Glueball-Induced Partonic Energy Loss in Quark-Gluon Plasma

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Abstract

We discuss the energy loss of energetic parton jets in quark-gluon plasma above the deconfinement temperature $T_c$ by the interaction with scalar and pseudoscalar glueballs. It is shown that the loss by this mechanism is quite important and may play the important role of the observed jet-quenching.

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The investigation on jets in the relativistic heavy ion collisions (RHIC) provides us insights to understand the properties of quark-gluon plasma (QGP)\cite{1,2,3,4}. One of the important RHIC discoveries is the jet quenching phenomenon coming from the partonic energy loss in QGP. In the conventional approach to the jet quenching the perturbative (pQCD) type of energy loss is taken into account by the channels, elastic and radiative, of one-gluon exchange between the jet and the massless gluons and quarks (see recent discussion in \cite{5}). However, the large quark-gluon rapidity density $dN_{qg}/dy \approx 2000$ which is needed to describe the RHIC jet quenching data within this approach, seems to be in contradiction with the restriction $dN_{qg}/dy \leq 1/4dS/dy \approx 1300$ coming from the measured final entropy density $dS/dy \approx 5000$ \cite{6}. Furthermore, the lattice calculations show that even at very high temperature gluons and quarks still interact strongly in QGP \cite{7}.

Recently, it was suggested that the glueballs, the bound states of gluons, can exist above deconfinement temperature and may play an important role in the dynamic of strongly interacting QGP \cite{8,9}. In particular, in \cite{9} it is suggested that a very light pseudoscalar glueball can exist in QGP and might be responsible for the residual strong interaction between gluons. The lattice results showing a change of sign of the gluon condensate \cite{7} and a small value of the topological susceptibility \cite{10} above $T_c$ can be explained in the glueball picture as well. Furthermore, one expects that the suppression of the mixing between glueballs and quarkonium states in the QGP leads to a smaller width for former as compared to the vacuum \cite{8}. This property opens the possibility for a clear separation of the glueball and the quark states in heavy ion collisions. Such separation is rather difficult in other hadron reactions due to existence of strong glueball-quarkonium mixing in the vacuum.

In this communication we report our study on the contribution of glueballs to the energy loss by high energy partons propagated in QGP. We will argue that significant partonic energy loss can result from strong glueball-gluon coupling.

Our starting point is the effective pseudoscalar glueball-gluon vertex employed in Refs.\cite{9,11}

\begin{equation}
\mathcal{L}_{Ggg} = \frac{1}{f_S}(\alpha_s G_{\mu
u}^a G_{\mu\nu}^a S + \xi \alpha_s G_{\mu
u}^a \tilde{G}_{\mu
u}^a P),
\end{equation}

where $G_{\mu\nu}^a$ is gluon field strength, $\tilde{G}_{\mu\nu}^a = \epsilon_{\mu\nu\alpha\beta} G_{\alpha\beta}^a / 2$, $S$ and $P$ are scalar and pseudoscalar glueball fields, respectively, $\xi \approx 1$, and $f_S \approx 0.35$ GeV which is fixed by low energy theorem \cite{9}. In Fig.1 the diagrams contributing to the energy loss in high energy limit $s \gg (-t, M_{S,P}^2)$ are illustrated.

The elastic energy loss is given by Bjorken’s formula \cite{12}

\begin{equation}
\frac{dE}{dx}(T) = \int d^3 kn(k, T)[\text{Flux factor}] \int dt \frac{d\sigma}{dt} \nu, \quad (2)
\end{equation}

where $\nu = E' - E$ energy difference between fast incoming and outcoming partons, $[\text{Flux factor}] = (1 - \cos\theta)$, $\theta$ is the laboratory angle between the incident partons, $d\sigma/dt$ is partonic cross section and $n(k, T)$ is density of target parton in QGP at the temperature $T$. The result of the calculation of diagrams in Fig.1 is

\begin{align*}
\frac{d\sigma_b}{dt} & \approx \frac{15\alpha_s^3}{4f_S^2|t|} F(t), \quad \frac{d\sigma_c}{dt} \approx \frac{16\alpha_s^3}{3f_S^2|t|} F(t), \\
\frac{d\sigma_a}{dt} & \approx \frac{15\alpha_s^3}{f_S^2|t|} F(t), \quad \frac{d\sigma_d}{dt} \approx \frac{\alpha_s^3}{3f_S^2|t|} F(t), \quad (3)
\end{align*}
Figure 1: The diagrams contributed to a), b), d) gluon and c), d) quark energy losses. The g (G) denotes gluon (glueball) and q the quark.

where $|t| = 2k\nu(1 - \cos\theta)$, and the form factor in gluon-glueball vertex reads

$$F(t) = e^{-\Lambda^2|t|},$$

with $\Lambda \approx 0.6$ GeV$^{-1}$. In the high energy limit we will neglect the small effect coming from finite masses of the produced glueballs but we will take into account the finite value of their masses in the densities, Eq.6. Furthermore, our consideration here is restricted by calculation to the leading order in $\alpha_s$. So the possible thermal gluon mass effects, $m_g \propto \alpha_s T$, are not considered. Therefore, in the case of energetic parton it is enough to keep only leading energy independent terms of the partonic cross sections shown in Eq.3.

The final result for energy loss for gluon and quark jets reads

$$\frac{dE_g}{dx}(T) = \frac{15\alpha^3_s}{2f_\Lambda^2} \int \frac{d^3k}{k} \left[ n_S(k, T) + n_P(k, T) + \frac{n_g(k, T)}{4} + \frac{n_q(k, T)}{45} \right]$$

$$\frac{dE_q}{dx}(T) = \frac{8\alpha^3_s}{3f_\Lambda^2} \int \frac{d^3k}{k} \left[ n_S(k, T) + n_P(k, T) + \frac{n_g(k, T)}{8} \right],$$

For estimation we will assume in QGP gluons, quarks and glueballs are in thermodynamical equilibrium and will use the gas approximation for gluon and glueball densities

$$n_i(k, T) = \frac{N_i}{(2\pi)^3 \left( \exp(\sqrt{k^2 + M_i^2}/T) \pm 1 \right)},$$

where the plus (minus) sign is for fermions (bosons) and numbers of degrees of freedom are $N_S = 1$ for scalar and $N_P = 1$ for pseudoscalar glueballs, respectively, $N_g = 16$ for gluons and $N_q = 12$ for number of light quark flavors $N_F = 2$. In our previous paper it was argued that in the model with Lagrangian Eq.4 the behaviour of the masses of pseudoscalar and scalar glueballs above $T_c$ is very different. Indeed, it was shown that the scalar glueball remain to be massive, $M_S \approx 1.5$ GeV, but pseudoscalar glueball is very light, $M_P \approx 0$, above deconfinement temperature. Within such approximation we obtain

$$\frac{dE_{g,q}}{dx}(T) \approx C_{g,q} \alpha^3_s T^2,$$
where $C_g^G = 79/24$ is the coefficient for the glueball contribution to gluon energy loss and $C_q^G = 2/3$ is the correspondent coefficient for quark energy loss.\footnote{We neglect the small contribution arising from the interaction of energetic parton with massive scalar glueball in QGP due to small value of its density $n_S << n_P$.}

The numerical result presented in Figs.(2,3) of the temperature dependence of elastic energy loss due to interaction with glueballs is to be compared with the recent re-analysis of perturbative QCD elastic contribution in the range of temperatures $T_c < T < 2T_c$, which is accessible at RHIC experiments. The pQCD elastic contribution is as following [13]

$$
\frac{dE_{g,q}^{\text{pQCD}}}{dx}(T) = C_{g,q}^{p} 8\pi^2 \alpha_s T^2 \frac{b_0}{b_0} \left(1 + \frac{N_F}{6}\right),
$$

where $C_g^p = 3/2$, $C_q^p = 2/3$ are coefficients for the perturbative gluon and quark energy loss, respectively, and $b_0 = 11/3N_c - 2/3N_F$. We take $T_c = 170$ MeV for $N_F = 2$ [14] and $\alpha_s \approx 0.6$ at $T_c < T < 2T_c$ [15, 16] for the estimation of energy loss in gluon-glueball plasma. It follows from Figs. 2,3 that glueball-induced energy loss is large for both gluon and quark jets. In particular, for the gluon jet such contribution is about of few GeV/fm and approximately twice larger than the perturbative elastic loss [13]. In spite of the fact that for the quark jet the glueball contribution is smaller than perturbative elastic loss, it can not be neglected in comparison with latter one. It is evident that the origin of such large contribution is in strong glueball-gluon coupling in Eq.\footnote{We neglect the small contribution arising from the interaction of energetic parton with massive scalar glueball in QGP due to small value of its density $n_S << n_P$.} We should point out that more than one half of contribution to the gluon energy loss comes from interaction of gluon with the light pseudoscalar glueball in QGP. Therefore, existence of such light bound state of gluons above $T_c$ is crucial for the understanding of the large observed partonic energy loss in QGP.

In summary, we made the estimation of the energy loss induced by interaction of
an energetic parton, which was produced in the hard scattering of two heavy ion’s part-
ons, with glueballs in hot quark-gluon plasma. It is shown that such contribution leads
to a significant energy loss. We conclude that not only pQCD type of energy loss but
also glueball-induced loss, arising from existence of scalar and pseudoscalar glueballs in
QGP, are important for the understanding of the RHIC results such as the jet quenching.
We should emphasize that the main goal of our paper is to show the significance of the
glueball-induced energy loss and we left the detailed comparison with experiment, which
should include also the consideration of the effects of both elastic and radiative pQCD
losses, for a forthcoming publication.

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