Eur. Phys. J. C (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02233-x

THE EUROPEAN
PHYSICAL JOURNAL C

Charm and beauty tomography of the sQGP

M. Djordjevic[a], M. Gyulassy, S. Wicks

Columbia University, Physics Department, Pupin Labs, 538 West 120-th Street, New York, NY 10027, USA

Received: 28 February 2005 /
Published online: 18 May 2005 –

Abstract. Heavy quark production and attenuation provide unique tomographic probes of QCD matter produced at ultrarelativistic heavy ion experiments. In these proceedings we study the suppression pattern of open charm and beauty in Au+Au collisions at RHIC energies based on the DGLV formalism of radiative energy loss.

PACS. 12.38.Mh, 24.85.+p, 25.75.-q

1 Introduction

One of the most important goals of ultrarelativistic heavy ion experiments is to create, observe and explore new forms of matter, consisting of interacting quarks, antiquarks and gluons. One primordial form of matter, called the quark gluon plasma (QGP), is believed to have existed only up to a microsecond after the Big Bang. If this QGP phase can be created in the laboratory, then a wide variety of probes and observables could be used to diagnose and map out its physical properties.

The striking set of new phenomena observed [1] at the Relativistic Heavy Ion Collider (RHIC), such as strong collective elliptic flow and light quark and gluon jet quenching, together with the decisive null control $d+$ Au data, provide strong evidence that a strongly coupled quark gluon plasma (sQGP) has been discovered at RHIC. While there has been considerable convergence on the theoretical interpretation [2,3] of RHIC data, a further detailed test of jet tomography [4] using heavy quarks could be decisive as a complementary test of the theory.

Heavy quarks provide important independent observables that can probe the opacity and color field fluctuations in the sQGP produced in high energy nuclear collisions. In these proceedings, we present predictions of open charm and beauty quark suppression that can be tested at RHIC facilities.

2 Theoretical framework

The prediction of the D and B meson suppression pattern, in principle requires theoretical control over the interplay between many competing nuclear effects [5] that can modify the $p_\perp$ hadron spectra of heavy quarks. To study high $p_\perp$ ($p_\perp > 6\,\mathrm{GeV}$) heavy quark suppression, we concentrate on the interplay between the two most important effects, i.e. jet quenching [4,5] and the energy dependence of the initial pQCD heavy quark $p_\perp$ distribution. We note that, for lower, $p_\perp < 6\,\mathrm{GeV}$, spectra non-perturbative effects neglected here, for example collective hydrodynamic flow, quark coalescence and the strong gluon shadowing in the initial CGC state, may become important [3].

To compute the heavy quark meson suppression we apply the DGLV generalization [8] of the GLV opacity expansion [9] to heavy quarks. We take into account multi-gluon fluctuations as in [10].

To apply this method, we need to know the following.
(1) The initial heavy quark $p_\perp$ distribution $\frac{\mathrm{d}N_q^0}{\mathrm{d}p_0}$. Here, p_0 is the initial momentum of the quark.
(2) The difference between the medium and vacuum gluon radiation spectrum $P(\epsilon, p_0)$. Here, ϵ is the fractional energy loss. To compute the full fluctuating gluon spectrum we have applied (4) from [10] to the heavy quark case.
(3) Heavy quark fragmentation functions, $D^0_{h/q}(z_h)$. Here, $z_h = p_h/p_q$, and p_h is the hadron momentum, while p_q is the final momentum of the quark.

It is easy to show that the observable hadron spectrum $\frac{\mathrm{d}N_h}{\mathrm{d}p_h}$ is then given by

$$\frac{\mathrm{d}N_h}{\mathrm{d}p_h} = \int_{p_h} \frac{\mathrm{d}p_0}{p_0}\, \frac{\mathrm{d}N_q^0}{\mathrm{d}p_0} \int_0^{1-z_h} \mathrm{d}\epsilon P(\epsilon, p_0) \frac{D^0_{h/q}\left(\frac{z_h}{1-\epsilon}\right)}{1-\epsilon}. \quad (1)$$

To obtain the initial heavy quark $p_\perp$ distributions in the central rapidity region ($|y| < 0.5$) we used the MNR code [11]. As in [12] we assume the charm mass to be $M_c = 1.2\,\mathrm{GeV}$ and the bottom mass $M_b = 4.75\,\mathrm{GeV}$. For simplicity, we have concentrated only on bare quark distributions ($\langle k_\perp^2 \rangle = 0\,\mathrm{GeV}^2$), and the runs were performed by using CTEQ5M parton distributions. The initial $p_\perp$ distributions used in our computations are shown in Fig. 1.

[a] e-mail: dmani@phys.columbia.edu

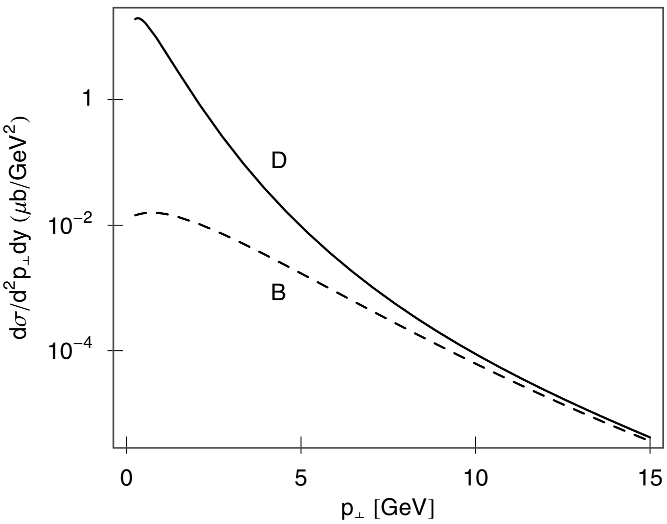

Fig. 1. Initial $p_\perp$ distributions are shown for charm (full curve) and bottom (dashed curve)

To compute the full fluctuating gluon radiation spectrum ($P(\epsilon, p_0)$), we have to include three medium effects that control heavy quark energy loss. These effects are
(1) the Ter-Mikayelian, or massive gluon effect [13,14]; (2) transition radiation [15] which comes from the fact that the medium has a finite size, and
(3) the medium induced energy loss [14,8], which corresponds to the additional gluon radiation induced by the interaction of the jet with the medium. In [16] we stated that the first two effects are not important for heavy quark suppression, and therefore in that letter we addressed only the medium induced gluon radiation spectrum. For completeness, in these proceedings we will compute the suppression by including all three medium effects. A comparison with the results from [16] will therefore enable us to test whether it is justified to neglect the dielectric effects in our computations.

The difference between the medium and vacuum gluon radiation spectrum is given by

$$\frac{\mathrm{d}N}{\mathrm{d}x} = \frac{\mathrm{d}N_{\mathrm{p}}^{(0)}}{\mathrm{d}x} - \frac{\mathrm{d}N_{\mathrm{v}}^{(0)}}{\mathrm{d}x} + \frac{\mathrm{d}N_{\mathrm{ind}}^{(1)}}{\mathrm{d}x}. \tag{2}$$

Here, $\frac{\mathrm{d}N_{\mathrm{p}}^{(0)}}{\mathrm{d}x}$ is the total radiation spectrum 0th order in the opacity in the QGP. It includes both the Ter-Mikayelian effect and transition radiation [15,17]. $\frac{\mathrm{d}N_{\mathrm{v}}^{(0)}}{\mathrm{d}x}$ is the radiation spectrum 0th order in opacity in the vacuum [13]. $\frac{\mathrm{d}N_{\mathrm{ind}}^{(1)}}{\mathrm{d}x}$ is the medium induced gluon radiation spectrum given by [8].

The relevant gluon radiation spectrum expressions are given below:

$$\begin{aligned}
&\frac{\mathrm{d}N_{\mathrm{p}}^{(0)}}{\mathrm{d}x} - \frac{\mathrm{d}N_{\mathrm{v}}^{(0)}}{\mathrm{d}x} \\
&= \frac{2C_F\alpha_{\mathrm{s}}}{\pi}\int_0^1 \mathrm{d}xE\int \mathbf{k}^2\,\mathrm{d}\mathbf{k}^2 \\
&\quad\times\frac{\theta(2x(1-x)p_\perp - |\mathbf{k}|)(m_{g,v}^2 - m_{g,p}^2)}{(\mathbf{k}^2+m_{g,p}^2+M^2x^2)^2(\mathbf{k}^2+m_{g,v}^2+M^2x^2)} \\
&\quad\times\left[1-\cos\left(\frac{(\mathbf{k}^2+m_{g,p}^2+M^2x^2)L}{2p_\perp x(1-x)}\right)\right]
\end{aligned} \tag{3}$$

and

$$\begin{aligned}
\frac{\mathrm{d}N_{\mathrm{ind}}^{(1)}}{\mathrm{d}x} &= \frac{C_F\alpha_S}{\pi}\frac{L}{\lambda_g}\int_0^\infty \frac{2\mathbf{q}^2\mu^2\mathrm{d}\mathbf{q}^2}{\left(\frac{4Ex}{L}\right)^2 + (\mathbf{q}^2+M^2x^2+m_{g,p}^2)^2} \\
&\times\int\frac{\mathrm{d}\mathbf{k}^2\;\theta(2x(1-x)p_\perp - |\mathbf{k}|)}{((|\mathbf{k}|-|\mathbf{q}|)^2+\mu^2)^{3/2}((|\mathbf{k}|+|\mathbf{q}|)^2+\mu^2)^{3/2}} \\
&\times\left\{\mu^2 + (\mathbf{k}^2-\mathbf{q}^2)\frac{\mathbf{k}^2-M^2x^2-m_{g,p}^2}{\mathbf{k}^2+M^2x^2+m_{g,p}^2}\right\}.
\end{aligned} \tag{4}$$

Here, $\mathbf{k}$ is the transverse momentum of the radiated gluon and $\mathbf{q}$ is the momentum transfer to the jet. M is the heavy quark mass, $\mu = 2(\rho/2)^{1/3}$ is the Debye mass, $\lambda_g = \frac{8}{9}\frac{\mu^2}{4\pi\alpha_S^2\rho}$ is the mean free path [9], $m_{g,p} = \mu/\sqrt{2}$ is the gluon mass in the medium, $m_{g,p} \approx \Lambda_{\mathrm{QCD}}$ is the gluon mass in the vacuum and $E = \sqrt{p_\perp^2 + M^2}$ is the initial heavy quark energy. We assume a constant $\alpha_S = 0.3$. For central collisions we take $L = R_x = R_y = 6\,\mathrm{fm}$, and assume that ρ is given by ($1+1$D Bjorken longitudinal expansion [18]) $\rho = \mathrm{d}N_{\mathrm{g}}/\mathrm{d}y\tau\pi L^2$, where $\frac{\mathrm{d}N_{\mathrm{g}}}{\mathrm{d}y}$ is the gluon rapidity density, and τ is the proper time.

The energy loss was computed for both $1+1$D Bjorken longitudinal expansion and using an effective *average* ρ approximation, where we replace τ by $\langle\tau\rangle = \frac{L}{2}$. Since both procedures produce similar results, in these proceedings we present only the computationally simpler (average ρ) results.

One of the main problems in applying the approach [10] to compute heavy meson suppression, is that we do not know the fragmentation functions for charm and beauty quarks. Two different types of heavy quark fragmentation function that appear in the literature are the δ-function fragmentation [19] and the Peterson fragmentation [20]. In these proceedings we will also test how the heavy meson suppression results depend on the choice of the fragmentation functions.

3 Heavy quark suppression at RHIC

In these proceedings we concentrate on the RHIC conditions and study how the suppression for charm and beauty quarks depend on
(1) dielectric effects,
(2) fragmentation functions, and
(3) fractional energy loss distributions. For a comparison between RHIC and LHC suppression results, please refer to [16], where we compared heavy meson suppression at RHIC and LHC as a function of momentum, collision energy and gluon rapidity density.

In Fig. 2 we show the heavy quark $R_{AA}(p_\perp)$ as a function of momentum. By comparing the charm and beauty

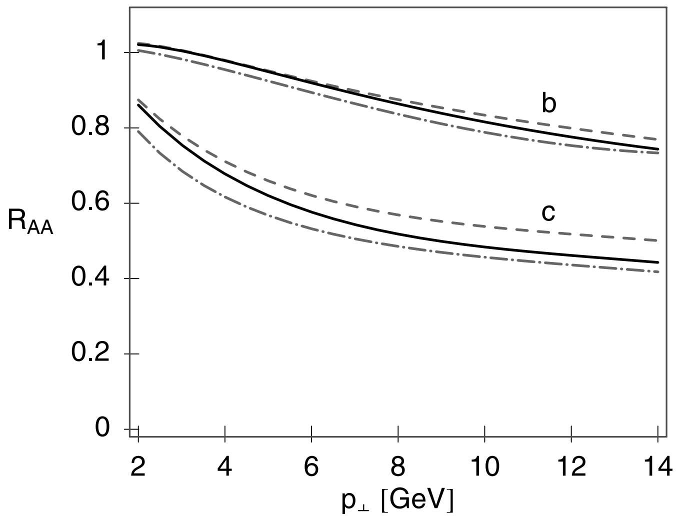

Fig. 2. The suppression ratio R_{AA} as a function of $p_\perp$ is shown for D (lower curves) and B mesons (upper curves). We consider the RHIC case ($\sqrt{s}_{NN} = 200\,\mathrm{GeV}$, $\frac{\mathrm{d}N_g}{\mathrm{d}y} \approx 1000$). Full (dashed) curves are obtained by neglecting (including) the Ter-Mikayelian effect and transition radiation. For both full and dashed curves we assumed δ-function fragmentation. Dot-dashed curves were obtained by taking only the medium induced energy loss into account and assuming Peterson fragmentation functions. For D (B) mesons we used $\epsilon = 0.06$ ($\epsilon = 0.006$) [12]

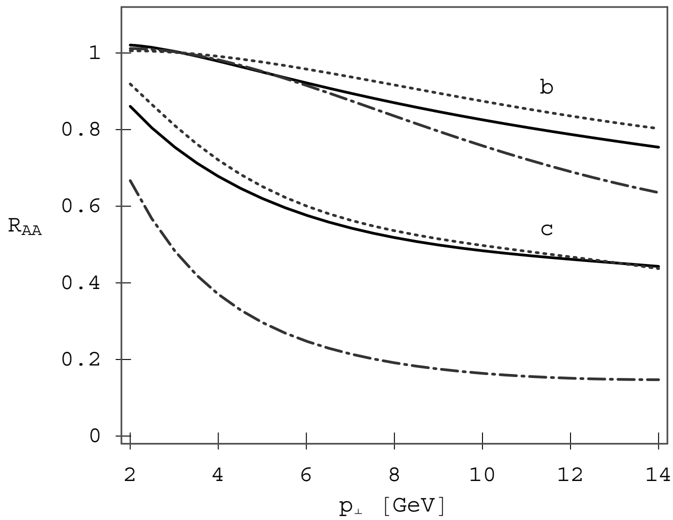

Fig. 3. The suppression ratio R_{AA} as a function of $p_\perp$ is shown for charm (lower curves) and beauty quarks (upper curves). Full curves are obtained by using a multi-gluon fluctuation procedure. Dot-dashed curves are computed by using mean energy formulas. Dotted curves are obtained by using the renormalized average energy loss formula with $Z = 0.5$

suppressions on Fig. 2, we see that, at RHIC conditions, high ($p_\perp$) charm will be suppressed by the factor of 2, while bottom is only slightly suppressed ($R_{AA} \approx 0.8$). That is, we notice that significantly less suppression is expected for beauty than for charm quarks. This is due to the following two reasons:
(1) from Fig. 1 we see that beauty p_T distributions have significantly smaller slopes than the charm ones, and
(2) due to the dead cone effect [21], the beauty energy loss is much smaller than the charm energy loss, as shown on Figs. 1 and 5 in [8]. This suggests in large part that no significant suppression should be observed for $p_\perp > 2\,\mathrm{GeV}$ single electrons at RHIC [22]. In this kinematic range there is a significant beauty contribution to the single electron yields and that component is essentially unquenched. Cronin and possibly collective flow effects in this low, $p_\perp < 6\,\mathrm{GeV}$, region also may play a role.

In Fig. 2 we also test how the suppression depends on dielectric effects and the choice of fragmentation functions. As a baseline for our comparison we use the full curves [16], which show the heavy quark suppression computed by using only the medium induced energy loss (dielectric effects are neglected), and decay to mesons by using the δ-function fragmentation [16].

To study the importance of dielectric effects we compare full with dashed curves. We see that the Ter-Mikayelian effect and transition radiation are negligible for beauty quarks. For the charm quark, the inclusion of dielectric effects leads to a small (0.05) increase in R_{AA}. Therefore, we can safely neglect the dielectric effects, as it was done in [16].

The sensitivity of heavy quark suppression on the choice of the fragmentation function can be tested by comparing the full (δ-function fragmentation) with the dot-dashed curves (Peterson fragmentation). We see that Peterson fragmentation increases the suppression by less than 10%. This is not unusual, having in mind that the slopes of the initial D and B meson $p_\perp$ distributions do not significantly change by using two different types of fragmentation function (for details see Fig. 1 in [16]). Since the suppression is directly proportional to the slope of these functions, it is therefore expected that the final suppression is insensitive to the choice of the fragmentation functions.

3.1 Alternative approaches

Though the multi-gluon fluctuation procedure is probably the most appropriate approach for the computation of the quenching spectrum, the practical problem is that it is computationally very involved. On the other hand, it is common in the literature (for example see [23–25]) to use much easier ways to compute the quenched spectrum of hadrons. Two alternative approaches are the following.
(1) The mean energy loss pQCD formulas [23–25]. Here, $P(\epsilon, E) \approx \delta(\epsilon - \Delta E(E)/E)$. Or
(2) the renormalized average energy loss formula [10]. Here, $P(\epsilon, E, Z) \approx \delta(\epsilon - Z\Delta E(E)/E)$. For the pion case, Z is suggested to be ≈ 0.5.

We here computed the suppression by applying both approaches, and tested how they compare with the results obtained by multi-gluon fluctuation procedure. Results are shown on Fig. 3. We see that the widely used mean energy loss pQCD approximation [23–25] significantly overestimates the quenching pattern for both charm and high $p_\perp$ bottom. On the other hand, the renormalized average energy loss formula [10], with $Z \approx 0.5$, shows a nice agreement with the result obtained by using a multi-gluon fluctuation procedure. Therefore, we can conclude that, for the RHIC case, the distortion of jet tomography due to gluon number fluctuations can be well approximated by renormalizing the mean energy loss calculations by a factor of $Z \approx 0.5$.

4 Conclusions

In these proceedings we predicted the momentum dependence of the nuclear modification factor $R_{AA}(p_\mathrm{T})$ for charm and beauty quark production in central Au + Au reactions with $\sqrt{s} = 200$ AGeV (RHIC). We expect a moderate D meson suppression, $R_{AA} \approx 0.5 \pm 0.1$, and a small B meson suppression, $R_{AA} \approx 0.8 \pm 0.1$, for $\frac{\mathrm{d}N_g}{\mathrm{d}y} \approx 1000 \pm 200$ inferred from π^0. By comparing our heavy quark predictions to the suppression patterns for the neutral pions in [5] (light quark and gluon case), we expect a striking difference in the suppression pattern between light and heavy mesons. This is because the much more strongly quenched gluon jets component of light hadrons does not play a role in D and B production.

Our high $p_\perp > 6$ GeV predictions are robust within our approach, and significant experimental deviations would pose a serious challenge to the pQCD based theory of radiative energy loss in sQGP matter. Future D meson data on 200 GeV d + Au and Au + Au and eventually at LHC will thus enable critical consistency tests of the theory and the tomographic inferences drawn from the observed jet quenching patterns.

Acknowledgements. The authors would like to thank R. Vogt on her help with MNR code, and valuable discussions of heavy quark production. This work is supported by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under Grant No. DE-FG02-93ER40764.

References

1. International Conference Quark Matter, Oakland, January 11–17, 2004, J. Phys. G **30**, 1 (2004)
2. M. Gyulassy, L. McLerran, nucl-th/0405013, Nucl. Phys. A, in press
3. Proceedings RBRC Workshop, New Discoveries at RHIC, BNL, May 14–15, 2004, Vol. 62, BNL-72391-2004, Nucl. Phys. A, in press (see J.P. Blaizot, T.D. Lee, E. Shuryak, H. Stoecker, X.N. Wang)
4. M. Gyulassy, I. Vitev, X.N. Wang, B.W. Zhang, Quark Gluon Plasma 3, edited by R.C. Hwa, X.N. Wang (World Scientific, Singapore), p. 123–191; nucl-th/0302077; A. Kovner, U. Wiedemann, p. 192–248; hep-ph/0304151; P. Jacobs, X.N. Wang, hep-ph/0405125
5. I. Vitev, M. Gyulassy, Phys. Rev. Lett. **89**, 252301 (2002) [hep-ph/0209161]; X.N. Wang, M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992)
6. B.B. Back et al., Phys. Rev. Lett **88**, 022302 (2002); K. Adcox et al., Phys. Rev. Lett **86**, 3500 (2001)
7. D. Kharzeev, E. Levin, M. Nardi, hep-ph/0408050 (2004); L. McLerran, hep-ph/0402137
8. M. Djordjevic, M. Gyulassy, Nucl. Phys. A **733**, 265 (2004) [nucl-th/0310076]
9. M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. B **594**, 371 (2001) [nucl-th/0006010]
10. M. Gyulassy, P. Levai, I. Vitev, Phys. Lett. B **538**, 282 (2002)
11. M.L. Mangano, P. Nason, G. Ridolfi, Nucl. Phys. B **373**, 295 (1992)
12. R. Vogt, Int. J. Mod. Phys. E **12**, 211 (2003)
13. M. Djordjevic, M. Gyulassy, Phys. Rev. C **68**, 034914 (2003)
14. M. Djordjevic, M. Gyulassy, Phys. Lett. B **560**, 37 (2003)
15. B.G. Zakharov, JETP Lett. **76**, 201 (2002)
16. M. Djordjevic, M. Gyulassy, S. Wicks, hep-ph/0410372; Phys. Rev. Lett., in press
17. M. Djordjevic, M. Gyulassy, Influence of Transition Radiation to the Light and Heavy Quark R_{AA}, in preparation
18. J.D. Bjorken, Phys. Rev. D **27**, 140 (1983)
19. An Tai for The STAR Collaboration, J. Phys. G **30**, S809 (2004)
20. C. Peterson, D. Schlatter, I. Schmitt, Peter M. Zerwas, Phys. Rev. D **27**, 105 (1983)
21. Yu.L. Dokshitzer, D.E. Kharzeev, Phys. Lett. B **519**, 199 (2001)
22. K. Adcox et al. [PHENIX Collaboration], Phys. Rev. Lett. **88**, 192303 (2002); PHENIX Collaboration (Ralf Averbeck for the collaboration), nucl-ex/0410007
23. M. Gyulassy, I. Vitev, X.N. Wang, Phys. Rev. Lett. **86**, 2537 (2001)
24. X.N. Wang, Z. Huang, I. Sarcevic, Phys. Rev. Lett. **77**, 231 (1996)
25. P. Levai, G. Papp, G. Fai, M. Gyulassy, G.G. Barnafoldi, I. Vitev, Y. Zhang, Nucl. Phys. A **698**, 631 (2002)