Quenching of light hadrons at RHIC in a collisional energy loss scenario

Pradip Roy\textsuperscript{a}, Jane Alam\textsuperscript{b}, Abhee K. Dutt-Mazumder\textsuperscript{a}
\textsuperscript{a) Saha Institute of Nuclear Physics, 1/A F Bidhannagar, Kolkata, India
\textsuperscript{b) Variable Energy Cyclotron Centre, 1/A F Bidhannagar, Kolkata, India

Abstract. We evaluate the nuclear suppression factor, $R_{AA}(p_T)$ for light hadrons by taking into account the collisional energy loss. We show that in the measured $p_T$ domain of RHIC the elastic process is the dominant mechanism for the partonic energy loss.

1. Introduction

The suppressions of high $p_T$ hadrons and unbalanced back-to-back azimuthal correlations of the dijet events in Au+Au collisions measured at RHIC\textsuperscript{1} provide experimental evidence in support of the jet quenching. Most of the calculations (see \textsuperscript{2} for a review) consider the energy loss due to induced bremsstrahlung radiation and reproduce the observed nuclear suppression of light hadrons ($\pi^0$) in Au+Au collisions for centre of mass energy $\sqrt{s_{NN}} = 200$ GeV at RHIC. The effect of collisional loss was completely ignored in most of the previous calculations. However, the non-photonic single electron spectrum from heavy meson decays measured by PHENIX Collaboration\textsuperscript{3} shows much larger suppression than expected. By considering radiative energy loss for heavy quarks, the data cannot be reproduced as radiation is suppressed for heavy quarks due to dead-cone effects. Thus, there has been a renewed interest to revisit the importance of collisional energy loss both for light as well as heavy quarks.

The partonic energy loss due to collisional processes was revisited in \textsuperscript{4} and its importance was demonstrated in the context of RHIC in\textsuperscript{5}. It is the purpose of the present work to show that the omission of the collisional energy loss to explain the RHIC data is not justified. To this end, we calculate the nuclear suppression factor ($R_{AA}$) for pions ($\pi^0$) considering only the collision energy loss.

2. Theoretical framework

In order to calculate the $p_T$ distribution of hadrons from parton fragmentation we need the phase space distribution of partons, $f(p;t)$. The dynamical evolution of $f(p;t)$ is obtained by solving the Fokker-Planck (FP) equation which reads,

$$ \frac{d}{dt} \frac{\partial}{\partial p_k} f(p;t) = \frac{\partial}{\partial p_i} \left[ \partial_i f(p;t) \right] + \frac{1}{2} \frac{\partial^2}{\partial p_k^2} \left[ B_k(p)f(p;t) \right] + \frac{1}{2} \frac{\partial^2}{\partial p_i^2} \left[ B_i f(p;t) \right]; \quad (1) $$

where the second term on the left hand side arises due to expansion\textsuperscript{6}. Bjorken hydrodynamical model\textsuperscript{7} has been used here for spacet ime evolution. In Eq. (1) $f(p;t)$ represents the distribution function of the partons under study, $\gamma$-$\text{jet}$ energy $= dx$, denotes drag coe cient, $B_k = dh( p_k^2 i = dt)$, $B_i = dh( p_i^2 i = dt)$.
represent diffusion constants along parallel and perpendicular directions of the propagating partons.

The matrix elements required to calculate the transports coefficients include diagrams involving exchange of massless gluons which render $dE/dx$ and $B_{x,y}$ infrared divergent. Such divergences can naturally be cured by using the hard thermal loop (HTL) [8] corrected propagator for the gluons, i.e. the divergence is shielded by plasma effects. For jet with energy $E >> T$ (see [4] for details) the energy loss is given by

$$\frac{dE}{dx} = \frac{2}{\pi} T^2 C_{R} \ln \frac{E}{g^2 T}$$  \hspace{1cm} (2)

Having known the drag and diffusion [4], we solve the FP equation using Green's function techniques with the initial condition

$$P(p; t = t_{i}; p_{0}; t_{0}) = \left( 3 \right) \left( \hat{p} \cdot \hat{p}_{0} \right)$$ \hspace{1cm} (3)

along the line of Refs. [3,10].

The solution with an arbitrary initial momentum distribution can now be written as [3,10],

$$E \frac{dN}{d^3p} |_{\hat{p}=0} = \int \frac{d^3p_{0}}{|p_{0}|} P(p_{0}; \hat{p}_{0}; t_{i}; t_{0}) E \frac{dN}{d^3p_{0}} |_{\hat{p}=0}$$ \hspace{1cm} (4)

where $j$ stands for any parton species.

In order to take into account the jet production geometry we assume that all the jets are not produced at the same point and the path length traversed by these partons before fragmentation are not the same. It is also assumed that the jet initially produced at $(r; \theta)$ leave the plasma after a proper time $t_{i}$ or equivalently after traversing a distance $L$ (for light quarks $t_{i} \sim L$) given by $t_{i} = \frac{R^2 \sin \theta}{R \cos \theta}$. As this is not a measurable quantity, we have to average it out to obtain the $p_T$ spectra of hadrons:

$$\frac{dN_{\hat{p}=0}^{(j)}}{d^3p_{T} dy} = \int X \frac{Z}{d^3P} (r) \frac{Z}{t_{i}} \frac{dt}{t_{i}} \frac{dz}{z^2} D \left( \frac{1}{2} (r; Q^2) \right)_{\hat{p}=0} E \frac{dN_{\hat{p}=0}^{(j)}}{d^3p_{T} dy}$$ \hspace{1cm} (5)

where $t_{i}$ is the time when temperature cools down to the transition temperature $T_{c} = 190 \text{ M eV}$ [11]. The temperature profile is taken as Ref. [9]. The nuclear suppression factor $R_{AA}$ is defined as

$$R_{AA} (p_{T}) = \frac{\frac{dN_{\hat{p}=0}^{(j)}}{d^3p_{T} dy}}{\frac{dN_{\hat{p}=0}^{(j)}}{d^3p_{T} dy}}$$ \hspace{1cm} (6)

where the suffix $Q'$ in the denominator indicates that energy loss has not been considered while evaluating the suppression.
3. Results

To understand the relative importance of the energy loss mechanisms we plot the contributions from radiative and collisional processes in Fig. 1. It is observed that collisional energy loss is the dominant mechanism of energy loss for parton energy up to $E = E_c = 85(60)$ GeV for quark (gluon).

Nuclear suppression factor, $R_{AA}$, for neutral pions is plotted as a function of transverse momentum in Fig. 2 which describes the PHENIX data for Au + Au at $\sqrt{s} = 200$ GeV reasonably well. It should be noted here that the $R_{AA}$ ($p_T$) with collisional loss has a tendency to increase for higher $p_T$, indicating diminishing importance of collisional loss at this domain, where the radiative loss may become important. Therefore, a detailed calculation with both collisional and radiative loss may be useful to delineate the importance of individual mechanism.

It is important to note that the result for $R_{AA}$ is very sensitive to the initial temperature ($T_i$), equation of state (EOS) (through velocity of sound ($c_s$)) and the thermalization time ($t_i$). This is demonstrated in Fig. 3. This aspect, has not been received much attention in the literature. Our calculations show that the data can be reproduced reasonably well with $T_i = 450$ M eV, $c_s^2 = 0.2$ and $t_i = 0.15$ fm/c similar to those required to reproduce the single photon data.

4. Summary

In conclusion, we have used the $R_{AA}$ ($p_T$) for $^0_\pi$ measured by PHENIX collaboration to characterize the QCD medium created after the Au + Au collisions at RHIC. The data can be explained with $T_i = 450$ to 500 M eV depending upon the EOS, i.e. velocity of sound, $c_s$ in the medium. For a lower value of $c_s$ the expansion is slow. Consequently, the energy loss process occurs for a longer duration in the medium for a given $T_c$. Therefore, for smaller values of $c_s$ the corresponding $T_i$ is smaller.

Our investigations suggest that in the measured $p_T$ range of light hadrons at RHIC collisional, rather than the radiative, is the dominant mechanism of jet quenching. This is in sharp contrast to all the previous analyses.

References

[1] First Three Years of Operation of RHIC, Nucl. Phys. A. 757 (2005) 1-283.
[2] M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, [nucl-th/0302077].
[3] S. S. Adler et al., Phenix Collaboration, Phys. Rev. Lett. 96 (2006) 032301.
[4] A. K. Dutt-Mazumder, J. Alam, P. Roy and B. Sinha, Phys. Rev. D 71 (2005) 094016.
[5] P. Roy, A. K. Dutt-Mazumder and J. Alam, Phys. Rev. C 73 (2006) 044911.
[6] G. Baym, Phys. Lett. B 138 (1984) 18.
[7] J. D. Bjorken, Phys. Rev. D 27 (1983) 140.
Figure 3. Same as Fig. 2 for various values of initial temperature, sound velocity and thermalization time.

[9] G. D. Moore and D. Teaney, Phys. Rev. C 71 (2005) 064904.
[10] H. v. Hees and R. Rapp, Phys. Rev. C 71 (2005) 034907.
[11] M. Cheng et al., Phys. Rev. D 74 (2006) 054505.
[12] M. Gyulassy, P. Levrail and L. Vitev, Phys. Rev. Lett., 85, 5535 (2000).
[13] S. Adler et al., PHENIX collaboration, Phys. Rev. Lett. 96 (2006) 202301.
[14] J. Alam, J. K. Nayak, P. Roy, A. K. Dutta and B. Sinha, J. Phys. G 24 (2007) 871.