

High-Energy Photons from Passage of Jets through Quark-Gluon Plasma

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We calculate the production of high-energy photons from Compton scattering and annihilation of a quark jet passing through a quark gluon plasma produced in a relativistic heavy ion collision. The contributions are large and reflect the momentum distribution of the jets and the initial conditions of the plasma.

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Relativistic heavy ion collisions are studied with the aim of producing a plasma of quarks and gluons (QGP). Photons are considered to be an important probe for the investigation of the formation and evolution of such a plasma due to their weak final-state interactions [1]. Once produced they carry the information about the conditions of the environment in which they were created, encoded in their momentum distribution, thus providing a glimpse deep into the bulk of strongly interacting matter. Though most of the measured photons have their origin in the decay of hadrons after the QGP phase, it has become possible to isolate the direct photons produced in such collisions [2].

The sources of direct photons considered so far include quark annihilation, Compton scattering, and bremsstrahlung following the initial hard scattering of partons of the nuclei [3], as well as thermal photons from the QGP [4–8] and from hadronic interactions in the hot hadronic gas after the hadronization of the plasma [4,9]. The preequilibrium production of photons has also been investigated by several authors [10]. Results are available for production from the entire history of the system [11].

In this Letter we study a new source of direct photons originating from the passage of the produced high-energy quark jets through the QGP (jet-photon conversion). A fast quark passing through the plasma will produce photons by Compton scattering with the thermal gluons and annihilation with the thermal antiquarks. This process is higher-order in α_s compared with photons from initial hard scatterings, but it is not a subleading contribution, since it corresponds to double scattering, which is enhanced by the size of the system. For cold nuclear matter this effect is encoded in multiparton matrix elements which are enhanced by powers of $A^{1/3}$ [12]. Below, we find that this source is at least comparable in strength to the other direct photon sources and even dominates in the range $p_\perp \leq 6$ GeV for Au + Au collisions at the Relativistic Heavy Ion Collider (RHIC).

We also demonstrate that the p_\perp distribution of these photons is directly proportional to the momentum distribution of jets at an early stage after their production, before they have lost energy on their travel through the plasma. Since the measured high- p_\perp hadron spectrum is proportional to the spectrum of partons after they have left the plasma, a comparison of both spectra could provide a quantitative determination of the energy loss and help confirm the mechanism of jet quenching [13,14].

Furthermore, the photon yield depends on the integrated density of the matter traversed by the jets and thus can provide a measurement of this quantity. We emphasize that our mechanism is distinct from the back-to-back correlation among direct photons and leading hadrons, which was proposed as a direct measurement of the jet energy loss in dense matter [15].

The idea of jet-photon conversion is based on the properties of the annihilation and Compton cross sections. The kinematics of the annihilation of a quark antiquark pair ($q + \bar{q} \rightarrow \gamma + g$) is expressed in terms of the Mandelstam variables $s = (p_q + p_{\bar{q}})^2$, $t = (p_q - p_\gamma)^2$, and $u = (p_{\bar{q}} - p_\gamma)^2$, where the p_i are the four-momenta of the particles. The differential cross section at Born level for massless partons has the form $d\sigma/dt = 8\pi\alpha\alpha_s e_q^2 (u/t + t/u)/9s^2$, where e_q is the fractional charge of the annihilating quarks. This implies that the largest contribution to the production of photons arises from small values of t or u , corresponding to $\mathbf{p}_\gamma \approx \mathbf{p}_q$ or $\mathbf{p}_\gamma \approx \mathbf{p}_{\bar{q}}$. The process can be visualized as a conversion of one of the annihilating quarks to a photon. This picture immediately suggests that the photons from this process provide a direct measurement of the quark (or antiquark) momentum. For the Compton process ($g + q \rightarrow \gamma + q$) we have $d\sigma/dt = -\pi\alpha\alpha_s e_q^2 \times (u/s + s/u)/3s^2$. The dominant contribution now comes from the region of small u , when $\mathbf{p}_\gamma \approx \mathbf{p}_q$, corresponding to the conversion of the quark (or the antiquark) into a photon.

Following [16,17] we approximate the invariant photon differential cross sections for the annihilation and Compton processes as

$$E_\gamma \frac{d\sigma^{(a)}}{d^3 p_\gamma} \approx \sigma^{(a)}(s) \frac{1}{2} E_\gamma [\delta(\mathbf{p}_\gamma - \mathbf{p}_q) + \delta(\mathbf{p}_\gamma - \mathbf{p}_{\bar{q}})], \quad (1)$$

$$E_\gamma \frac{d\sigma^{(c)}}{d^3 p_\gamma} \approx \sigma^{(c)}(s) E_\gamma \delta(\mathbf{p}_\gamma - \mathbf{p}_q). \quad (2)$$

Here $\sigma^{(a)}(s)$ and $\sigma^{(c)}(s)$ are the corresponding total cross sections. Now consider an ensemble of fast quarks passing through a hot medium. A certain fraction, determined by the total cross section, will undergo these annihilation or Compton processes initiated by the medium and will emit photons. Whenever this happens the energy of the emitted photon will reflect the initial energy of the converted quark.

Using (1) and (2) the rate of production of photons due to annihilation and Compton scattering are given by [16]

$$\begin{aligned} E_\gamma \frac{dN^{(a)}}{d^4 x d^3 p_\gamma} &= \frac{16E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(\mathbf{p}_\gamma) \int d^3 p f_{\bar{q}}(\mathbf{p}) \\ &\times [1 + f_g(\mathbf{p})] \sigma^{(a)}(s) \frac{\sqrt{s(s-4m^2)}}{2E_\gamma E} \\ &+ (q \leftrightarrow \bar{q}), \end{aligned} \quad (3)$$

$$\begin{aligned} E_\gamma \frac{dN^{(c)}}{d^4 x d^3 p_\gamma} &= \frac{16E_\gamma}{(2\pi)^6} \sum_{q=1}^{N_f} f_q(\mathbf{p}_\gamma) \int d^3 p f_g(\mathbf{p}) \\ &\times [1 - f_q(\mathbf{p})] \sigma^{(c)}(s) \frac{(s-m^2)}{2EE_\gamma} \\ &+ (q \rightarrow \bar{q}). \end{aligned} \quad (4)$$

The f_i are distribution functions for the quarks, antiquarks, and gluons. Inserting thermal distributions for the gluons and quarks one can obtain an analytical expression for these emission rates for an equilibrated medium [4,5,16].

We propose that the phase-space distribution of the quarks and gluons produced in a nuclear collision can be approximately decomposed into two components, a thermal component f_{th} characterized by a temperature T and a hard component f_{jet} given by hard scattering of partons and limited to transverse momenta $p_\perp \gg 1 \text{ GeV}/c$: $f(\mathbf{p}) = f_{\text{th}}(\mathbf{p}) + f_{\text{jet}}(\mathbf{p})$. We note that f_{jet} dominates for large momenta, while at small momenta f is completely given by the thermal part.

The phase-space distribution for the quark jets propagating through the QGP is given by the perturbative QCD result for the jet yield [18]:

$$\begin{aligned} f_{\text{jet}}(\mathbf{p}) &= \frac{1}{g_q} \frac{(2\pi)^3}{\pi R^2 \tau p_\perp} \frac{dN_{\text{jet}}}{d^2 p_\perp dy} R(r) \\ &\times \delta(\eta - y) \Theta(\tau_{\text{max}} - \tau) \Theta(R_\perp - r), \end{aligned} \quad (5)$$

where $g_q = 2 \times 3$ is the spin and color degeneracy of the quarks, R_\perp is the transverse dimension of the system, $\tau_i \sim 1/p_\perp$ is the formation time for the jet, and η is the space-time rapidity. $R(r)$ is a transverse profile function. We shall take τ_{max} as the smaller of the lifetime τ_f of the QGP and the time τ_d taken by the jet produced at position \mathbf{r} to reach the surface of the plasma. The boost invariant correlation between the rapidity y and η is assumed here [19]. Similar results are obtained when a Gaussian correlation between y and η , characterized by a width $\Delta_p \sim 2/p_\perp$ coshy is assumed [18].

We calculate the jet production and the direct production of photons in lowest-order perturbative QCD [3]. We have used the CTEQ5L parton distributions [20] and EKS98 nuclear modifications [21] with the scale set to p_\perp . We further use a K factor of 2.5 in the jet production to account for higher-order corrections cf. [22]. We neglect the weak dependence of K on p_\perp and \sqrt{S} in this study [23]. Our results for the number of quarks, antiquarks and gluons at $y = 0$ can be parametrized as

$$\left. \frac{dN^{\text{jet}}}{d^2 p_\perp dy} \right|_{y=0} = T_{AA} \left. \frac{d\sigma^{\text{jet}}}{d^2 p_\perp dy} \right|_{y=0} = K \frac{a}{(1 + p_\perp/b)^c}. \quad (6)$$

Here $T_{AA} = 9A^2/8\pi R_\perp^2$ is the nuclear thickness for a head-on collision. Numerical values for the parameters a , b , and c are listed in Table I.

The integral over \mathbf{p} in Eqs. (3) and (4) is dominated by small momenta. We can therefore drop the jet part in the decomposition of the distributions $f(\mathbf{p})$ in the integrands and approximate them by the thermal part. After performing the integrals the results for annihilation and Compton scattering are identical and read [16]

$$\begin{aligned} E_\gamma \frac{dN_\gamma^{(a)}}{d^3 p_\gamma d^4 x} &= E_\gamma \frac{dN_\gamma^{(c)}}{d^3 p_\gamma d^4 x} \\ &= \frac{\alpha \alpha_s}{8\pi^2} \sum_{f=1}^{N_f} \left(\frac{e_{q_f}}{e} \right)^2 \\ &\times [f_q(p_\gamma) + f_{\bar{q}}(p_\gamma)] T^2 \left[\ln \left\{ \frac{4E_\gamma T}{m^2} \right\} + C \right] \end{aligned} \quad (7)$$

TABLE I. Parameters for the minijet distribution $dN/d^2 p_\perp dy$ given in Eq. (5) at $y = 0$ for Au + Au at $\sqrt{S_{\text{NN}}} = 200 \text{ GeV}$ (RHIC) and for Pb + Pb at $\sqrt{S_{\text{NN}}} = 5.5 \text{ TeV}$ (LHC). Numbers for quarks and antiquarks are mean values for the three lightest flavors: $q = (u + d + s)/3$, $\bar{q} = (\bar{u} + \bar{d} + \bar{s})/3$, $K = 2.5$. The range of validity is $2 \text{ GeV}/c < p_\perp < 20 \text{ GeV}/c$.

		$a [1/\text{GeV}^2]$	$b [\text{GeV}]$	c
RHIC	q	5.0×10^2	1.6	7.9
	\bar{q}	1.3×10^2	1.9	8.9
LHC	q	1.4×10^4	0.61	5.3
	\bar{q}	1.4×10^5	0.32	5.2

with $C = -1.916$. We have included the three lightest quark flavors so that $\sum_f e_{q_f}^2/e^2 = 2/3$.

Once again we apply the decomposition of the distributions to (7). Inserting the thermal part we recover the known rate of emission of high-energy photons from interactions within the plasma. Since we are dealing with (nearly) massless partons we have to address the infrared divergence in (7) in the limit $m \rightarrow 0$. It has been shown [4,5] that the divergence can be eliminated by including higher-order effects from the interaction of the quarks in the thermal medium with the result that m^2 in the argument of the logarithm must be replaced with $2m_{\text{th}}^2 = g^2 T^2/3$.

We assume that these considerations remain valid for the emission of photons even when one of the partons is from a jet while the other one is from a thermal medium. This assumption remains to be verified. We add that the thermal photon production from the plasma has recently been calculated up to two loops [7] and to complete leading order [8], and is about a factor of 2 larger than the lowest-order results given here. It will be of considerable interest to extend our present work to account for these effects.

Now the rate of high-energy photon emission from the passage of quark jets through the QGP is obtained by substituting the jet contributions for f_q and $f_{\bar{q}}$ in (7). In order to calculate the photon yields we specify our model for the medium. Here we are interested in the emission of photons from the QGP phase alone. We assume that a thermally and chemically equilibrated plasma is produced in the collision at time τ_0 with temperature T_0 , and we ignore the transverse expansion of the plasma. Further assuming an isentropic longitudinal expansion [19], we can relate $T_0^3 \tau_0$ to the observed particle rapidity density dN/dy . We take $dN/dy \approx 1260$, based on the charged particle pseudorapidity density measured by the PHOBOS experiment [24] for central collisions of Au nuclei at $\sqrt{s_{NN}} = 200$ GeV. For central collision of Pb nuclei at LHC energies we use $dN/dy = 5625$ estimated by [25]. Imposing a rapid thermalization limited by $\tau_0 \sim 1/3T_0$ [25] we fix our initial conditions to be $T_0 = 446$ MeV and $\tau_0 = 0.147$ fm/c for RHIC and $T_0 = 897$ MeV and $\tau_0 = 0.073$ fm/c for LHC.

We model the nuclei as uniform spheres and assume a transverse profile for the initial temperature as $T(r) = T_0[2(1 - r^2/R_\perp^2)]^{1/4}$ where $R_\perp = 1.2A^{1/3}$ fm. We use the same profile $R(r) = 2(1 - r^2/R_\perp^2)$ for the jet production in (5) while performing the space-time integration $d^4x = \tau d\tau r dr d\eta d\phi$. The limits of the τ integration are $[\tau_0, \tau_f]$ where τ_f is fixed through the relation $T^3 \tau = \text{const}$, when the temperature reaches $T_f = 160$ MeV.

We also give results for the competing photon processes, the direct production in primary hard annihilation or Compton processes and the production via bremsstrahlung from a produced jet parton. For both cases the leading order results can again be found in [3]. No K factor is used for direct photon production. Our results

here obey the scaling for single photons suggested in [26] from empirical considerations.

In Fig. 1 we plot the results for thermal photons, direct photons due to primary processes, bremsstrahlung photons and the photons coming from jets passing through the QGP in central collision of gold nuclei at RHIC energies. The corresponding results for LHC energies are shown in Fig. 2. We see that the quark jets passing through the QGP give rise to a large yield of high-energy photons. This contribution should be absent in pp collisions. For RHIC this contribution is the dominant source of photons up to $p_\perp \approx 6$ GeV. Note that the jet-to-photon conversion falls more rapidly with p_\perp than the direct photon yield, similar to a higher twist correction.

A suppression of the bremsstrahlung contribution due to the multiple scattering suffered by the fragmenting partons [27] will further enhance the importance of the jet-photon conversion process. The effects of a possible chemical nonequilibrium may be estimated as follows. A reduced quark abundance will enter at least linearly into the thermal rate but can reduce the jet-photon conversion by at most a factor of 2, as the Compton contribution will remain unaffected. Therefore the thermal rate will be more strongly suppressed than the jet-photon conversion. Similarly, the jet-photon conversion is only moderately sensitive to the initial conditions and the transit time of the jet in the medium. We have found that increasing τ_0 to 1 fm/c, keeping $T_0^3 \tau_0$ fixed, reduces our results for RHIC only by about 40%.

One may ask how our results will be modified by the energy loss experienced by the quark jets passing through the QGP. This effect will be relatively small for two

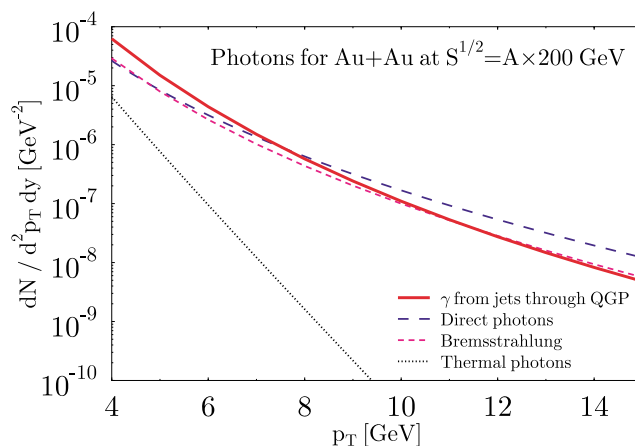


FIG. 1 (color online). Spectrum $dN/d^2 p_\perp dy$ of photons at $y = 0$ for central collision of gold nuclei at $\sqrt{s_{NN}} = 200$ GeV at RHIC. We show the photons from jets interacting with the medium (solid line), direct hard photons (long dashed), bremsstrahlung photons (short dashed), and thermal photons (dotted).

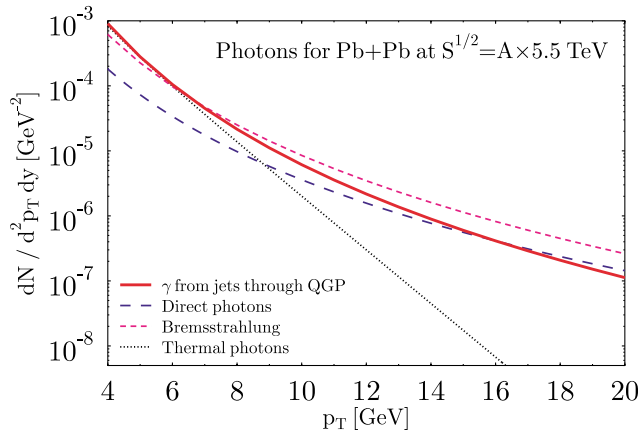


FIG. 2 (color online). The same as Fig. 1 for central collision of lead nuclei at $\sqrt{s_{NN}} = 5.5$ TeV at LHC.

reasons. First, we are concerned here with quark jets which lose energy at less than half the rate as gluons, which form the dominant fraction of jet events. Second, as the energy loss scales as the square of the distance traveled through the medium [14], the average energy loss at the moment of jet-photon conversion is only one-third of the total normal energy loss. This argument implies that, while the high- p_{\perp} hadron spectra encode information about the energy loss in the plasma, the photons from medium induced emission, on average, carry information about jets at an earlier stage. Obviously, the comparison of the high- p_{\perp} hadron and direct photon spectra can shed light on the evolution of the jet spectrum. We believe that this could be a useful method for the analysis of jet quenching and medium effects on hard particles in the QGP. More details of the calculation together with a careful analysis of the assumptions made here will be presented in a forthcoming paper.

In summary, we have discussed a novel mechanism for the production of high-energy photons in relativistic heavy ion collisions. The photons arise from the passage of quark jets through the medium, when a quark is converted into a photon due to Compton scattering from a gluon or annihilation by an antiquark. Our calculations indicate that this mechanism is the leading source of directly produced photons at RHIC in the region $p_{\perp} \leq 6$ GeV/c. The spectrum of the resulting photons reflects the initial distribution of the hard scattered quarks and is sensitive to the initial conditions and the traversal time of the jet in the plasma.

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