Probing QGP medium properties using identified particles and new detector technology

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Abstract. Two physics topics, jet quenching at high transverse momentum ($p_T$) and baryon enhancement at intermediate $p_T$ at the Relativistic Heavy Ion Collider (RHIC) will be introduced. Identified particle measurements up to high $p_T$ will be presented to study the color charge dependence of energy loss in the medium. The physics capabilities of the Time-of-Flight detector (TOF) at the Solenoidal Tracker at RHIC (STAR) will be discussed.

1. Introduction
Data taken in the last decade have demonstrated that the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) has created a strongly interacting hot, dense medium with partonic degrees of freedom, the Quark Gluon Plasma (QGP) in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [1, 2, 3, 4]. Such matter is believed to have existed a few microseconds after the big bang. Understanding the properties of this matter, such as the colored degrees of freedom and the equation of state, is the physics goal of RHIC and of broad interest. I will show two experimental measurements which were used to identify the existence of the hot, dense medium and probe the medium properties. The physics capabilities of recent upgrades will be discussed as well.

RHIC at Brookhaven National Laboratory is the first hadron accelerator and collider consisting of two independent rings. It is designed to operate at high collision luminosity over a wide range of beam energies and particle species ranging from polarized proton to heavy ion [5, 6], where the top energy of the colliding center-of-mass energy per nucleon-nucleon pair is $\sqrt{s_{NN}} = 200$ GeV. The RHIC facility consists of two rings with superconducting magnets, each with a circumference of 3.8 km, which focus and guide the beams. There are four experiments at RHIC, BRAHMS [7], PHENIX [8], PHOBOS [9], and STAR [10]. BRAHMS and PHOBOS are relatively small experiments. They have finished their experimental program and were decommissioned after year 2008. STAR and PHENIX, the two large detectors, are still in operation.

2. The hot and dense medium that RHIC has created
In 2000, the experiments started to take data. In 2005, the four experiments published white papers summarizing what has been discovered [1, 2, 3, 4]. The focus of RHIC was to identify the existence of the QGP. Two probes, bulk probes and penetrating probes, were used very commonly to identify QGP. Bulk probes include measurements of the majority of produced particles at low $p_T$ ($p_T < 2$ GeV/$c$) to address the energy density, collectivity and freeze-out.
properties of the hot, dense medium. For example, the rapidity dependence of the particle multiplicity demonstrates that the 26 TeV energy has been dumped into the system to produce particles in 200 GeV central Au+Au collisions [11]. As the energy density is much higher than normal nuclear matter density, it is believed that partonic matter is formed in such collisions [12]. Penetrating probes are the measurements of the rarely produced particles such as heavy flavor, jets and identified particles at high $p_T$ ($p_T > 6$ GeV/$c$) to see the medium effect on their productions and thereby are used to deduce medium properties. The measurements at intermediate $p_T$ ($2 < p_T < 6$ GeV/$c$) probe the interplay between bulk and hard components and reveal some unique interesting features of the collisions at RHIC.

2.1. Jet quenching at high $p_T$

Hard probes such as identified particles at high $p_T$, jets and and heavy flavor are thought to be ideal probes for quark gluon plasma. They are thought to be well calibrated since they are believed to be produced from hard processes with high $Q^2$ transfer and thus can be calculated in the perturbative Quantum Chromodynamic (pQCD) framework [13]. In pQCD calculations, identified particle production can be described as a convolution of parton distribution functions, parton parton interaction cross sections and parton fragmentation functions. When hard partons traverse the hot and dense medium created in the collision, they lose energy by gluon radiation and/or colliding elastically with surrounding partons [14, 15, 16]. This phenomenon is also called jet quenching. Jet quenching leads to a softening of the final measured hadron spectra at high $p_T$. The amount of energy loss can be calculated in QCD and is expected to be different for energetic gluons, light quarks and heavy quarks [17, 18]. In experiments, in order to quantify the effect of the medium, the nuclear modification factors ($R_{AB}$ or $R_{CP}$) are measured, where the invariant yield in A+B collisions is divided by that in p+p or peripheral A+B collisions, scaled by their respective numbers of binary nucleon-nucleon collisions. If there was no nuclear medium effect, the ratio would be 1 at high $p_T$. Any deviation from unity therefore indicates nuclear medium effects. This is similar to medical imaging techniques, where the picture of a human body can be obtained through the calibrated gamma ray interaction.

The $R_{AA}$ of inclusive hadrons in central Au+Au collisions at 200 GeV at mid-rapidity shows a factor of 5 suppression with respective to unity at $p_T > 6$ GeV/c [15, 16], as shown in the left panel of Fig. 1. There could be two effects: partonic energy loss in the medium or the initial nuclear wave function difference in Au+Au collisions. In 2004 d+Au collisions were used to distinguish these two effects. Shown on the same plot are the $R_{dAu}$ of inclusive charged hadrons in minimum-bias and central d+Au collisions. The $R_{dAu}$ of inclusive charged hadrons in d+Au collisions shows enhancement at intermediate $p_T$ and equals to unity at high $p_T$ [19, 20]. Furthermore, shown on the right panel of Fig. 1 are the $R_{dAu}$ for identified charged hadrons, pions, kaons and protons [21]. It shows that pions and protons are enhanced at intermediate $p_T$ in $R_{dAu}$ [21]. At high $p_T$, the $R_{dAu}$ of pions and protons are close to unity [22]. All these measurements indicate that the strong suppression observed in $R_{AA}$ in central Au+Au collisions is due to final state effects and not due to an initial wave function difference such as a possible color glass condensate (CGC) [23] at mid-rapidity. The pQCD calculation with gluon density $dN_g/dy = 1000$ and with radiative energy loss can describe the suppression [14] in central Au+Au collisions for inclusive charged hadrons.

The above measurements indicate that the suppression on $R_{AA}$ of high $p_T$ particles in central Au+Au collisions are consistent with partonic energy loss picture.

2.2. Baryon enhancement at intermediate $p_T$

Between low $p_T$ where the physics is dominated by bulk properties and high $p_T$ where the particle production is by jet fragmentation, there is also rich physics which can be used to explore the properties of the medium created in heavy ion collisions. In central Au+Au collisions, the $p/\pi$
ratio reaches unity at $p_T \sim 2$ GeV/c, which is much larger than that from elementary $p+p$ collisions [24]. This was very surprising. Furthermore, it was found that at intermediate $p_T$, $R_{dAu}$ for baryons (protons and $\Lambda$) is larger than that for mesons (pions and kaons), indicating strong baryon enhancement in $Au+Au$ collisions [24, 25], as shown in Fig. 2. Coalescence or recombination models [26], in which two or three constituent quarks are combined into mesons or baryons, were proposed to explain the data. Such a model can qualitatively reproduce the feature. The parton density at RHIC is significant so that parton recombination into hadrons is efficient. In the same $p_T$ region, the parton $p_T$ for baryons is effectively lower than that for mesons. The baryon over meson ratio can therefore be significantly enhanced in the intermediate $p_T$ region in central $Au+Au$ collisions.

The above measurements are consistent with the picture that a hot, dense medium was created at RHIC. Jets lose energy when traversing the medium and partons can recombine into hadrons at hadronization.

3. Probing color charge dependence of energy loss in the medium

To further understand energy loss mechanisms and medium properties, nuclear modification factors for direct photons were measured. The $R_{AA}$ from direct photons, which are the inclusive photon yields subtracting hadronic decay contributions, is consistent with no suppression at high $p_T$ [27]. This confirms that the suppression observed in the $R_{AA}$ for hadrons is due to jet quenching, rather than initial wave function change which would affect the direct photons as well.

In addition, nuclear modification factors for protons and pions were also measured to test color charge dependence of energy loss. For example, gluons carry different Casimir factor from quarks. The coupling of gluons to the medium is stronger than the coupling of quarks to the medium thus gluons are expected to lose more energy than quarks when traversing the medium. At RHIC energy, the gluon jet contribution to protons (even more so for anti-protons) is significantly larger than to pions at high $p_T$ [17, 21, 22, 28]. Therefore, protons, even more so...
Figure 2. Left panel: $R_{CP}$ of protons and pions for central Au+Au collisions. The grey bands show the normalization uncertainties. This figure is taken from ref. [24]; right panel: $R_{CP}$ for $K^0_S$, $K^\pm$, $\Lambda$ in central Au+Au collisions. This figure is taken from ref. [25].

Figure 3. Nuclear modification factors $R_{CP}$ for $\pi^+ + \pi^-$ and $p + {\bar p}$ in 200 GeV Au+Au collisions. The point-to-point systematic uncertainties are shown as the shaded boxes around the data points. The dark shaded bands show the normalization systematic uncertainty in the number of binary collisions. The figure is taken from ref. [29].

for anti-protons, are expected to be more suppressed than pions in $R_{AA}$ or $R_{CP}$ measurements.

The data used for this analysis were taken in the year 2004 by the STAR experiment [10]. Measurements of the ionization energy loss ($dE/dx$) of charged tracks in the Time Projection Chamber (TPC) gas are used to identify pions (protons) in the region $p_T \leq 0.75$ ($\leq 1.1$) GeV/c and $2.5 \leq p_T \leq 12$ GeV/c [30, 31]. In order to identify charged hadrons at $1 < p_T < 3$ GeV/c, a Time-of-Flight detector (TOF) based on Multi-gap Resistive Plate Chamber Technology was
proposed at STAR [32]. It has full azimuthal coverage at mid-rapidity. Based on its excellent timing resolution, pions and kaons can be identified up to \( p_T \sim 1.6 \text{ GeV}/c \) while protons can be identified up to 3 GeV/c. Over the last three years, we started to install a big portion of the full system and the upgrade was finished last summer. Before 2008, a prototype Time-of-Flight detector covering \( \pi/30 \text{ rad} \) in azimuth and \(-1<\eta<0\) in pseudorapidity [31], was used for many physics data analyses. By combining the particle identification capability of \( dE/dx \) from the TPC and velocity from the TOF, pions and protons can be identified up to 12 GeV/c [21, 31].

Shown in Fig. 3 are nuclear modification factors \( R_{CP} \) for pions and protons in central Au+Au collisions [29]. At intermediate \( p_T \), \( p \) and \( \bar{p} \) are less suppressed, with respect to binary scaling, than \( \pi^\pm \), but a significant suppression is still observed in central Au+Au collisions. This is in contrast to nuclear modification factors in d+Au collisions, where a significant enhancement is seen for protons [21, 22]. Previous measurements at lower transverse momentum [24] showed that \( R_{CP} \) for protons is close to 1 for \( 1.5 < p_T < 4.5 \text{ GeV}/c \). Our results agree with those measurements within systematic errors, but our data do not suggest that \( R_{CP} \) is constant over the range \( 1.5 < p_T < 4.5 \text{ GeV}/c \) and the extended \( p_T \) reach shows that \( R_{CP} \) for protons decreases again at higher \( p_T \).

The results in Fig. 3 clearly show a different \( R_{CP} \) for protons and pions at intermediate \( p_T \). A similar effect has been observed for \( K_S^0 \) and \( \Lambda \) [25], with \( K_S^0 \) (\( \Lambda \)) \( R_{CP} \) similar to pion (proton) \( R_{CP} \). The grouping of particle production according to the number of constituent quarks has been attributed to quark coalescence at hadronization from a collective partonic medium [26]. Our high statistics measurements show that these effects disappear at high \( p_T \), where baryons and mesons show a common degree of suppression. This is consistent with the general expectation that collective and coalescence effects have a finite \( p_T \) reach. The common suppression observed in \( \pi^+ + \pi^- + p + \bar{p} \) challenges the naive pQCD energy loss model calculations and puts constraints on the characteristics of jet quenching.

4. Lepton program from the TOF and proposed Muon Telescope Detector (MTD) at STAR

In addition to its hadron identification capability, the TOF at STAR provides an excellent identification capability for muons at \( p_T < 0.25 \text{ GeV}/c \) [33] and electrons at \( 0.2 < p_T < 3 \text{ GeV}/c \) [34] together with the TPC. Many interesting physics topics can be investigated with its lepton identification capability. To further understand the medium properties, heavy flavor measurements serve as an ideal probe since the mass of charm and bottom quark is much larger than the possible temperature in QGP so that \( cc \) pairs are believed to be produced at initial impact. Any modification of the heavy flavor production would be sensitive to the medium modifications and properties. The electrons and muons from charm decay can put constraints on the charm cross section as well as on the flavor dependence of energy loss calculations [34]. Furthermore, the precise measurement of transverse momentum distributions of \( J/\psi \rightarrow e^+e^- \) at different centralities, collision systems, and energies will put constraints on two possible competing effects for \( J/\psi \), the color screening [35] and recombination effect [36, 37, 38, 39] in the medium. The efficiency by including the TOF for \( J/\psi \) measurement is enhanced by more than a factor of 10.

In addition, utilizing its lepton identification capabilities, the di-lepton continuum from QGP thermal radiation and di-leptonic decays from vector mesons can be studied. The di-lepton spectra at intermediate mass range are directly related to thermal radiation of the QGP [40]. At low mass range, we can study the vector meson in-medium properties through their di-lepton decays, the observable of a possible chiral symmetry restoration. For example, we can measure \( \phi \rightarrow e^+e^- \) and \( \phi \rightarrow K^+K^- \) in p+p and Au+Au collisions to see whether the yield ratios from these two decay channels are the same or not. We can measure \( \rho \rightarrow e^+e^- \) to see whether there is a mass shift or broadening and also compare the possible \( a_1 \rightarrow \gamma\pi \) measurements. These
measurements will shed light on the study of chiral symmetry restoration. To further study the medium properties using quarkonia and di-leptons, we proposed a large-area and cost-effective Muon Telescope Detector (MTD) at mid-rapidity for STAR [41]. The proposed large-area MTD, based on Multi-gap Resistive Plate Chamber technology, covers $\sim 45\%$ in azimuth and $|\eta| < 0.5$ in pseudorapidity behind the return iron bars for the STAR magnetic. It will provide excellent muon trigger and identification capabilities at mid-rapidity in the high-luminosity era at RHIC. A large area detector identifying muons with momentum of a few GeV/c at mid-rapidity allows for the detection of di-muon pairs from QGP thermal radiation, quarkonia, light vector mesons, possible correlations of quarks and gluons as resonances in QGP, and Drell-Yan production. It also allows for the measurement of heavy flavor hadrons through their semi-leptonic decays into single muons [40]. Muons are less affected by Bremsstrahlung radiation energy loss in the detector materials than electrons, thus providing excellent mass resolution of vector mesons and quarkonia. This is essential for separating the ground state (1S) of $\Upsilon$ from its excited states (2S+3S). They are predicted to melt at very different temperatures.
Shown in the bottle panel of Fig. 4 is the invariant mass distribution of di-muon decayed from $\Upsilon$ at $0 < p_T < 5$ GeV/$c$. The different $\Upsilon$ states can be clearly separated through di-muon decay channel.

5. Summary

Two physics topics, jet quenching and baryon enhancement are introduced in this paper. The common suppression observed in the nuclear modification factors $R_{CP}$ of pions, protons and anti-protons puts constraints on the characteristics of jet quenching. The future measurements on heavy flavor, quarkonia and di-lepton from the TOF and the proposed MTD at STAR will further the understanding of the properties of the hot, dense medium created at RHIC.

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References

[1] J. Adams et al., Nucl. Phys. A 757, 102 (2005).
[2] I. Arsene et al., Nucl. Phys. A 757, 1 (2005).
[3] K. Adcox et al., Nucl. Phys. A 757, 184 (2005).
[4] B.B. Back et al., Nucl. Phys. A 757, 28 (2005).
[5] http://www.rhic.bnl.gov/.
[6] T. Roser, Nucl. Phys. A 688, 23c-28c (2002).
[7] M. Adamczyk et al., Nucl. Instrum. Meth. A 499, 437 (2003).
[8] PHENIX Conceptual Design Report 1993 (PX20, BNL48922, internal report) 1993.
[9] B.B. Back et al., Nucl. Instrum. Meth. A 499, 603 (2003).
[10] J. Harris et al., Nucl. Instrum. Meth. A 499, 624 (2003).
[11] J.G. Bearden et al., Phys. Rev. Lett. 93, 102301 (2004).
[12] K. Adcox et al., Phys. Rev. Lett. 87, 052301 (2001).
[13] J.C. Collins, D.E. Soper, Annu. Rev. Nucl. Part. Sci. 37 (1987) 383; J.C. Collins, D.E. soper, G. Sterman, Adv. Ser. Direct. High Energy Phys. 5 (1988) 1.
[14] M. Gyulassy et al., nucl-th/0302077; A. Kovner et al., hep-ph/0304151, Review for: Quark Gluon Plasma 3, Editors: R.C. Hwa and X.N. Wang, World Scientific, Singapore.
[15] J. Adams et al., Phys. Rev. Lett. 91, 172302 (2003).
[16] S.S. Adler et al., Phys. Rev. Lett. 91, 072301 (2003); S.S. Adler et al., Phys. Rev. Lett. 91, 241803 (2003); B.B. Back et al., Phys. Rev. Lett. B 578, 297 (2004); I. Arsene et al., Phys. Rev. Lett. 91, 072305 (2003).
[17] X.N. Wang, Phys. Rev. C 58, 2321 (1998).
[18] Y. Dokshitzer et al., Phys. Lett. B 519, 199 (2001).
[19] J. Adams et al., Phys. Rev. Lett. 91, 072304 (2003).
[20] I. Arsene et al., Phys. Rev. Lett. 91, 072305 (2003); S.S. Adler et al., Phys. Rev. Lett. 91, 072303 (2003); B.B. Back et al., Phys. Rev. Lett. 91, 072302 (2003).
[21] J. Adams et al., Phys. Lett. B 616, 8 (2005); Lijuan Ruan, Ph.D thesis, "Pion, Kaon, Proton and Antiproton Spectra in d+Au and p+p Collisions at C^{p}$ at the Relativistic Heavy Ion Collider", University of Science and Technology of China, 2005, arXiv:nucl-ex/0503018.
[22] J. Adams et al., Phys. Lett. B 637, 161 (2006).
[23] A.H. Mueller, Nucl. Phys. B 335, 115 (1990); A.H. Mueller, Nucl. Phys. B 572, 227 (2002); L.D. McLerran, R. Venugopalan, Phys. Rev. D 49, 2233 (1994); L.D. McLerran, hep-ph/0311028; E. Iancu, R. Venugopalan, in: R.C. Hwa, X.N. Wang (Eds.), Quark Gluon Plasma 3, World Scientific, Singapore, 2003, hep-ph/0303204.
[24] K. Adcox et al., Phys. Rev. Lett. 88, 242301 (2002); S.S. Adler et al., Phys. Rev. Lett. 91, 172301 (2003).
[25] J. Adams et al., Phys. Rev. Lett. 92, 052302 (2004).
[26] D. Molnar et al., Phys. Rev. Lett. 91, 092301 (2003); R.C. Hwa et al., Phys. Rev. C 70, 024905 (2004); R.J. Fries et al., Phys. Rev. C 68, 044902 (2003); V. Greco et al., Phys. Rev. Lett. 90, 202302 (2003).
[27] S.S. Adler et al., Phys. Rev. Lett. 94, 232301 (2005).
[28] S. Albino et al., Nucl. Phys. B 725, 181 (2005).
[29] B.I. Abelev et al., Phys. Rev. Lett. 97, 152301 (2006); B.I. Abelev et al., Phys. Lett. B 655, 104 (2007).
[30] M. Anderson et al., Nucl. Instr. Meth. A 499, 659 (2003).
[31] B. Bonner et al., Nucl. Instr. Meth. A 508, 181 (2003); M. Shao et al., Nucl. Instr. Meth. A 492, 344 (2002).
[32] STAR Time-of-Flight Proposal: http://www.star.bnl.gov/STAR/tof/publications/TOF_20040524.pdf.
[33] B.I. Abelev et al., arXiv:0805.0364.
[34] J. Adams et al., Phys. Rev. Lett. 94, 62301 (2005); B.I. Abelev et al., Phys. Rev. Lett. 98, 192301 (2007).
[35] T. Matsui and H. Satz, Phys. Lett. B 178, 416 (1986).
[36] P. Braun-Munzinger and J. Stachel, Phys. Lett. B 490, 196 (2000).
[37] L. Grandchamp and R. Rapp, Phys. Lett. B 523, 60 (2001).
[38] M. I. Gorenstein et al., Phys. Lett. B 524, 265 (2002).
[39] R. L. Thews, M. Schroedter and J. Rafelski, Phys. Rev. C 63, 054905 (2001).
[40] R. Rapp and J. Wambach, Adv. Nucl. Phys. 25 (2000) 1; Electromagnetic Probes at RHIC II (Working Group Report), G. David, R. Rapp and Z. Xu, Phys. Rept. 462, 176 (2008); S. Afanasiev et al., nucl-ex/0706.3034; A. Adare et al., nucl-ex/0804.4168.
[41] Z. Xu, BNL LDRD project 07-007; L. Ruan et al., J. Phys. G 36, 095001 (2009); L. Ruan et al., WWND2008 proceedings, nucl-ex/0805.4638; STAR Muon Telescope Detector Proposal: http://drupal.star.bnl.gov/STAR/system/files/MTD_proposal_v14.pdf.