Jet quenching in semi-QGP

Balbeer Singh
Physical Research Laboratory
Collaborators: H. Mishra

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Matrix model of semi-QGP \(^{12}\)

- The region near the transition temperature (\(T_c \sim 155\) MeV) is termed as semi-QGP.

- Constant background gauge field

\[
A_{\mu}^{0ab} = \delta_{\mu 0} \delta^{ab} Q^a / g
\]

For \(SU(3)\), \(Q^a = 2\pi T(−q, 0, q)\).

\[
\phi = \frac{1}{3} (1 + 2 \cos 2\pi q).
\]

- The background gauge field acts as an imaginary chemical potential

\[
f_a(E) = \frac{1}{e^{\beta(E−iQ^a)} + 1}, \quad \tilde{f}_a(E) = \frac{1}{e^{\beta(E+iQ^a)} + 1},
\]

\[
f_{ab}(E) = \frac{1}{e^{\beta(E−i(Q^a−Q^b))} − 1}.
\]

\(^1\)Pisarski et al.,2009
\(^2\)Meisinger et al.,2002

quark→single index          gluon→double index
- Color averaged statistical distribution function

\[
f_q(E) = \frac{1}{3} \sum_{a=1}^{3} f_a(E) = \frac{\phi e^{-\beta E} + 2\phi e^{-2\beta E} + e^{-3\beta E}}{1 + 3\phi e^{-\beta E} + 3\phi e^{-2\beta E} + e^{-3\beta E}}.
\]

\[
9f_g(E) = \frac{3}{e^\beta E - 1} + \frac{e^\beta E (6\phi - 2) - 4}{1 + e^{2\beta E} + e^\beta E (1 - 3\phi)} + \frac{e^\beta E (9\phi^2 - 6\phi - 1) - 2}{1 + e^{2\beta E} + e^\beta E (1 + 6\phi - 9\phi^2)}.
\]

- Deviation in distribution function from distribution function from \(\phi = 0\) phase is proportional to \(\phi\) for quark and \(\phi^2\) for gluon

- Fluctuation of background field \(A_\mu = A^0_\mu + \delta A_\mu\)

\[
\mathcal{L} = \frac{1}{2} \text{tr}(G^2_{\mu\nu}) + \bar{\psi}(\not{\partial} + m)\psi
\]

\[
G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu], \quad D_\mu = \partial_\mu - igA_\mu
\]

Pisarski et al., 2010, Hidaka et al., 2012
In a process with hard momentum transfer the quark/gluon propagator does not depend on \( q^a \).

For a process with soft momentum transfer the quark/gluon propagators are resummed and depends on \( q^a \)

\[
D_{\mu\nu};abcd(K) = P^L_{\mu\nu} \frac{k^2}{K^2} D^L_{abcd}(K) + P^T_{\mu\nu} D^T_{abcd}(K)
\]

\[
D^L_{\mu\nu};abcd(K) = \left( \frac{i}{K^2 - F} \right)_{abcd}
\]

\[
D^T_{\mu\nu};abcd(K) = \left( \frac{i}{K^2 - G} \right)_{abcd}
\]

\( F \) and \( G \) have same structure as that of vanishing background field

\[
F = -2m^2 \left( 1 - \frac{x}{2} \ln \left( \frac{x + 1}{x - 1} \right) \right)
\]

\[
G = m^2 \left( x^2 + \frac{x(1 - x^2)}{2} \ln \left( \frac{x + 1}{x - 1} \right) \right), \quad x = \frac{k_0}{|k|}
\]
Debye mass small compared to perturbative Debye mass

\[
\left( m_D^2 \right)_{abcd} = \frac{g^2}{6} \left[ \delta_{ad} \delta_{bc} \left( \sum_{e=1}^{3} (D(Q_{ae}) + D(Q_{eb})) - N_f (\tilde{D}(Q_a) + \tilde{D}(Q_b)) \right) \right. \\
- \left. 2\delta_{ab}\delta_{cd} \left( D(Q_{ac}) - \frac{N_f}{N} \left( \tilde{D}(Q_a) + \tilde{D}(Q_c) \right) + \frac{N_f}{N^2} \sum_{e=1}^{3} \tilde{D}(Q_e) \right) \right]
\]

\[
D(Q_a) = \frac{3}{\pi^2} \int_0^\infty dEE \left( \frac{1}{e^{\beta(E+iQ_a)} - 1} + \frac{1}{e^{\beta(E-iQ_a)} - 1} \right)
\]

Debye mass is real
Debye mass

Figure: Debye mass as a function of T

Balbeer et al., 2019
Jet quenching

- Energetic parton interacts with a medium through multiple scattering with the medium parton and gluon radiation. As the result, the spectra of large transverse momentum is suppressed. This phenomena is known as jet quenching.

- Quenching parameter pQCD, \( \hat{q} = 1.2 \pm 0.3 \text{ GeV}^2 \text{ fm}^{-1} \)

\[
\hat{q} = \frac{1}{v} \int d^3 q \frac{d\Gamma}{d^3 q} |q_{\perp}^2
\]

- For fast parton \( (j) \) and medium thermal parton \( (l) \) scattering: \( j(p) + l(k) \rightarrow j(p') + l(p') \)

\[
\frac{d\Gamma}{d^3 q} = \frac{1}{4E_p^2(2\pi)^3} \int \frac{dk}{4E_k E_{k'}} \sum f_{a;ab}(E)(1 \pm f_{b;cd}(E'))|M|_{ab;abcd}^2 \\
\times (2\pi)\delta(E - E' - v \cdot q)
\]

- Contributing processes: Scatterings processes \( (2 \rightarrow 2) \), medium induced gluon radiation
Suppression for quark

- \( t \)-channel scattering diagrams give dominant contribution

\[
|\mathcal{M}|_{ab}^2 = 4g^4 \mathcal{P}_{ab} \mathcal{P}_{cd} \mathcal{P}_{ba} \mathcal{P}_{dc} \left( \frac{|\mathbf{q}|^4}{Q^4} D_{\mathcal{L} \mathcal{L}^*} [2(\mathbf{p}.\mathbf{P}^L.\mathbf{k}')(\mathbf{p}.\mathbf{P}^L.\mathbf{k}) - (\mathbf{k}.\mathbf{k}')] \right) \\
\times (\mathbf{p}.\mathbf{P}^L.\mathbf{p}) + D_{\mathcal{T} \mathcal{T}^*} [2(\mathbf{p}.\mathbf{P}^T.\mathbf{k}')(\mathbf{k}.\mathbf{P}^T.\mathbf{p}) - (\mathbf{k}'(\mathbf{p}.\mathbf{P}^T.\mathbf{p})] 
\]

- Jet interact with individual thermal partons

- For log approximation

\[
\mathcal{P}_{ab} \mathcal{P}_{ba} = \left( 1 - \frac{1}{N} \right) \delta_{ab}
\]
At leading log approximation, the Polyakov loop effect arises from the distribution functions

\[ \int k^2 \tilde{f}_a(E_k)(1 - \tilde{f}_b(E_k))\delta_{ab} = \int k^2 \sum_{n=1}^{\infty} (-1)^{n+1} ne^{-n\beta(E_k+iQ_a)} \]

\[ = T^3(1 - 8q^2) \]

For quark-gluon scattering

\[ |\mathcal{M}_{efgh}|^2 = g^4 f^{cd,ef,gh} f^{d',c',ef,gh} P_{ab} P_{c'd'} \[ \ldots \], \quad P_{cd} = \delta_c^a \delta_d^b - \frac{1}{N} \delta^{ab} \delta_{cd} \]

Suppression factor for e, f open index

\[ \sum_{e \neq f} \int k^2 f_{ef}(E_k) \left(1 - \frac{\delta_{ef}}{N}\right) = T^3(1 - 6q + 9q^2) \]
Suppression for gluon

For gluon-gluon scattering

\[ |\mathcal{M}_{efgh}|^2 = Ng^{4f_{ml,ef,gh}f_{lm,ef,gh}p_{lm}^l}|^{} \]

Leading order suppression for jet quenching

\[ \sum_{e \neq f} \int_k k^2 f_{ef}(E_k)(1 + f_{ef}(E_k)) = T^3(1 - 6q + 9q^2) = T^3 G(q) \]

\[ \sum_{a,b} \int_k k^2 \tilde{f}_a(E_k)(1 + \tilde{f}_b(E_k)) = T^3(1 - 8q^2) = T^3 J(q) \]
Results

- Suppression factors

![Graph showing suppression factors](image)

**Figure:** q value (left) and suppression factors from thermal quark and gluon scattering (right).
Summary and Conclusion

- Non-perturbative effects are included via Polyakov loop.
- With the inclusion of the Polyakov loop, Debye mass is suppressed.
- Interaction rate for both the quark and the gluon is suppressed suggesting a suppression of jet quenching compared to the pQCD estimates.
- Scattering from thermal gluon gives more suppression compared to thermal quark.
- Suppression is more at low temperature.
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Thank You
Quenching

Figure: Jet quenching parameter

Abhijit Majumder et al., 2020