ELECTROMAGNETIC RADIATION FROM BROKEN SYMMETRIES IN RELATIVISTIC NUCLEAR COLLISIONS

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A new channel of direct photon production from a quark gluon plasma (QGP) is explored in the framework of high-temperature QCD. This process appears at next-to-leading order, in the presence of a charge asymmetry in the excited matter. The photon production rate from this new mechanism is suppressed compared to the QCD annihilation and Compton scattering at low baryon density but assumes importance in baryon-rich matter.

1. Introduction

The exploration of highly excited strongly interacting matter produced in the collision of heavy nuclei has now entered a phase of detailed study. Lattice QCD simulations of such matter in equilibrium had predicted the existence of a phase transition in the vicinity of $T_c \sim 170$ MeV at vanishing chemical potential. This was inferred from the observed sudden rise of the scaled pressure and the entropy density at this temperature. The experimental results of the Relativistic Heavy-Ion Collider (RHIC) detector collaborations have set a lower bound of about 5 GeV/fm³ on the energy density at a time $\tau = 1$ fm/c in central Au+Au collisions. Based on Lattice QCD estimates, these numbers place the temperature of such matter upwards of 300 MeV, well into the expected deconfined phase of QCD matter.

In spite of the temperatures reached, the produced matter demonstrates considerable collective behaviour as witnessed by the large elliptic flow observed. This has led to the assertion that the produced matter is strongly interacting. A description of such collective behaviour within the picture of a weakly interacting quasi-particle plasma of quarks and gluons, using methods based on perturbative QCD, has so far not met with much success. This has spurred attempts to describe the matter through phenomenological models where the degrees of freedom are heavy quark and gluon quasi-particles and a tower of bound states of quarks and gluons.
vor off-diagonal susceptibilities, measured in lattice QCD simulations, place severe constraints on the existence of such bound states in the flavor sector \(^6\). The exploration of the degrees of freedom in the unflavored sector (i.e., pure glue degrees of freedom) can only be carried out by experimental probes. In recent articles, a means to probe this structure through jet correlations \(^7\) was considered. In these proceedings, we report on the first attempt to probe the pure glue sector through its possible electromagnetic signature.

Gluons do not carry electric charge, yet their interactions may generate electromagnetic signatures if the medium is itself electrically charged. The presence of a non-vanishing electric charge or a net asymmetry between the quark and antiquark populations leads to an explicit breaking of charge conjugation invariance by the medium. This allows for new channels of photon production at finite chemical potential \((\mu)\) which were absent at \(\mu = 0\). The possibility of such rates was first pointed out in Refs. \(^8\), \(^9\). In the current effort, the spectrum of real photons from such processes will be calculated and compared to the leading order rates of Refs. \(^10\), \(^11\), \(^12\). All such previous calculations of the photon rate at finite chemical potential have tended to focus on processes which are non-vanishing at \(\mu_B = 0\). The current effort extends the computations of the full photon production rates by the inclusion of new channels which arise solely at finite chemical potential.

2. Formalism and Calculation

At zero temperature, as well as, at finite temperature and zero charge density, diagrams in QED that contain a fermion loop with an odd number of photon vertices (e.g. Fig. 1) are cancelled by an equal and opposite contribution coming from the same diagram with fermion lines running in the opposite direction (Furry’s theorem \(^13\)). A physical perspective is obtained by noting that all these diagrams are encountered in the perturbative evaluation of Green’s functions with an odd number of gauge field operators. At zero temperature, the focus lies on quantities such as \(\langle 0| A_{\mu_1} A_{\mu_2} ... A_{\mu_{2n+1}} |0 \rangle\), which vanishes under the action of the charge conjugation operator \(C\). At a temperature \(T\), the corresponding quantity to consider is

\[
Tr[\rho(\mu, \beta) A_{\mu_1} A_{\mu_2} ... A_{\mu_{2n+1}}] = \sum_n \langle n| A_{\mu_1} A_{\mu_2} ... A_{\mu_{2n+1}} |n \rangle e^{-\beta(E_n - \mu Q_n)},
\]

where \(\beta = 1/T\) and \(\mu\) is a chemical potential. In the case of finite temperature and chemical potential, this quantity is non-vanishing and Furry’s theorem no longer holds. One may say that the medium, being charged, manifestly breaks charge conjugation invariance and these Green’s functions are thus finite, which leads to the appearance of new processes in a perturbative expansion.

The above statement can be generalized almost unchanged to QCD for processes with two gluons and an odd number of photon vertices. The Feynman diagrams corresponding to the leading contributions to the new channel of photon production are those of Fig. \(^18\). At non-zero density, this leads to two new sources for photon production: the fusion of gluons to form a photon \((gg \rightarrow \gamma)\) and the decay of a
massive gluon into a photon and a softer gluon ($g \rightarrow g\gamma$). The full, physical, matrix element is obtained by summing contributions from both diagrams, $T^{\mu\nu\rho}(p, k, k') = T_1^{\mu\nu\rho}(p, k, k') + T_2^{\mu\nu\rho}(p, k', k)$, where $k' = p - k$. At finite temperature and chemical potential, the amplitudes may be expressed as:

$$T^{\mu\nu\rho}(p, k, k') = T \sum_{q_0} \int \frac{d^3q}{(2\pi)^3} e^{\frac{iq_0}{2T}} T \gamma_{\mu\nu\rho\gamma} (q + k)_{\alpha} q_{\beta} (q - k')_{\gamma}$$

$$T^{\mu\nu\rho}(p, k', k) = T \sum_{q_0} \int \frac{d^3q}{(2\pi)^3} e^{\frac{iq_0}{2T}} T \gamma_{\mu\nu\rho\gamma} (q - k)_{\alpha} q_{\beta} (q + k')_{\gamma}$$

In the imaginary time formalism, the zeroth components of four momentum are discrete Matsubara frequencies, $q_0 = i\omega_n + \mu = (2n + 1)\pi T + \mu$ , $k_0 = i\omega_k = 2k\pi T$ , $p_0 = i\omega_p = 2p\pi T$, where integers $n, k$ and $p$ range from $-\infty$ to $\infty$, and $\mu$ is the quark chemical potential. The sum over the Matsubara frequencies may be conveniently performed using the non-covariant propagator method of Ref. 14.

Here, one defines a time-three-momentum propagator $\Delta(\tau, E)$, as

$$\Delta(i\omega_n \pm \mu, E) = \int_0^\beta d\tau e^{i\omega_n \tau} \Delta(\tau, E).$$

In the above equation, $E = |\vec{p}|$ represents the real energy of the particle. The evaluation of the photon production amplitudes as well as the ensuing rates are carried out in the gauge invariant effective field theory of QCD at high temperature, the Hard-Thermal-Loops (HTL) effective theory 15,16. In this formalism, one assumes the condition that the temperature $T \rightarrow \infty$ and as a result the coupling constant $g \rightarrow 0$. As a result a hierarchy of scales emerges i.e., $T >> gT >> g^2T$ etc. Within this limit, one can derive effective propagators and vertices for the soft modes $\sim gT$ by integrating out the hard modes $\sim T$. In the current effort, the effective two-gluon-photon vertex will be derived in this limit.

The production or absorption rate of photons from gluon fusion or decay in a dense medium is related to the imaginary part of the photon self-energy depicted in Fig. 2. In the case of a medium at equilibrium, the thermal photon emission rate $R = d^4N/d^4x$ is related to the discontinuity or the imaginary part of the retarded
The photon self-energy $\Pi_{\mu\nu}^{R}$ [10]

$$E \frac{dR}{d^3p} = \frac{-g_{\mu\nu}}{(2\pi)^3} \text{Im} \Pi_{\mu\nu}^{R} \frac{1}{e^{\frac{\omega}{T}} - 1}. \quad (4)$$

The photon self-energy from the Fig. 2 may be expressed formally as,

$$\Pi_{\mu\nu}'(p) = T \sum_{k_0} \int \frac{d^3k}{(2\pi)^3} T^{\mu\nu\rho}(p, k, k') S_{\nu\rho'}(k) T^{\mu'\nu'\rho'}(-p, -k, -k') S_{\rho\mu'}(k'), \quad (5)$$

where $T^{\mu\nu\rho}(p, k, k')$ is the effective photon-gluon-gluon vertex evaluated in the HTL limit and $S_{\nu\rho'}(k)$ is the effective gluon propagator, after summing up the HTL contributions to the self-energy of the gluon. After summing over the Matsubara frequency $k_0$ and evaluating the discontinuity across the real $p^0$, the photon production rate may be cast into a kinetic form,

$$E \frac{dR}{d^3p} = \sum_{l=\pm} \sum_{i,j=\pm} \frac{1}{2(2\pi)^2} \frac{1}{e^{\frac{\omega}{T}} - 1} \int \frac{d^3k}{(2\pi)^3} \int d\omega \int d\omega' \rho_l(\omega) \rho_j(\omega') \delta(\omega + \omega' - E)(1 + f(\omega) + f(\omega')) |M_{lij}|^2, \quad (6)$$

where the matrix element $M_{lij} = \epsilon_{i\mu}(p) \epsilon_{j\nu}(k) \epsilon_{l\rho}(k') T^{\mu\nu\rho}(p, k, k')$ and $\rho_l(\omega)$ and $\rho_j(\omega')$ are the spectral functions of the longitudinal or transverse gluon propagators. The product of two $\rho$ functions give three types of contribution: pole-pole, pole-cut, and cut-cut. In this first effort, the focus will lie on the hard photon production, i.e., photons with momenta $p \sim T$, which requires that at least one of the gluons in Fig. 2 to be hard. The cut-cut contribution with two space-like gluons is dominant only in the region where both gluon momenta are soft and is ignored in this effort.

3. Results

In this section, numerical results for the hard photon production rate from a plasma with a finite charge density will be presented. The calculation is performed for two massless flavors of quarks with $\mu_u = \mu_d = \mu = \mu_B/3$. In such a plasma, the strong coupling constant is fixed, $\alpha_s = 0.4$. The strange sector has been ignored in this

Fig. 2. The Feynman diagram of the photon self-energy evaluated in this work, where the blobs represent either the effective $gg\gamma$ vertices or the effective gluon propagators.
calculation. In Fig. 3, the photon production from our new channel is compared with the contribution from the leading order QCD processes of quark antiquark annihilation and quark gluon Compton scattering. One may immediately note that the contribution from the new channels, the \(gg\gamma\) vertex, to the photon production is much smaller than the QCD annihilation and Compton processes at low chemical potential. However, with increasing chemical potential at a fixed temperature, the photon production rate from the \(gg\gamma\) vertex tends to increase at a swifter rate than QCD annihilation and Compton contribution. This leads to the conclusion that in baryon-rich matter, such as that produced in low energy collisions of heavy ions, where the chemical potential of the medium is very large, the new channel from \(gg\gamma\) vertex will assume significance in comparison to the leading order rates.

In the above estimates, the chemical potential (\(\mu\)) and temperature (\(T\)) are held fixed separately. If the energy density were held constant, \(T\) and \(\mu\) would be related to each other by the equation of state (EOS). In this case, it has been shown that the photon production rate from QCD annihilation and Compton processes has a strong dependence on increasing chemical potential \(\mu\) of the medium \[11,12\]. Calculations of the photon production rate from the \(gg\gamma\) vertex for the case of a constant energy density will be presented in an upcoming publication \[17\].

4. Discussions and Conclusions

In these proceedings, the hard photon signature emanating from a new set of channels that arise solely when the medium explicitly breaks charge conjugation invariance was presented. The photon production from such channels is dependent on the gluon density of the medium and thus offers a window to probe the gluon sector of...
the highly excited strongly interacting matter. We employ an effective field theory of QCD at high temperatures (HTL) and focus on the photon spectrum emanating from a medium at equilibrium. In such a scenario, the photon rate from the new channels is suppressed compared to the leading order rates for realistic values of temperature and chemical potential, but will gain significance in baryon-rich matter. Our results may be easily extended to non-equilibrium cases, such as the early stages of relativistic nucleus-nucleus collisions, where the gluon population far exceeds that of quarks; the photon production from this new mechanism could outshine that from conventional channels. Another interesting application of these rates is to the photon production from jet plasma interactions\textsuperscript{18}. Estimates of photon production from such diverse scenarios will be explored in future efforts.

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