Observation of modified hadronization in relativistic Au+Au collisions: a promising signature for deconfined quark-gluon matter

Paul Sorensen
Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, California 94720
E-mail: prsorensen@lbl.gov

Abstract. Measurements of identified particles from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are reviewed. Emphasis is placed on nuclear modification, baryon-to-meson ratios, and elliptic flow at intermediate transverse momentum ($1.5 < p_T < 5$ GeV/c). Possible connections between (1) these measurements, (2) the running coupling for static quark anti-quark pairs at finite temperature, and (3) the creation of a deconfined quark-gluon phase are presented. Modifications to hadronization in Au+Au collisions are proposed as a likely signature for the creation of deconfined colored matter.

PACS numbers: 25.75.-q, 25.75.Ld

1. Introduction

A central question to be answered by scientists at Brookhaven National Laboratory’s Relativistic Heavy Ion Collider (RHIC) is: if nuclei are collided together with high enough center-of-mass energy, is it possible to create matter in which quarks and gluons become deconfined — i.e. are colored objects able to roam over distances greater than hadronic length scales? Lattice QCD calculations demonstrate that as the temperature of hadronic matter is increased above a critical value ($T_c$) quark and gluon degrees-of-freedom become accessible. This is most graphically demonstrated by the results from Ref. [2] shown in Fig. 1 (left) where the energy density $\epsilon$ scaled by $T^4$ is shown for different values of $T/T_c$. Calculations of the quark anti-quark coupling $\alpha_{qq}$ indicate, however, that even at temperatures several times greater than $T_c$, quarks and anti-quarks still feel effects of confinement [3]: i.e. “remnants of confinement”. Fig. 1 (right) shows the QCD coupling constant $\alpha(r,T/T_c)$ for static, heavy quark anti-quark pairs as a function of their separation $r$ for temperatures from $1.05 \cdot T_c$ to $12 \cdot T_c$. High-statistics lattice results from Ref. [4] for the coupling at $T = 0$ are shown on the figure as a thick, black line.
Measurements indicate that in Au+Au collisions at top RHIC energy, the energy density reaches values well above the critical energy density for deconfinement [5]. The fireball formed in these collisions rapidly expands and cools. If matter is formed with $T > T_c$, these calculations suggest that as the matter cools and approaches $T_c$ from above, the forces of confinement will turn on gradually. In this case, the process by which quarks and gluons become confined (i.e. hadronization) may be significantly modified in comparison to cases where a deconfined matter is not formed — in which case hadronization will take place in vacuum and $\alpha_{qq}(r)$ will have the form corresponding to the $T = 0$ case shown as a thick, black line in Fig. 1. Although the finite temperature calculations have only been made for static, heavy quark anti-quark pairs, the modifications to $\alpha(r, T/T_c)$ are likely to be robust and also present in the case of light quarks. As such, the best way to detect the presence of deconfined, colored matter in ultra-relativistic nuclear collisions may be to study how hadron formation is modified in Au+Au collisions compared to more elementary collisions (e.g. $e^+ + e^-$ or $p + p$ collisions).

According to de Broglie’s relation ($p = h/\lambda$) the momentum $p$ of a probe and the corresponding length scale that it can resolve (i.e. the wavelength $\lambda$) are inversely related. As the momentum transfer involved in scatterings increases, the resolution with which matter can be probed also increases. In nucleus-nucleus collisions at RHIC it is not feasible to probe the collision system with an external probe (as in scattering electrons or protons off the system formed after the gold ions collide). Instead, we rely on the particles produced by the collision to probe the matter formed.

For particles produced with sufficiently large momentum, a picture of the collision system as being composed of point-like particles (partons) should hold. Most particles produced in nucleus-nucleus collisions, however, are at much lower momentum and their long wavelengths probe the bulk characteristics of the produced matter (i.e. temperature, collective velocity, system-sizes, etc. [6, 7]). For momenta between the
two extremes (e.g. above 1 GeV/c), one might expect to probe length scales that are commensurate with the systems constituents — whether hadrons, “remnants of confinement”, or constituent quarks — without yet reaching the limit where the most appropriate description of the system is that of point-like partons. If the momentum is too high, we’ll probe the region of $\alpha(r, T/T_c)$ that, according to Fig. 1, is independent of temperature. If the momentum is too low, we may not have sensitivity to the modifications shown in the figure. For these reasons, the kinematic range where we would most naturally expect to find evidence for modifications to hadron formation is just below the momentum scale where a partonic, point-like picture holds.

2. Observations at intermediate-$p_T$

Three measurements from RHIC in the intermediate $p_T$ range (1.5 GeV/c $< p_T <$ 5 GeV/c) point towards modifications to the process of hadron formation in Au+Au collisions:

- the nuclear modification factors — i.e. the ratio of yields in central Au+Au collisions compared to peripheral Au+Au ($R_{CP}$) or p+p ($R_{AA}$) collision scaled by the number of binary nucleon-nucleon collisions [8, 9].
- the baryon-to-meson ratios [8, 10].
- the anisotropy in azimuth of particle production relative to the reaction plane — i.e. the elliptic flow parameter $v_2$ [9, 11, 12, 13, 14].

Fig. 2 shows the nuclear modification factor $R_{CP}$ for various identified particles measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR collaboration. In the case that the centrality dependence of particle yields scales with the number of binary nucleon-nucleon collisions, $R_{CP}$ will equal one. At $p_T = 5$ GeV/c, charged hadron yields in central collisions are suppressed from expectations by a factor of four. This
suppression is taken as a signature of the quenching of jets in the bulk matter formed in central collisions. The charged and neutral kaons show a suppression and $p_T$ dependence similar to that of charged hadrons. By contrast, the $R_{CP}$ values for $\Lambda_s+\bar{\Lambda}_s$ and $\Xi_s+\bar{\Xi}_s$ rise above the charged hadron values at $p_T \approx 1.5$ GeV/c and approach unity. They remain above charged hadron and kaon $R_{CP}$ values until $p_T \approx 5–6$ GeV/c. Similar observations were made by the PHENIX collaboration with proton $R_{AA}$ rising above pion $R_{AA}$ in a similar $p_T$ region [8].

$R_{CP}$ values for baryons being greater than those of mesons signifies that baryon production increases with centrality (and therefore collision overlap-density) more quickly than meson production. When $R_{CP}$ or $R_{AA}$ values for different particle types take on the same value (e.g. at $p_T = 5–6$ GeV/c), it means that the relative abundances of the different particles matches that observed in $p+p$ collisions. As such, the baryon-to-meson ratios in central Au+Au collisions at intermediate $p_T$, must also reflect the same baryon excesses. Fig. 3 shows measurements of proton/pion, anti-proton/pion [8] and $\Xi/K^0$ [10] ratios as a function of $p_T$ for various centralities and collision systems. At intermediate $p_T$, a striking difference is observed between the baryon-to-meson ratios in central Au+Au collisions and those in $e^+e^-$ or $p+p$ collisions [17]. The measurements in Figs. 2 and 3 demonstrate that the process by which parton distributions are mapped onto hadron distributions is drastically different in Au+Au and $p+p$ collisions. As long as hadronization is not modified, a change to the underlying parton distributions will not lead to such a drastic change in the relative abundances.

In non-central nucleus-nucleus collisions, the collision overlap region is elliptic in shape. Secondary interactions, can convert this initial coordinate-space anisotropy to an azimuthal anisotropy in the final momentum-space distributions. That anisotropy is commonly expressed in terms of the coefficients from a Fourier expansion of the
azimuthal component of the invariant yield $v_2$. The second component (the “elliptic flow” parameter $v_2$) is the largest and most commonly studied of the coefficients. Fig. 4 shows $v_2$ for pions, kaons, protons and Lambda hyperons $[9, 11]$. In the low momentum region ($p_T < 1.5$ GeV/c), $v_2$ is increasing with $p_T$ $[20]$. In this region, for a given $p_T$, the $v_2$ values are ordered by mass; with more massive particles having smaller $v_2$ values $[9, 11, 12, 21]$. This mass ordering is reasonably well described by the hydrodynamic model calculations $[22]$ also shown in the figure.

For $p_T > 1.5$ GeV/c, the data and model calculations deviate. The model over-predicts the measured $v_2$ values and the particle-type dependence reverses: the $v_2$ values for the more massive baryons are larger than those for the mesons. A model that relies on partonic, in-medium, energy-loss and vacuum fragmentation will predict smaller $v_2$ values when $R_{CP}$ is closer to one $[23]$. The data, however, indicate that although protons, $\Lambda$s, and $\bar{\Lambda}$s have $R_{CP}$ values near unity, their maximum $v_2$ values exceed those of pions and kaons by approximately 50%. Models that assume hadrons form via the coalescence of co-moving constituent-quarks, however, are able to simultaneously reproduce the particle-type dependencies of $R_{CP}$ and $v_2$ $[24]$. By extension, these models also account for the anomalously large baryon-to-meson ratios for central Au+Au collisions.

Coalescence models for hadronization predict that at intermediate $p_T$, $v_2$ for different hadrons will follow a scaling law based on the number of valence quarks in the corresponding hadron ($n_q$):

$$v_2^h(n_q \cdot p_T^2) = n_q \cdot v_2^q(p_T^2),$$  \hspace{1cm} (1)

where $v_2^h$, $v_2^q$, $p_T^h$, and $p_T^q$ are hadron $v_2$, quark $v_2$, hadron $p_T$, and quark $p_T$ respectively. If this scaling holds then $v_2^h(p_T^h/n_q)/n_q$ should fall on a universal curve. In these models this universal curve represents the $v_2$ value for the quark distributions prior to hadronization. In Fig. 5 this scaling is tested by plotting $v_2$ versus $p_T$, where both axes have been scaled by $n_q$. A polynomial curve is fit to all the data and the ratio of the data to the universal
Modified hadronization in Au+Au collisions

curve is plotted in the bottom panel. Very good agreement with the scaling prediction is found for all the hadron species except pions. The pion $v_2$ values deviate from the universal curve throughout the measured $p_T$ range and are not included in the fit. This deviation does not necessarily signal a violation of the scaling law because, the pion sample used to calculate $v_2$ is dominated by pions from resonance decays. Although the effect of resonance decays on the $v_2$ for other hadrons has been found to be relatively small, the effect was found to significantly increase the measured pion $v_2$ [25].

![Graph showing data and fits](image)

**Figure 5.** Quark number scaled $v_2$ ($v_2(p_T/n_q)/n_q$) for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from Ref. [14]. The bottom panel shows the ratio of the data to the fit. Pions are excluded from the fit but are shown in the figure for comparison.

The larger rate-of-increase for baryon production (i.e. $R_{CP}^{Baryon} > R_{CP}^{Meson}$), the anomalously large baryon-to-meson ratios in Au+Au collisions, and the quark-number-scaling for $v_2$, point to possible modifications of hadron formation in Au+Au collisions compared to p+p collisions. Models in which hadronization occurs via coalescence of co-moving constituent quarks successfully account for these three observations [24]. These hadronization models demonstrate one way that the hadron formation process could be modified. Whether these models remain successful as more precise measurements are made is still an open question. The evidence for modifications to hadronization from data, however, are clear and independent of the theoretical models.
3. Conclusions

Identified particle nuclear modification $R_{CP}$ and elliptic flow $v_2$ measurements made in Au+Au collisions at RHIC have revealed an apparent quark-number dependence in the $p_T$ region from 1.5 GeV/c to 5 GeV/c. The $v_2$ measurements follow a quark-number scaling predicted by models of hadron formation via coalescence of co-moving quarks. The $R_{CP}$ measurements show that baryon production increases more rapidly with centrality than meson production — an observation that also supports a picture of hadron formation by quark coalescence or recombination. These observations are consistent with the presence of modifications to the hadronization process in Au+Au collisions compared to $e^+ + e^-$ or $p + p$ collisions.

A picture of hadron formation with an intermediate, constituent-quark step, is highly suggestive of the formation of deconfined quark-gluon matter. The modified hadron formation process points to a scenario where matter is created with a temperature above $T_c$ and then cools — approaching $T_c$ from above — until confinement is gradually re-enforced. Lattice calculations of the QCD coupling constant $\alpha(r, T/T_c)$ for static quark anti-quark pairs show that this process is consistent with the equations of QCD. These calculations and the empirical observations presented here demonstrate that modifications to the hadronization process in nuclear collisions are promising signatures for the creation of deconfined quark-gluon matter.

Acknowledgements

The author thanks the conference organizers and acknowledges valuable input from H. Huang, K. Schweda, R. Seto, and N. Xu.

References

[1] M. Harrison, T. Ludlam and S. Ozaki, Nucl. Instrum. Meth. A 499, 235 (2003).
[2] F. Karsch, Lect. Notes Phys. 583, 209 (2002).
[3] O. Kaczmarek, F. Karsch, F. Zantow and P. Petreczky, arXiv:hep-lat/0406036; O. Kaczmarek, F. Karsch, P. Petreczky and F. Zantow, Phys. Lett. B 543, 41 (2002).
[4] S. Necco and R. Sommer, Nucl. Phys. B 622, 328 (2002).
[5] B. B. Back et al. [PHOBOS Collaboration], Phys. Rev. Lett. 85, 3100 (2000); K. Adcox et al. [PHENIX Collaboration], Phys. Rev. Lett. 87, 052301 (2001).
[6] C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 87, 182301 (2001).
[7] C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 87, 082301 (2001).
[8] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 172301 (2003).
[9] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 92, 052302 (2004).
[10] H. Long [STAR Collaboration], J. Phys. G 30, S193 (2004).
[11] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 182301 (2003).
[12] P. Sorensen [STAR Collaboration], J. Phys. G 30, S217 (2004); P. R. Sorensen, Ph.D. thesis, UCLA, 2003. arXiv:nucl-ex/0309003
[13] K. Schweda [STAR Collaboration], J. Phys. G 30, S693 (2004); J. Castillo [STAR Collaboration], J. Phys. G 30, S1207 (2004).
Modified hadronization in Au+Au collisions

[14] J. Adams et al. [STAR Collaboration], arXiv:nucl-ex/0409033.
[15] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 91, 172302 (2003).
[16] H. b. Zhang [STAR Collaboration], arXiv:nucl-ex/0403010.
[17] P. Abreu et al. [DELPHI Collaboration], Eur. Phys. J. C 17, 207 (2000).
[18] B. Alper et al. [British-Scandinavian Collaboration], Nucl. Phys. B 100, 237 (1975).
[19] S. Voloshin and Y. Zhang, Z. Phys. C 70, 665 (1996); A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998).
[20] K. H. Ackermann et al. [STAR Collaboration], Phys. Rev. Lett. 86, 402 (2001).
[21] C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 89, 132301 (2002).
[22] P. Huovinen, P. F. Kolb, U. W. Heinz, P. V. Ruuskanen and S. A. Voloshin, Phys. Lett. B 503, 58 (2001).
[23] R. Baier, D. Schiff and B. G. Zakharov, Ann. Rev. Nucl. Part. Sci. 50, 37 (2000); M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, arXiv:nucl-th/0302077.
[24] D. Molnar and S. A. Voloshin, Phys. Rev. Lett. 91, 092301 (2003); R. C. Hwa and C. B. Yang, Phys. Rev. C 67, 064902 (2003); R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. C 68, 044902 (2003); V. Greco, C. M. Ko and P. Levai, Phys. Rev. C 68, 034904 (2003); V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. 90, 202302 (2003); R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003).
[25] V. Greco and C. M. Ko, Phys. Rev. C 70, 024901 (2004); X. Dong, S. Esumi, P. Sorensen, N. Xu and Z. Xu, Phys. Lett. B 597, 328 (2004).