Heavy Quark Radiative Energy Loss - Applications to RHIC

Magdalena Djordjevic and Miklos Gyulassy

Dept. Physics, Columbia University, 538 W 120-th Street, New York, NY 10027, USA

January 7, 2022

Abstract

Heavy quark energy loss in a hot QCD plasma is computed taking into account the competing effects due to suppression of zeroth order gluon radiation below the plasma frequency and the enhancement of gluon radiation due to transition energy loss and medium induced Bremsstrahlung. Heavy quark medium induced radiative energy loss is derived to all orders in opacity, \((L/\lambda_g)^n\). Numerical evaluation of the energy loss suggests small suppression of high \(p_\perp\) charm quarks, and therefore provide a possible explanation for the null effects observed by PHENIX in the prompt electron spectrum in \(Au + Au\) as \(\sqrt{s} = 130\) and 200 AGeV.

1 Introduction

One of the most important goals of high energy heavy ion physics is the formation and observation of quark-gluon plasma (QGP). The discovery of a factor of 4 \(\sim 5\) suppression of high \(p_\perp \sim 5 - 10\) GeV hadrons produced in central \(Au + Au\) at the Relativistic Heavy Ion Collider (RHIC) has been interpreted as evidence for jet quenching of light quark and gluon jets. Jet quenching was predicted \([4]\) to occur due to radiative energy loss of high energy partons that propagate through ultra-dense QCD matter. The observed quenching pattern therefore provides a novel tomographic tool that can be used to map the evolution of the quark gluon plasma (QGP) produced in ultra-relativistic nuclear collisions.

Though the observed jet quenching for light partons strongly suggest that QGP has been formed at RHIC, further detailed tests may provide the decisive proof for the discovery of QGP. It is believed that good test of QGP formation is the open charm suppression, which can now be measured at RHIC by comparing \(p_\perp\) distributions of \(D\) mesons in \(d + Au\) and \(Au + Au\) collisions.

The main effect which lead to open charm suppression is the radiative heavy quark energy loss in a dense QCD medium. The first estimates for heavy quark energy loss \([5, 6]\) proposed that similar quenching may occur for charm jets as for light partons. However, in ref. \([7]\) it was estimated that the heavy quark mass leads to a kinematical “dead cone” effect for \(\theta < M/E\) that reduces significantly the induced radiative energy loss of heavy quarks. Experimentally, the PHENIX data \([8]\) on “prompt” single electron production in \(Au + Au\) collisions at \(\sqrt{s} = 130\) and 200 AGeV provided a first rough look at heavy quark transverse momentum distributions at RHIC. Remarkably, no indication for a QCD medium effect was found within the admittedly large experimental errors. On the other hand, new STAR \(D\) meson data may indicate large energy loss. Fortunately, in the near future, data with much higher statistics and wider \(p_\perp\) range will become accessible.

In this proceedings we concentrate on the theory of heavy quark radiative energy loss, and how to use these results to present theoretical predictions that can be compared with upcoming experimental results. Such comparisons may provide decisive test for QGP existence.

Only the main results for heavy quark energy loss are presented here. For more detailed version see \([1, 2, 3]\), and references therein.

2 Heavy quark energy loss

There are three important medium effects that control the radiative heavy quark energy loss in QCD matter.

Here we first study the non-abelian analog of the Ter-Mikayelian \([9]\) effect. The first estimates of the influence of a plasma frequency cutoff in QCD plasmas were reported in ref. \([10]\) using a constant plasmon mass. In our study, we extend those results by taking both longitudinal as well as transverse modes consistently into account via the frequency and wavenumber dependent hard thermal self energy \([11]\).
The detailed derivation of the QCD Ter-Mikayelian effect was presented in paper [2]. An important conclusion from [2] is that the effects due to the plasmon dispersion relation can be well approximated for high $p_T$ jets ignoring the longitudinal modes, and applying the asymptotic (short wavelength transverse) plasmon mass $m_g = \mu / \sqrt{2}$, where $\mu \approx gT$ GeV is chromoelectric Debye screening.

In addition to the Ter-Mikayelian effect, we also need to take into account that medium has finite size. Additional radiation which occurs in the boundary between medium and vacuum has to be included. We will call this energy loss transition radiation. To estimate transition radiation we use the results from Zakharov [12], which assume of static medium. This calculation should be improved by considering the more realistic case of expanding medium.

On Fig. 1 we show the numerical results for a medium characterized by a Debye screening scale $\mu = 0.5$ GeV. We see that the transverse plasmon mass effect reduces the zeroth order energy loss by, $\sim 30\%$, relative to the vacuum case. The gray region represents the additional energy loss which comes from transition radiation computed using [12]. This transition radiation lowers Ter-Mikayelian effect from $\sim 30\%$ to $\sim 15\%$. Therefore, these two effects would effectively enhance the yield of high transverse momentum charm quarks were it not for the extra medium induced radiation.

The second part of our study is (1) to generalize the GLV opacity series [13] to include massive quark kinematic effects and (2) to take into account the Ter-Mikayelian plasmon effects for gluons as described in [2]. The detailed study of this effect is presented in [3]. We have derived heavy quark medium induced radiative energy loss to all orders in opacity, $(L/\lambda_g)^n$. The analytic expression generalizes the GLV opacity expansion for massless quanta to heavy quarks with mass $M$ in a QCD plasma with a gluon dispersion characterized by an asymptotic plasmon mass, $m_g = \mu / \sqrt{2}$. Remarkably, we find that the general result is obtained by simply shifting all frequencies in the GLV series by $(m_g^2 + x^2 M^2)/(2xE)$.

![Figure 1](image1.png)  
**FIG 1.** The reduction of the zeroth order (vacuum) energy loss for charm quark due to the QCD Ter-Mikayelian and transition radiation effects is shown as a function of the charm quark energy. The upper curve shows the vacuum energy loss if gluons are treated as massless and transversely polarized. The lower solid curve shows medium modified (but zeroth order in opacity) transverse fractional energy loss. The dot-dashed curve shows the additional effect of transverse radiation.

![Figure 2](image2.png)  
**FIG 2.** The 1st order in opacity fractional energy loss for heavy quarks is shown as a function of their energy. Upper curve correspond to charm, and lower to bottom quarks in a plasma characterized by $\alpha_s = 0.3$, $\mu = 0.5$ GeV, and $L = 5\lambda = 5$ fm.
The numerical results for the first order induced radiative energy loss are shown on Fig. 2 for charm and bottom quarks. We fix the effective static plasma opacity to be $L/\lambda = 5$. We see that, in the energy range $E \sim 5 - 15$ GeV, the induced energy loss fraction is $\Delta E^{(1)}/E \approx 0.2$ for charm quarks while only about half that is predicted for bottom.

## 3 The net heavy quark energy loss

Figure 3 shows the competition between the medium dependence of the induced energy loss and the zeroth order energy loss taking into account the Ter-Mikayelian effect and transition radiation. Even in the absence of a medium ($L = 0$), a charm quark with energy $\sim 10$ GeV suffers an average energy loss, $\Delta E^{(0)}_{\text{vac}}/E \approx 1/3$, due to the sudden change of the color current when it is formed in the vacuum. The dielectric plasmon effect reduces this to about $\Delta E^{(0)}_{\text{med}}/E \approx 1/4$. The additional transitional radiation lowers the difference between $\Delta E^{(0)}_{\text{vac}}$ and $\Delta E^{(0)}_{\text{med}}$.

![FIG 3. The fractional energy loss for a 10 GeV charm quark is plotted versus the effective static thickness $L$ of a plasma characterized by $\mu = 0.5$ GeV and $\lambda = 1$ fm. The dashed middle horizontal line corresponds to the energy loss in the vacuum taking into account the kinematic dead cone of radiation for heavy quarks [7]. The lower horizontal solid line shows our estimate of the reduction of the zeroth order energy loss due to the QCD analog of the Ter-Mikayelian effect. The dot-dashed middle curve shows the additional effect of transverse radiation. The upper solid curve corresponds to the net energy loss, $\Delta E^{(1)} + \Delta E^{(0)}_{\text{med}} + \Delta E^{(0)}_{\text{trans}}$.](image)

By comparing the net energy loss in the medium ($\Delta E^{(0)}_{\text{med}} + \Delta E^{(0)}_{\text{trans}} + \Delta E^{(1)}_{\text{ind}}$) with the naive vacuum value ($\Delta E^{(0)}_{\text{vac}}$), we find that additional energy loss in the medium is approximately 15% of initial energy of the quark.

To estimate the value of suppression that comes from this energy loss we use the method described in [14]. We assume that initial charm $p_\perp$ distribution is in the region $\frac{C_1}{p_\perp} < \frac{dN^{AA}}{dp_\perp} < \frac{C_2}{p_\perp}$, where $C_1$ and $C_2$ are constants, and that the medium opacity is in the region $4.5 - 5.5$ fm.

![FIG 4. Charm $p_\perp$ suppression is shown as a function of $p_\perp$.](image)
From Fig. 4 we see that the charm quark suppression will be small \((0.6 − 0.8)\). Such value is expected having in mind low value of additional energy loss \((\approx 15\%)\). This prediction of suppression seems to be consistent with current PHENIX experimental single electron data \([5]\), but it is possibly inconsistent with STAR data. Unfortunately, the problem with current data is that they have large error bars, and that single electrons are less sensitive to the heavy quark energy loss than \(D\) mesons. Therefore, high statistics \(D\) meson data will allow us to make more reliable conclusions.

4 Conclusions

The upcoming \(D\) meson data for 200 GeV \(d + Au\) and \(Au + Au\) results will soon become available. According to our results, charm quark suppression should be small \((0.6 − 0.8)\). Therefore, this suppression should be definitely much smaller than the already observed pion suppression \((0.2)\).

If our predictions are confirmed, then existence of QGP will pass another stringent test. Together with already observed jet quenching and elliptic flow of light partons, this may provide decisive argument in the favor of the QGP production at RHIC.

Acknowledgments: We would like to thank R. Vogt for carefully reading the paper and giving valuable suggestions. 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] M. Djordjevic and M. Gyulassy, Phys. Lett. B 560, 37 (2003)
[2] M. Djordjevic and M. Gyulassy, Phys. Rev. C 68, 034914 (2003)
[3] M. Djordjevic and M. Gyulassy, Nucl. Phys. A 733, 265 (2004)
[4] M. Gyulassy and M. Plumer, Nucl. Phys. A 527, 641 (1991).
[5] E. V. Shuryak, Phys. Rev. C 55, 961 (1997)
[6] Z. W. Lin and R. Vogt, Nucl. Phys. B 544, 339 (1999); Z. W. Lin, R. Vogt and X. N. Wang, Phys. Rev. C 57, 899 (1998)
[7] Y. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B 519, 199 (2001)
[8] K. Adcox et al. [PHENIX Collaboration], Phys. Rev. Lett. 88, 192303 (2002); Takashi Hachiya, Poster Q15, Quark Matter 2004.
[9] M. L.Ter-Mikayelian, Dokl. Akad. Nauk SSSR 94 1033 (1954)
[10] B. Kampfer, O. P. Pavlenko, Phys. Lett. B 477 171 (2000)
[11] A. V. Selikhov, M. Gyulassy, Phys. Lett. B 316 373 (1993); Phys. Rev. C 49 1726 (1994).
[12] B. G. Zakharov, JETP Lett. 76, 201 (2002)
[13] M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. B 594 371 (2001)
[14] M. Gyulassy, P. Levai, I. Vitev, Phys. Lett. B 538 282 (2002).