Cherenkov Radiation from Jets in Heavy-Ion Collisions

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(Received 23 August 2005; published 4 May 2006)

The possibility of Cherenkov-like gluon bremsstrahlung in dense matter is studied. We point out that the occurrence of Cherenkov radiation in dense matter is sensitive to the presence of partonic bound states. This is illustrated by a calculation of the dispersion relation of a massless particle in a simple model in which it couples to two different massive resonance states. We further argue that detailed spectroscopy of jet correlations can directly probe the index of refraction of this matter, which in turn will provide information about the mass scale of these partonic bound states.

DOI: 10.1103/PhysRevLett.96.172302 PACS numbers: 25.75.Nq, 11.10.Wx, 12.38.Mh, 25.75.Dw

The goal of high-energy heavy-ion collisions is to create and explore a novel state of matter in which quarks and gluons are deconfined over distances considerably larger than that of a hadron. Lattice QCD calculations [1] have predicted such a transition with a rapid rise in the entropy density at a critical temperature of about $T_c \simeq 170$ MeV. However, the entropy density is seen to level off somewhat below the ideal gas limit. Calculations with a more sophisticated resummation of quasiparticle modes [2] within the hard-thermal-loop approximation [3] improve upon the ideal gas picture but are still above the lattice QCD results near and just above T_c, suggesting that the plasma may possess a somewhat more complex structure in this regime. Indeed, recent lattice QCD calculations of spectral functions find the presence of bound states above T_c in both the heavy [4] and light [5] quark sector. While corrections due to lattice artifacts and the quenched approximation have been investigated in detail for the heavy quark bound states, the light quark sector has not yet received this level of scrutiny. This has led to the suggestion that at moderate temperatures, $T \simeq (1\text{–}2)T_c$, there exist many bound states [6] both in the color singlet and other colored representations, though lattice QCD results on baryon-strangeness correlations can rule out the presence of many light bound states involving only quarks and antiquarks [7]. Furthermore, strong collective flow observed in experiments at the Relativistic Heavy-Ion Collider (RHIC) [8] also suggest a strongly interacting plasma. Therefore, the nature of the relevant degrees of freedom in the matter created at RHIC needs to be further explored.

It is the purpose of this Letter to argue and demonstrate that one can probe the resonance structure of the dense matter via the production of Cherenkov-like soft hadrons along the path of quenched jets. The results derived will be most applicable to matter just above T_c. Jet quenching or medium modification of the jet structure has emerged as a new diagnostic tool for the study of partonic properties of the dense matter [9]. The modification goes beyond a mere suppression of inclusive spectra of leading hadrons [10] and has been extended to include the modification of two-hadron correlations [11,12]. Of particular interest for the present work is the experimental observation that soft hadrons correlated with a quenched jet have an angular distribution that is peaked at a finite angle away from the jet [13,14], whereas they peak along the jet direction in vacuum. In the picture of normal gluon bremsstrahlung induced by multiple parton scattering, one can identify these associated soft hadrons with those from the hadronization of radiated gluons. Because of the Landau-Pomeranchuck-Midgal interference, the angular distribution of the induced gluon bremsstrahlung does peak at an angle $\theta \sim \sqrt{2/\omega_g L}$ away from the initial jet direction [15,16]. However, this angle decreases with the length of the jet propagation or with the centrality of the nuclear collisions. This is currently not supported by the experimental data [13,14].

Two other known phenomena can, however, result in such an emission pattern: Mach cones generated by the hydrodynamical propagation of energy deposited by a quenched jet along its path [17,18] and Cherenkov gluon radiation. The angle of particle emission from the generated Mach cone is determined by the velocity of sound which can be calculated in lattice QCD. In the case of Cherenkov gluon radiation, the situation is less clear. While the general phenomenon has been discussed [19,20], the essential question of whether the index of refraction, which determines the cone angle, is larger than unity in deconfined QCD matter has not been addressed. Indeed, calculations in the hard-thermal-loop approximation of QCD [3] do not allow for Cherenkov gluon radiation [19]. Quenched lattice QCD calculations also indicate a timelike dispersion relation for large momenta ($p \gg T$) at $T > T_c$ [21]. The situation, however, is unclear for soft modes $p < T$ and at around T_c.

In this Letter, we start with the realization that a large index of refraction and therefore Cherenkov-like gluon bremsstrahlung can result only from coherent gluon scattering off partonic bound states in the quark-gluon plasma (QGP). The situation is analogous to photons in a gas, where the coherent scattering off atoms in the gas allows for Cherenkov radiation, but not in a gas of single elementary charged particles. Thus the observation of Cherenkov-like bremsstrahlung in heavy-ion collisions would serve as a signal for the presence of bound states in the QGP.

Obviously, a large index of refraction, corresponding to a spacelike dispersion relation, requires attractive interaction. This is where the bound states enter the picture: It is natural to assume that these bound states have excitations, just like an atom, and gluon interaction can cause transition between these bound states through simple resonant scattering. If the energy of the gluon is smaller than that of the first excited state, the scattering amplitude is attractive, leading to an attractive optical potential for such a gluon. As a consequence, the gluon dispersion relation in this regime becomes spacelike and Cherenkov radiation will occur. Similar effects have been noted in the context of gluon scattering in nuclei [20] or pion scattering in nuclear matter, where the transition of the nucleon to the Delta resonance provided the necessary attraction [22].

To illustrate this effect within finite temperature field theory, a simplified model is employed: a massless scalar Φ (representing the radiated gluon) coupled to two massive scalars ϕ_1, ϕ_2, representing a bound state and its excitation. The interaction is such that Φ may induce a transition from ϕ_1 to ϕ_2 and vice versa. The Lagrangian for such a system, ignoring the self-interactions between the scalars, has the form

$$\mathcal{L} = \sum_{i=1}^{2}\frac{1}{2}(\partial\phi_i)^2 + \frac{1}{2}(\partial\Phi)^2 + \sum_{i=1}^{2}\frac{1}{2}m_i^2\phi_i^2 + g\Phi\phi_2\phi_3. \quad (1)$$

The coupling constant g is dimensionful; this along with all other scales in this Letter will be expressed in units of the temperature. Ignoring issues related to vacuum renormalizability of such a theory, we focus on a study of the dispersion relation of the massless scalar in such an environment. The thermal propagator of Φ in the interacting theory is given in general as

$$D(p^0, \vec{p}) = \frac{1}{(p^0)^2 - |\vec{p}|^2 - \Pi(p^0, \vec{p}, T)}, \quad (2)$$

and the dispersion relation is given by the on-shell condition: $(p^0)^2 - |\vec{p}|^2 - \Pi(p^0, \vec{p}, T) = 0$. Here, $\Pi(p^0, \vec{p}, T)$ is the thermal self-energy of Φ due to loop diagrams such as the one shown in Fig. 1. The imaginary parts of this self-energy at finite temperature has been discussed in Ref. [23]. In this Letter, the focus will be on the real part of the one-loop self-energy.

In order to discuss the essential contributions to the self-energy, it is decomposed, following Ref. [24], as

$$\begin{aligned}\Pi(p^0, p) = g^2 \int \frac{d^3k}{(2\pi)^3}\frac{1}{2}\Bigg[&\frac{1}{2E_1(\vec{k})}\left\{\frac{\{1+n[E_1(\vec{k})]\}+\{n[E_1(\vec{k})]\}}{[p^0+E_1(\vec{k})]^2-[E_2(\vec{p}+\vec{k})]^2}\right\} + \frac{1}{2E_1(\vec{k})}\left\{\frac{\{1+n[E_1(\vec{k})]\}+\{n[E_1(\vec{k})]\}}{[p^0-E_1(\vec{k})]^2-[E_2(\vec{p}-\vec{k})]^2}\right\}\\ &+\frac{1}{2E_2(\vec{k})}\left\{\frac{\{1+n[E_2(\vec{k})]\}+\{n[E_2(\vec{k})]\}}{[p^0+E_2(\vec{k})]^2-[E_1(\vec{p}+\vec{k})]^2}\right\} + \frac{1}{2E_2(\vec{k})}\left\{\frac{\{1+n[E_2(\vec{k})]\}+\{n[E_2(\vec{k})]\}}{[p^0-E_2(\vec{k})]^2-[E_1(\vec{p}-\vec{k})]^2}\right\}\Bigg],\end{aligned} \quad (3)$$

where $n(E)$ denotes the thermal (Bose-Einstein) distribution. In the subsequent discussion, only the temperature dependent parts of the self-energy, i.e., terms involving thermal distributions, are relevant. In the case when $m_2 - m_1 \gg T$, the last two terms are suppressed by Boltzmann factors as compared to the first two. In the above equation, the first term represents the standard resonant scattering contribution, where the "gluon," Φ, absorbs the lower bound state, ϕ_1, and propagates through the spacelike off-shell intermediate state ϕ_2. At low gluon momenta p, this is the dominant term which provides the necessary attraction. In Fig. 2, the real and imaginary parts of the self-energy are plotted as functions of the energy for a fixed momentum $|\vec{p}| = 1.5T$, $m_1 = T$, $m_2 = 3T$, and $g = 2T$. Contributions to the real part from the first two terms which

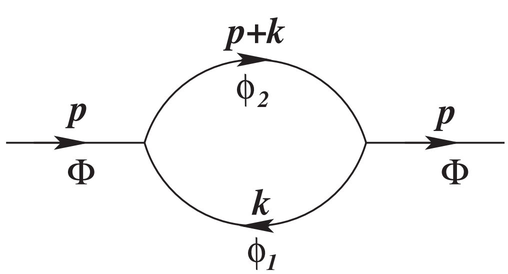

FIG. 1. The general contribution to the self-energy of Φ due to transitional interaction.

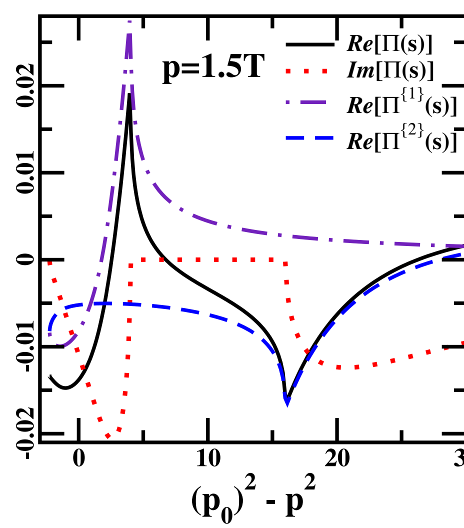

FIG. 2 (color online). The real (solid line) and imaginary parts (dotted line) of the full self-energy and the first two contributions (dashed and dot-dashed lines) from Eq. (3).

are the dominant contributions are also plotted. Note that at low energies, below the resonance [$s \equiv p_0^2 - \vec{p}^2 = (m_2 - m_1)^2$], we find attraction as expected from resonance scattering. At higher energies, just before the threshold [$s = (m_1 + m_2)^2$] for the production of a pair of ϕ_1, ϕ_2 states, additional attraction is also found for the given four momentum. This corresponds to the emission of a ϕ_1 by Φ and the creation of an spacelike off-shell ϕ_2. This region, however, is not relevant for the subsequent discussion of Cherenkov radiation.

In principle, one should include the contribution from the self-coupling of Φ to the self-energy. For vector gluons, such a contribution, in isolation, gives rise to a timelike dispersion relation, and in combination with the gluon-resonance coupling may lead to a complicated momentum dependence of the dispersion relation. However, if the gluon-resonance coupling is much stronger than the gluon self-coupling, one may neglect such a contribution to the self-energy.

The resulting dispersion relations for different choices of masses of ϕ_1, ϕ_2 are shown in Fig. 3. As expected we obtain a spacelike dispersion relation in low momentum which approaches the light cone as (p^0, p) is increased. Even though we have studied a simple scalar theory, the attraction leading to Cherenkov-like bremsstrahlung has its origin in resonant scattering. Thus, the result is genuine and depends only on the masses of the bound states and their excitations.

Another essential issue is the behavior of the imaginary part of the self-energy along the curve of the quasiparticle dispersion relation. The imaginary parts are always found to be negative, which in our convention indicates damping of the modes. In Fig. 4 we plot the real and imaginary parts of the self-energies for values of (p_0, p) which satisfy the in-medium dispersion relation. The two sets of curves correspond to the first two sets of parameters in Fig. 3. One notes that the real part has only moderate variation in this range of momentum. In contrast, the imaginary part seems to rise in magnitude. A large imaginary part indicates that the mode experiences strong damping and will not propagate far in the medium. However, there seems to exist a range of soft energies and momenta in the dispersion relation where the imaginary part is very small allowing the possibility for long range propagation of Cherenkov-like gluons. As the momentum is increased, ionization contributions to the self-energy will have to be included [25] which will enhance the imaginary part. In an alterative scenario, the imaginary part may be large at all energies [26]. However, even in the region where the imaginary part is large and the mode is considerably damped, there could still be a unique angular distribution of Cherenkov-like gluon bremsstrahlung [16] except that the energy of these gluons is absorbed by the medium. The propagation of this energy through the medium can also cause sonic shock waves, however, with modified Mach cone angles.

Cherenkov-like gluon bremsstrahlung may be observed as conical structures in two-particle correlations in jets. Shown in Fig. 5 is the dependence of the Cherenkov angle $\cos\theta_c = 1/n(p)$ on the gluon momentum, as determined from the dispersion relation in Fig. 3. It has a strong momentum dependence and vanishes quickly at large gluon momentum as the dispersion relation approaches the light cone. Such a momentum dependence of the emission angle is in contradistinction with that of a Mach cone, which is independent of the momentum of the emitted particle.

The normal Cherenkov radiation (without multiple scattering of the propagating energetic parton) also contributes

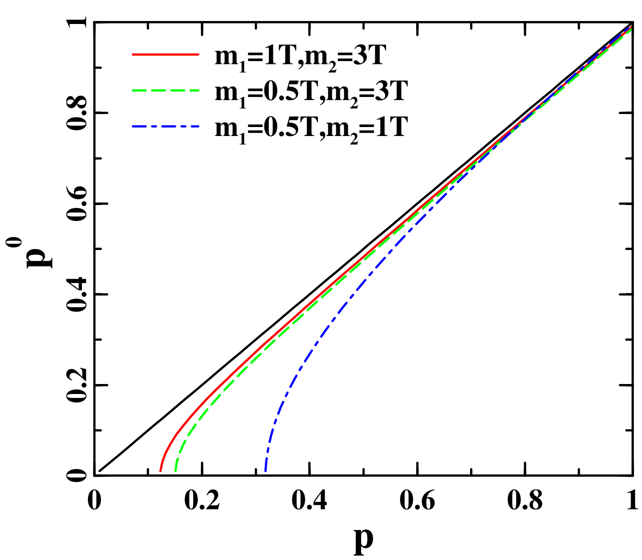

FIG. 3 (color online). The dispersion relation of Φ in a thermal medium with transitional coupling to two massive particles. The diagonal line represents the light cone.

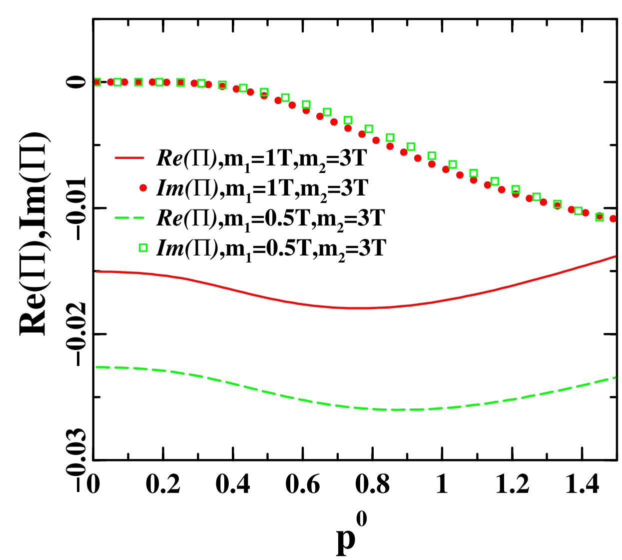

FIG. 4 (color online). The real and imaginary parts of $\Pi(p^0, p)$ for p^0, p which satisfy the quasiparticle dispersion relation. The choice of parameters and the legends for the real parts are the same as in Fig. 3.

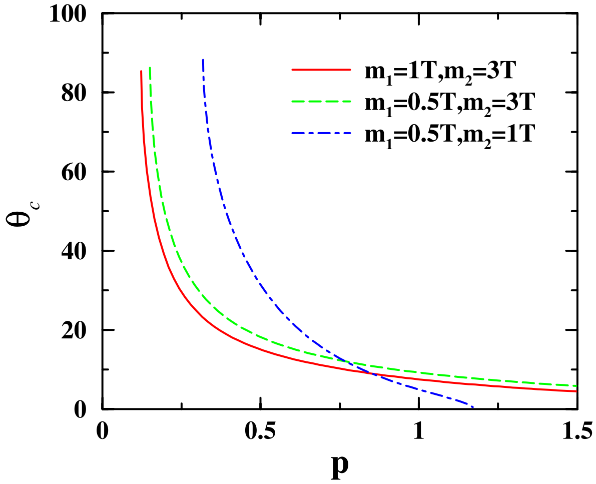

FIG. 5 (color online). Dependence of the Cherenkov angle on momentum of the emitted particle.

to the parton energy loss. Adopting the results obtained for photon Cherenkov radiation [27] we can estimate this energy loss by

$$\frac{dE}{dx} = 4\pi\alpha_s \int_{n(p_0)>1} p_0\left[1 - \frac{1}{n^2(p_0)}\right] dp_0, \tag{4}$$

where $n(p_0) = |\vec{p}|/p_0$ is the index of reflection. Using the dispersion relation in our simple model, the typical energy scale for the soft mode where Cherenkov radiation can happen is $p_0 \sim T$. The Cherenkov energy loss is about $dE/dx \sim 0.1$ GeV/fm for $T \sim 300$ MeV. This is much smaller than the normal radiative energy loss induced by multiple scattering of the energetic partons [9]. As discussed in Ref. [16], bremsstrahlung, induced by multiple scattering, of soft gluons with a spacelike dispersion relation can still lead to Cherenkov-like angular distributions due to Landau-Pomeranchuck-Migdal interference. Such Cherenkov-like gluon bremsstrahlung will lead to a similar emission pattern of soft hadrons as pure Cherenkov radiation. Thus, a distinctive experimental signature of the Cherenkov-like gluon radiation is the strong momentum dependence of the emission angle of soft hadrons leading to the disappearance of a conelike structure for large p_T asssociated hadrons.

In conclusion, we have shown how bound states in the QGP or more generally additional mass scales give rise to radiation of Cherenkov gluons off a fast jet traversing the medium. These Cherenkov gluons lead to a conelike emission pattern of soft hadrons. The cone angle with respect to the jet direction exhibits a strong momentum dependence in contrast to a Mach cone. Pure Cherenkov radiation leads to energy loss which, however, is too small to account for the jet suppression observed in RHIC experiments. Collision-induced Cherenkov-like bremsstrahlung [16] can explain both the observed energy loss and the emission pattern of soft hadrons in the direction of quenched jets.

We thank F. Karsch and E. Shuryak for helpful discussions. Research supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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