping in interpretation of existing data on net-proton directed flow, new higher event statistics measurements of the centrality dependence of $v_1$ at $\sqrt{s_{NN}} = 7.7$ to 19.6 GeV is needed.
4. Search for the critical point

Figure 3 shows the energy dependence of $S\sigma$ and $\kappa\sigma^2$ for $\Delta N_p$ for Au+Au collisions for two collision centralities (0-5% and 70-80%), corrected for $p(\bar{p})$ reconstruction efficiency [21, 22]. The Skellam expectations for $S\sigma$ are calculated using the data as $(\langle N_p \rangle - \langle N_{\bar{p}} \rangle) / (\langle N_p \rangle + \langle N_{\bar{p}} \rangle)$. The $S\sigma$ values normalized to the corresponding Skellam expectations are shown in the bottom panel of Fig. 3. The Skellam expectations reflect a system of totally uncorrelated, statistically random particle production. The central collision data shows deviation from Skellam expectation with maximum deviation occurring for $\sqrt{s_{NN}} = 19.6$ and 27 GeV. The corresponding results from $p+p$ collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV are also shown and found to be similar to peripheral Au+Au collisions within the statistical errors. For $\sqrt{s_{NN}} = 19.6$ and 27 GeV, differences are observed between the 0-5% central Au+Au collisions and the peripheral collisions. The results are closer to unity for $\sqrt{s_{NN}} = 7.7$ GeV. Higher statistics data for $\sqrt{s_{NN}} < 19.6$ GeV will
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help in quantitatively understanding the suggestive non-monotonic energy dependence of $\kappa\sigma^2$ and $S\sigma$.

The data also show deviations from the hadron resonance gas model [23, 24] which predict $\kappa\sigma^2$ and $S\sigma$/Skellam to be unity. The effect of decay is less than 2% as per the HRG calculations in Ref. [24]. To understand the effects of baryon number conservation [25], UrQMD model calculations (a transport model which does not include a CP) [18, 19] for 0-5% Au+Au collisions are shown in the middle and bottom panels of Fig. 3. The UrQMD model shows a monotonic decrease with decreasing beam energy [26]. The centrality dependence of the $\kappa\sigma^2$ and $S\sigma$ from UrQMD [26] (not shown in the figures) closely follow the data at the lower beam energies of 7.7 and 11.5 GeV. Their values are in general larger compared to data for the higher beam energies. The observed $\sqrt{s_{NN}}$ dependence for central Au+Au collisions is not explained by UrQMD model.

The current data provide the most relevant measurements over the widest range in $\mu_B$ (20 to 450 MeV) to date for the CP search, and for comparison with the baryon number susceptibilities computed from QCD to understand the various features of the QCD phase structure [16, 17]. The deviations of $S\sigma$ and $\kappa\sigma^2$ below Skellam expectation are qualitatively consistent with a QCD based model which includes a CP [27]. However, conclusions on the existence of CP can be made only after a high event statistics measurement for $\sqrt{s_{NN}} < 27$ GeV in the second phase of the beam energy scan program and comparison to QCD calculations with CP behavior.

5. Summary

We have discussed two striking observations from the RHIC beam energy scan program related to the first order quark–hadron phase transition and the critical point. The measurements uses the produced protons and antiprotons in Au+Au collisions at midrapidity for $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4$ and 200 GeV.

The slope of the directed flow of protons and net-protons in mid-central collisions (10-40% centrality) at midrapidity ($dv_1/dy$) shows a clear non-monotonic variation with respect to $\sqrt{s_{NN}} (\mu_B)$. The minimum value of $dv_1/dy$ lies somewhere between $\sqrt{s_{NN}} (\mu_B) = 27$ GeV (160 MeV) to 11.5 GeV (315 MeV). The net-proton $dv_1/dy$ changes sign twice in the beam energy range studied. This observable which is driven by the pressure gradients developed in the system is sensitive to first order phase transition effects. The energy dependence of the measured $dv_1/dy$ is consistent with a theoretical hydrodynamic model calculation with first order phase transition [24, 21].

Deviations of $\kappa\sigma^2$ and $S\sigma$ for net-proton distribution in 0-5% centrality is observed at $\sqrt{s_{NN}} = 19.6$ and 27 GeV from: (a) 70-80% peripheral collisions, (b) Poisson and hadron resonance gas expectation value of close to unity and (c) transport model based UrQMD calculation within the experimental acceptance. The deviations of $S\sigma$ and $\kappa\sigma^2$ below Poisson expectation are qualitatively consistent with a QCD based model which includes a CP [27]. Higher statistics data set at $\sqrt{s_{NN}} < 20$ GeV in the second phase of the beam energy scan program is needed to clarify whether the energy dependence of the observable will follow a non-monotonic variation with a minimum around $\sqrt{s_{NN}} = 27$ GeV to 11.5 GeV, as observed for the net-proton $dv_1/dy$, or a monotonic variation with $\sqrt{s_{NN}}$.

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