Soft photons from relativistic heavy ion collisions

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Production of soft photons in relativistic heavy ion collisions due to bremsstrahlung processes in quark matter and hadronic matter is studied. The contribution of pion-driven processes is found to dominate the yield. [S0556-2813(96)05405-2]

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I. INTRODUCTION

Soft photons and dileptons are expected to provide interesting information about all the stages of collisions involving heavy nuclei at relativistic energies, which are being carried out for an experimental verification of one of the most spectacular predictions of QCD—the existence of quark-gluon plasma (QGP). Low energy photons can be produced by a multitude of processes in such collisions and an identification of their source may provide valuable information about the development of the collision. Thus it has been argued that the low energy photons from the bremsstrahlung of the colliding nucleons [1,2] may provide information about the impact parameter and the initial conditions of the collision. Soft photons accompanying the production of secondary charged particles (pions, etc.) during the collision [3,4] have also been identified. These photons have transverse momenta limited to about 10 MeV/c.

It has been argued that the hadronization of QCD parton showers may lead to a residue consisting of a dense glob of cold quark gluon plasma [5]. Such globs may have a few dozen partons, with negligible virtualities and very low momenta. Noting that $\overline{p} \approx M_{\text{glob}}/N_{\text{partons}}$, and taking the mass of the glob as ~ 1 GeV, and the number of partons as 40, we see that $\overline{p}$ is of the order of a few tens of MeV/c. The Compton and annihilation processes taking place in this glob will lead to a production of soft photons, which will have transverse momenta $p_T \leqslant 50$ MeV/c. A number of experiments have reported such soft photons [6,7].

In the present work we concentrate on bremsstrahlung production of soft photons in the quark matter $[qq(g) \to qq(g)\gamma]$ and the hadronic matter $(\pi\pi \to \pi\pi\gamma)$ which may be produced during the course of the evolution of relativistic heavy ion collisions and which may have transverse momenta extending up to a few hundred MeV. It has also been argued that the production of a hot and dense matter in relativistic heavy ion collisions may be accompanied with a rapid transverse expansion of the interacting system during the last stages.

An attempt to get information about the system just before the freeze-out by analyzing the hadronic distribution (the inclusive p_T spectrum) may not result in a unique value for the freeze-out temperature or the transverse velocity (see Ref. [8] and references therein). One can understand this by recalling that inclusive spectra of hadrons are often characterized by a slope for the p_T distribution. If the transverse velocity of the particles and the temperature at the instant of freeze-out are β_f and T_f, respectively, then the Doppler shifted temperature is seen to be

$$T_{\text{apparent}} = T_f \left[\frac{1+\beta_f}{1-\beta_f} \right]^{1/2} \tag{1}$$

which has a built-in recipe for a continuous ambiguity between T_f and β_f. We may further add that the condition of freeze-out is also not defined very uniquely [9].

Soft photons can perhaps be used with advantage for this study. Their rate of production is a very sensitive index of the temperature of the system and they could be very reliable chroniclers of the collective flow and the last stages of the interacting system. We shall see later that modest variations in the freeze-out temperature cause a large variation in their production. The sensitivity comes about from the dependence of the slope as well as the overall yield of the transverse momentum distribution on the freeze-out temperature.

II. FORMULATION

The production of soft photons (see Ref. [10] for a general discussion) is most conveniently calculated by invoking the soft photon approximation [11] which provides that the invariant cross section for scattering and at the same time production of a soft real photon of four-momentum q^μ can be written as

$$q_0 \frac{d^4\sigma^\gamma}{d^3q\,dx} = \frac{\alpha}{4\pi^2} \left\{ \sum_{\text{pol}\lambda} J\cdot\epsilon_\lambda J\cdot\epsilon_\lambda \right\} \frac{d\sigma}{dx}, \tag{2}$$

where $d\sigma/dx$ is the strong interaction cross section for the reaction $ab \to cd$, ϵ_λ is the polarization of the photon, and

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$$J^{\mu}=-Q_a\frac{p_a^{\mu}}{p_a\cdot q}-Q_b\frac{p_b^{\mu}}{p_b\cdot q}+Q_c\frac{p_c^{\mu}}{p_c\cdot q}+Q_d\frac{p_d^{\mu}}{p_d\cdot q} \quad (3)$$

is the current. The Q's and p's represent the charges (in units of charge of a proton) and the four-momenta of the particles, respectively. The production of soft virtual photons, e.g., is then obtained by continuing from $q^2=0$ to $q^2=M^2$, where M is the invariant mass of the virtual photon, so that

$$E_+E_-\frac{d^6\sigma^{e^+e^-}}{d^3p_+d^3p_-}=\frac{\alpha}{2\pi^2}\frac{1}{q^2}q_0\frac{d^3\sigma^{\gamma}}{d^3q}. \quad (4)$$

Lichard [12] has pointed out that already two inaccuracies have crept into the above formulation. First, the factor $\alpha/2\pi^2$ should be $\alpha/3\pi^2$, so that one recovers the natural limiting equality,

$$\left(\frac{d\sigma^{\gamma^\star}}{d^3q}\right)_M \overset{M\ll q_0}{=} \frac{d\sigma^{\gamma}}{d^3q}. \quad (5)$$

The second suggestion of Lichard pertains to the use of the current appropriate for a virtual photon. It is not relevant for the production of real photons. Thus, if we proceed along the lines of, e.g., Ref. [10], the cross section for the production of soft photons is written as

$$q_0\frac{d\sigma^{\gamma}_{ab\to cd}}{d^3q}=\frac{\alpha}{4\pi^2}\frac{\hat{\sigma}(s)}{q_0^2}. \quad (6)$$

We have further taken an average of the electromagnetic factor over the solid angle of the photon and defined

$$\hat{\sigma}(s)=\int_{-\lambda(s,m_a^2,m_b^2)/s}^{0}dt\frac{d\sigma_{ab\to cd}}{dt}(q_0^2|\epsilon\cdot J|^2_{ab\to cd}). \quad (7)$$

The expressions are further corrected for the neglect of the momentum of the photon in the phase space δ function by inserting the factor

$$\Phi(s,s_2,m_a^2,m_b^2)=\frac{\lambda^{1/2}(s_2,m_a^2,m_b^2)}{\lambda^{1/2}(s,m_a^2,m_b^2)}\frac{s}{s_2}, \quad (8)$$

where $s_2=s-2\sqrt{s}q_0$ and $\lambda(x,y,z)=x^2-2(y+z)x+(y-z)^2$.

Now we can write down the rate of production of photons at the temperature T, using kinetic theory as

$$E\frac{dN^{\gamma}}{d^4xd^3q}=\frac{T^6g_{ab}}{16\pi^4}\int_{z_{\min}}^{\infty}dz\frac{\lambda(z^2T^2,m_a^2,m_b^2)}{T^4}\times\Phi(s,s_2,m_a^2,m_b^2)K_1(z)q_0\frac{d\sigma^{\gamma}_{ab}}{d^3q}, \quad (9)$$

where $z_{\min}=(m_a+m_b)/T$, $z=\sqrt{s}/T$, and $g_{ab}=N_aN_b(2s_a+1)(2s_b+1)$ is the color and spin degeneracy appropriate for the collision. The expressions for angle-averaged electromagnetic factors for scattering of two pions, two quarks, and quarks and (massless) gluons can be found in Ref. [10].

A. Soft photon production from quark matter

For emission of soft photons from the light quarks (u and d) in the QGP we consider the bremsstrahlung processes $ab\to ab\gamma$ where a is a quark or an antiquark, and b is either a quark, or an antiquark, or a gluon. The annihilation and the Compton processes $q\overline{q}\to\gamma g$ and $q(\overline{q})g\to q(\overline{q})g\gamma$ in the QGP have already been studied in fair detail by a number of authors [13–16] and we shall use the results of Ref. [13] in the following, for a comparision:

$$E\frac{dN_{\gamma}^{C+\text{ann}}}{d^4xd^3q}=\frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}T^2e^{-E/T}\ln\left(\frac{2.912ET}{6m_q^2}+1\right), \quad (10)$$

where $m_q=\sqrt{2\pi\alpha_s/3}T$ is the thermal mass of the quarks.

In order to evaluate the strong interaction differential cross sections $d\sigma_{qq}/dt$ and $d\sigma_{qg}/dt$ we have used the approximation developed [17] and used [10] earlier for scattering of quarks and gluons in hot QCD matter,

$$\frac{d\sigma^{ab}}{dt}=C_{ab}\frac{\pi}{2}\frac{\alpha_s^2(T)(2t-m_E^2-m_M^2)^2}{(t-m_E^2)^2(t-m_M^2)^2}, \quad (11)$$

where

$$C_{ab}=\begin{cases}1 & (qg\to qg)\\ \frac{4}{9} & (qq\to qq)\end{cases}, \quad (12)$$

m_E is the color electrical mass

$$m_E\approx 4\sqrt{\frac{\pi\alpha_s}{3}}T \quad (13)$$

for a baryon-free plasma having two flavors ($N_f=2$), m_M is the color magnetic mass

$$m_M\approx 5\alpha_sT, \quad (14)$$

and α_s is the strong coupling constant which we fix as

$$\alpha_s(T)=\frac{6\pi}{(33-2N_f)\ln(\kappa T/T_c)}, \quad (15)$$

with $\kappa\approx 8$. In the following we shall fix the transition temperature T_c at 160 MeV.

B. Soft photon production from hadronic matter

We shall concentrate on bremsstrahlung production of soft photons from processes of the type $\pi\pi\to\pi\pi\gamma$. In order to be able to use the correct electromagnetic factor, it is important to have the t dependence of the scattering cross section of pions. For this purpose, we perform a field-theoretical calculation using σ, ρ, and $f(1270)$ meson exchange to treat the strong interaction as in Ref. [10]. Thus the effective Lagrangian which has been used is given by

$$\mathcal{L}_{\text{int}}=g_{\sigma}\sigma\partial_{\mu}\vec{\pi}\cdot\partial^{\mu}\vec{\pi}+g_{\rho}\vec{\rho}^{\mu}\cdot(\vec{\pi}\times\partial_{\mu}\vec{\pi})+g_ff_{\mu\nu}\partial^{\mu}\vec{\pi}\cdot\partial^{\nu}\vec{\pi}. \quad (16)$$

We shall include reactions $\pi^+\pi^-\to\pi^+\pi^-$, $\pi^+\pi^-\to\pi^0\pi^0$, $\pi^+\pi^0\to\pi^+\pi^0$, and $\pi^-\pi^0\to\pi^-\pi^0$ in the following. Other processes are expected to make only a marginal contribution. The accuracy of these model calculations has already been tested earlier [10], and we recapitulate the arguments for obtaining the $d\sigma/dt$ for, e.g., the $\pi^+\pi^-\to\pi^+\pi^-$ scattering in the following. We note that the differential cross section is proportional to the square of the matrix element describing the overlap of initial and final two-hadron states. This leads to six terms in this matrix element: t and s channel σ-exchange, ρ-exchange, and f-exchange processes. The composite nature of mesons calls for a modification at high momentum transfers. This results in an effective suppression in the high momentum regime and the vertices in the t-channel diagrams are given momentum-transfer damping monopole form factors

$$h_\alpha(t)=\frac{m_\alpha^2-m_\pi^2}{m_\alpha^2-t}, \tag{17}$$

where m_α stands for the mass of the (exchanged) meson σ, ρ, or the f. The treatment also incorporates the finite resonance lifetimes into the scalar, vector, and tensor boson propagators. For the f propagator we use

$$i\mathscr{P}^{\mu\nu\alpha\beta}=\frac{-i\{\frac{1}{2}(\frac{1}{3}g^{\mu\nu}g^{\alpha\beta}-g^{\mu\alpha}g^{\nu\beta}-g^{\mu\beta}g^{\nu\alpha})\}}{k^2-m_f^2+im_f\Gamma_f}. \tag{18}$$

Now the full matrix element is given by

$$\mathscr{M}=\mathscr{M}_1+\mathscr{M}_2+\mathscr{M}_3+\mathscr{M}_4+\mathscr{M}_5+\mathscr{M}_6, \tag{19}$$

where

$$\mathscr{M}_1=\frac{-g_\sigma^2h_\sigma^2(t)(2m_\pi^2-t)^2}{t-m_\sigma^2+im_\sigma\Gamma_\sigma},$$

$$\mathscr{M}_2=\frac{-g_\sigma^2(s-2m_\pi^2)^2}{s-m_\sigma^2+im_\sigma\Gamma_\sigma},$$

$$\mathscr{M}_3=\frac{-g_\rho^2h_\rho^2(t)(s-u)}{t-m_\rho^2+im_\rho\Gamma_\rho}, \tag{20}$$

$$\mathscr{M}_4=\frac{g_\rho^2(u-t)}{s-m_\rho^2+im_\rho\Gamma_\rho},$$

$$\mathscr{M}_5=\frac{g_f^2h_f^2(t)}{t-m_f^2+im_f\Gamma_f}\,\frac{1}{2}\left(\frac{1}{3}(2m_\pi^2-t)^2-(s-2m_\pi^2)^2-(2m_\pi^2-u)^2\right),$$

$$\mathscr{M}_6=\frac{g_f^2}{s-m_f^2+im_f\Gamma_f}\,\frac{1}{2}\left(\frac{1}{3}(s-2m_\pi^2)^2-(2m_\pi^2-t)^2-(2m_\pi^2-u)^2\right).$$

It may be noted that in the above g_σ and g_f are not dimensionless, but $g_\sigma m_\sigma$ and $g_f m_f$ are. The full amplitude is seen to be symmetric under the interchange of the final states as required for bosons. The elastic differential cross section is now obtained as

$$\frac{d\sigma}{dt}=\frac{|\mathscr{M}|^2}{16\pi s(s-4m_\pi^2)}. \tag{21}$$

As mentioned earlier the above description is known [10] to give an accurate description of the elastic scattering data. For the sake of completeness we list the values of the parameters: $g_\sigma m_\sigma=1.85$, $m_\sigma=0.525$ GeV, $\Gamma_\sigma=0.100$ GeV, $g_\rho=6.15$, $m_\rho=0.775$ GeV, $\Gamma_\rho=0.155$ GeV, $g_f m_f=7.2$, $m_f=1.274$ GeV, and $\Gamma_f=0.176$ GeV. The matrix elements for the other reactions are listed in the Appendix B of Ref. [18].

C. Integration over the space-time history of the system

The photon spectrum is then obtained by convoluting the rates for the emission of photons from the QGP and the hadronic matter with the space-time history of the system as

$$\frac{dN}{d^2q_Tdy}=\int \tau d\tau r dr d\phi d\eta\left[f_Q q_0\frac{dN^q}{d^4xd^3q}+(1-f_Q)q_0\frac{dN^\pi}{d^4xd^3q}\right], \tag{22}$$

where $f_Q(r,\tau,\eta,\phi)$ gives the fraction of the quark matter [19] in the system. This expression will simplify considerably for a boost-invariant longitudinal expansion [20], which we shall employ for our preliminary results.

We shall perform model calculations for a central collision of two lead nuclei, which is assumed to lead to the formation of a QGP of u and d quarks, and gluons at T_i at the initial time τ_i. This then expands, cools, and undergoes a first order phase transition to hadronic matter at $T=T_c=160$ MeV. When all the matter has converted to hadrons, it cools again and undergoes a freeze-out at $T_f=$ 140 MeV. We assume the system to have a transverse dimension R_T equal to the radius of lead nucleus. For an isentropic expansion, the initial temperature (T_i) and the initial time (τ_i) are related [21] to the particle rapidity density dN/dy by

$$T_i^3\tau_i=\frac{2\pi^4}{45\zeta(3)\pi R_T^2\,4a_k}\,\frac{dN}{dy}, \tag{23}$$

where $a_k=a_Q=37\,\pi^2/90$, if the system is initially in the QGP phase consisting of (massless) u and d quarks, and gluons. We model the hadronic phase as consisting of the mesons, π, ρ, ω, and η with $a_k=a_H\approx4.6\pi^2/90$ [22]. It is well known that $\tau_q=(T_i/T_c)^3\tau_i$ gives the proper time at the end of the QGP phase, $\tau_h=r\tau_q$ is the proper time at the end of the mixed phase, and $\tau_f=(T_c/T_f)^3\tau_h$ gives the time of freeze-out, where $r=37/4.6$ is the ratio of the degrees of freedom in the QGP and the hadronic matter and T_f is the freeze-out temperature. For the case of a boost-invariant longitudinal expansion $f_Q=1$ during the QGP phase, $f_Q=0$ during the hadronic phase, and

$$f_Q(\tau)=\frac{1}{r-1}\left[r\frac{\tau_q}{\tau}-1\right] \tag{24}$$

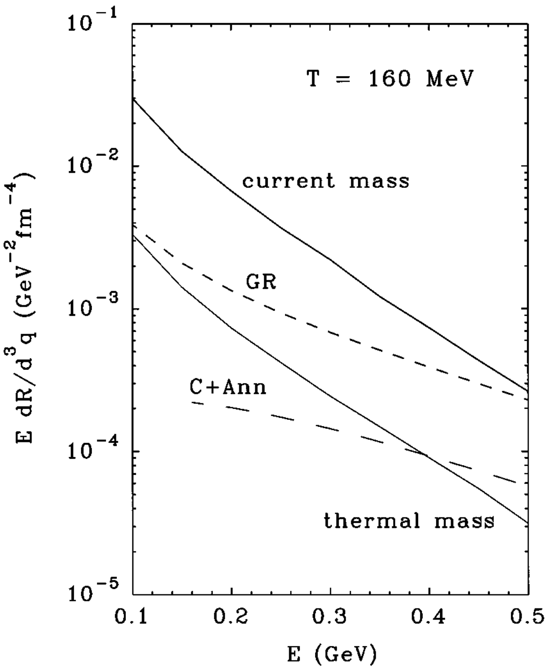

FIG. 1. Bremsstrahlung production of soft photons from quark driven processes $[qq(g)\rightarrow qq(g)\gamma]$ in the quark gluon plasma. We have also shown the estimate for these from the work of Ref. [24] (labeled ''GR''), which however does not account for the phase space reductions. The contribution of Compton and annihilation processes, for $E\geqslant T$, is given for a comparison.

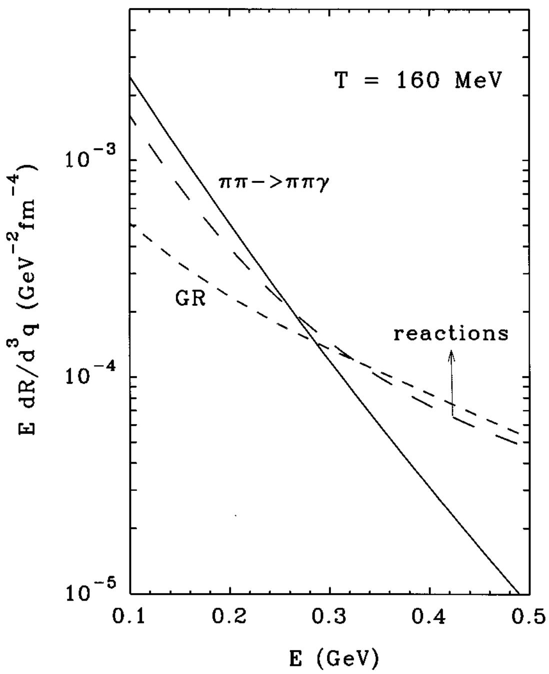

FIG. 2. Bremsstrahlung production of soft photons from pion driven processes $\pi\pi\rightarrow\pi\pi\gamma$ in the hadronic matter. We have also shown the estimate for these from the work of Ref. [24] (labeled ''GR''), which however does not account for the phase space reductions. The sum of the contribution of reactions $\pi\pi\rightarrow\rho\gamma$, $\pi\rho\rightarrow\pi\gamma$, $\pi\rho\rightarrow a_1\rightarrow\pi\gamma$, and the decays $\rho\rightarrow\pi\pi\gamma$ and $\omega\rightarrow\pi\gamma$ is given under the general heading ''reactions.''

during the mixed phase spanning the temporal stretch from τ_q to τ_h.

III. RESULTS AND DISCUSSIONS

In Fig. 1, we give our results for the rate of the production of soft photons due to quark driven processes. Results are given for the thermal mass as well as the current mass for the quarks. We find a very strong dependence on the mass of the quarks.

What is the appropriate value for the mass which should be used here? A current mass for the quarks would be appropriate if we had a system without interactions. However a quark moving in a hot medium is burdened with a thermal mass. This thermal mass also shields the singularity in the scattering cross section $d\sigma/dt$ which has been used in Eq. (11) above. The Compton and annihilation contributions which are shown for a comparison, are obtained by assigning a thermal mass to the quarks. It has been shown [13] that this is equivalent to using the resummation method of Braaten and Pisarski [23] to regulate the divergences of the QCD rates for these processes. We shall thus use the thermal mass for quarks for our subsequent results, to maintain a consistency. We shall, however, neglect the mass of the quarks while writing the equation of state as the temperatures we encounter are larger than the thermal mass of the quarks. The error introduced will be barely a few percent. In any case, we shall see later that the contribution of the QGP phase to the soft photons is only a small part of the total yield, and thus any moderate uncertainty in this contribution will not affect the final results drastically. It may be noted that the rates given by Kapusta, Lichard, and Seibert [Eq. (10)] are considered reliable for $E\geqslant T$ [13], and thus we show them only for such values in all the figures.

The biggest surprise is provided by the results of Goloviznin and Redlich [24], for the bremsstrahlung process involving quarks. Even after inclusion of the Landau-Pomeranchuk suppression, their results are larger than that due to the Compton and annihilation processes at all energies. Looking closely we find that their treatment, which closely follows the developments of Cleymans *et al.* [25,26] for soft dileptons, does not include the corrections for the phase space Φ mentioned above [Eq. (8)]; it is obviously quite important. This aspect has already been noted by Haglin *et al.* [10]. We do realize that the soft photon approximation will not be strictly valid for larger values of the energy but this should serve, at least, as a reasonable estimate. We see that the bremsstrahlung production of soft photons can be substantial once the energy is less than half a GeV or so. Recalling that the lower energy photons come out mostly at low temperatures, these could be a good probe for the later stages of the QGP.

The results for the pion driven bremsstrahlung processes are given in Fig. 2. We have also plotted this contribution as estimated by Golovizin and Redlich [24]. The sum of rates for the reactions $\pi\pi\rightarrow\rho\gamma$, $\pi\rho\rightarrow\pi\gamma$ as estimated by Kapusta *et al.* [13], and the $\pi\rho\rightarrow a_1\rightarrow\pi\gamma$ as estimated by Xiong *et al.* [27] along with the decays $\rho\rightarrow\pi\pi\gamma$ and $\omega\rightarrow\pi\gamma$ is given under a general label ''reactions.'' First of all we note the overestimation of the bremsstrahlung contribution by Goloviznin and Redlich due to the neglect of the

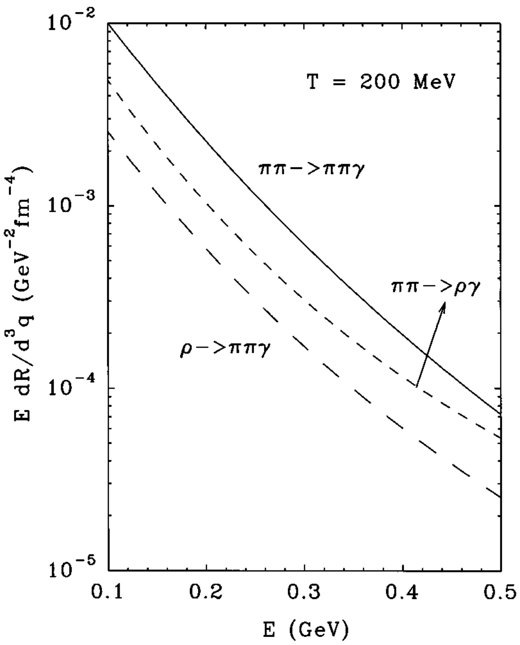

FIG. 3. A comparison of rates for thermal processes leading to production of soft photons at $T=200$ MeV.

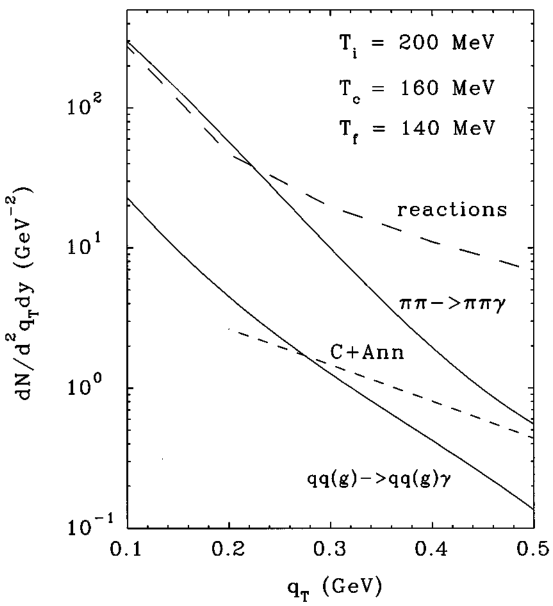

FIG. 4. The distribution of soft photons from bremsstrahlung processes in the quark matter and hadronic matter which may be produced in a relativistic heavy ion collision of two lead nuclei. We assume the collision to lead to a QGP (of u and d quarks, and gluons) at an initial temperature of $T_i=200$ MeV at $\tau_i = 1$ fm/c, which then expands, cools, undergoes a first order phase transition to a hadronic matter of π, ρ, ω, and η at 160 MeV, and freeze-out at 140 MeV. The Compton plus annihilation contributions are shown only for $E\geqslant$ the largest temperature encountered during the evolution.

phase space correction factor mentioned earlier. The difference with our results at lower energies deserves a closer look. Recall that we have used the exact electromagnetic factor and not the approximate one of Gale and Kapusta [28] and used by authors of Refs. [24–26, 29]. We have used our field theoretical estimates and not a parametrization of scattering cross sections [25] and also made corrections for the numerical factor advocated by Lichard [12].

In order to explore the ''equivalence'' of the reaction $\pi\pi\rightarrow\rho\gamma$ and the decay $\rho\rightarrow\pi\pi\gamma$ with the bremsstrahlung process $\pi\pi\rightarrow\pi\pi\gamma$ for very soft photons discussed by the authors of Ref. [24], we have plotted their contributions separately in Fig. 3. We find that, indeed, the sum of the first two processes does converge to the bremsstrahlung production for very low energy photons supporting the argument that once the energy of the photon is small it is not able to ''see'' the ρ meson, it only sees the two incoming (and the outgoing) pions, which combine to form a ρ meson which immediately dissociates to give two pions. We are reluctant, however, to carry this argument too far as the two calculations are performed under different approximations. We also note that, e.g., the $\pi\pi\rightarrow\rho\gamma$ is basically a two body reaction and hence the momenta of the pions uniquely determine the momentum of the photon. On the other hand, the bremsstrahlung process leads to a three body final state and the photon with a given momentum can be generated by pions having a variety of relative momenta, as indeed indicated by Eq. (8) above. This, among other things, enhances the bremsstrahlung contribution for the low energy photons. For higher energies the phase space reduction takes over and suppresses the bremsstrahlung contribution. In order to avoid confusion, we shall explicitly plot the bremsstrahlung contribution and the contribution of the ''reactions'' separately, till a more detailed and self-consistent calculation can settle this issue. We thus summarize that the bremsstrahlung contribution as obtained by us is comparable to the sum of all the reactions considered by Kapusta *et al.* and Xiong *et al.* at energies of the order of a few hundred MeV, beyond which it falls rapidly.

In Fig. 4 we present a model calculation for soft photons produced in a central collision involving two lead nuclei. The system is assumed to be in the form of a QGP initially, at $T_i = 200$ MeV and $\tau_i=1$ fm/c, consisting of u and d quarks, and gluons. The hadronization takes place at the critical temperature of $T_c=$ 160 MeV, and the freeze-out takes place at 140 MeV. The pions are now seen to provide the largest contribution to production of soft photons due to the bremsstrahlung process. Results for a higher initial temperature and a higher T_c are given in Fig. 5.

Finally in Fig. 6 we have tried to depict the sensitivity of the production of soft photons on the freeze-out temperature. We vary the freeze-out temperature from 100 MeV to 160 MeV. In the last case the system breaks up right after the mixed phase, without admitting a phase of interacting hadrons. We see that the bremsstrahlung production of the soft photons is large and it is quite sensitive to the value of the freeze-out temperature. For example, we find that a decrease of 10% in the freeze-out temperature enhances the yield of soft photons at q_T =200 MeV by more than 15%. This sensitivity may get considerably magnified when the transverse expansion of the system is accounted for and holds out the promise of elevating the soft photons to the status of reliable chroniclers of the last moments of the interacting system. This aspect is under investigation.

We have kept our discussions limited to photon energies of more than 100–200 MeV, in the hope that the Landau-

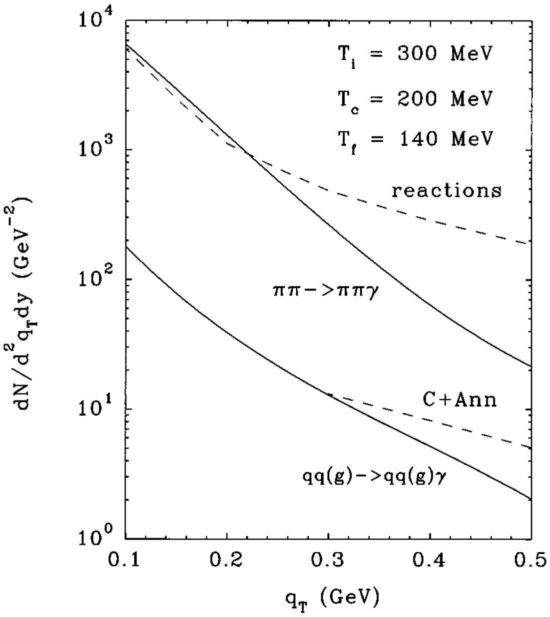

FIG. 5. Same as Fig. 4 for T_i=300 MeV, and T_c=200 MeV. The Compton plus annihilation contributions are shown only for $E\geqslant$ the largest temperature encountered during the evolution.

Pomeranchuk suppression there may not be substantial. How accurate is this assumption? Recall that the ''time between two collisions,'' $\tau_{\rm coll}$, can be defined as

$$\tau_{\rm coll}=\frac{\lambda}{v}, \tag{25}$$

where λ is the mean free path and v is the velocity of the particles. Thus we have

$$\tau_{\rm coll}=\frac{1}{n\sigma v}, \tag{26}$$

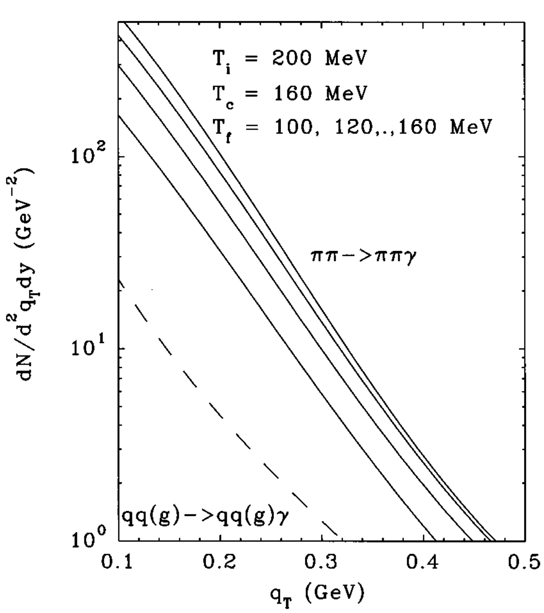

FIG. 6. The dependence of soft photon yield on the freeze-out temperature. The initial conditions are as in Fig. 4.

where now σ is the collision cross section, and n is the density of the particles. The mean free path will decrease with increase in temperature. For pions, as the temperature changes from 100 MeV to 200 MeV, the mean free path drops from $\sim$10 fm to $\sim$2 fm [30]. The formation time for photons having a transverse momentum p_T is given by

$$\tau_{\rm form}\sim\frac{1}{p_T}. \tag{27}$$

This is about 2 fm for p_T= 100 MeV, and about 0.4 fm for p_T= 500 MeV. Noting that the Landau-Pomeranchuk suppression should become important if $\tau_{\rm form}\gg\tau_{\rm coll}$, we realize that its effect will only be marginal for the pion driven processes, in the energy range that we have considered. It will be severe, though, if we wish to study photons having much smaller transverse momenta.

In order to extend this discussion to quark driven processes we first note that the density of the partons [31] can be written as

$$n\simeq 4.3\left[\frac{T({\rm MeV})}{200}\right]^3 \text{partons/ fm}^3. \tag{28}$$

Now taking the parton collision cross section as $\sim$10 mb [20], we estimate the $\tau_{\rm coll}$ as $\sim$ 0.5 fm at T= 160 MeV. The system spends most of its time in the mixed phase at this temperature.

Thus we see that the neglect of the Landau-Pomeranchuk suppression may not be quite severe even for the quark driven processes, though it may not be as justified as for the pion driven processes, in the energy range that we have considered.

We also realize that the inclusion of this effect along the lines of Refs. [26,24] gets quite difficult once we try to model the scatterings and electromagnetic factors more accurately, as has been done in the present work. It should be noted here that due to the expansive evolution of the system, the four-volume occupied by the hadronic matter is very large. This gives an extra weight to its contribution in the total yield of the soft photons. However, during this phase the temperature is much lower and the system is rapidly expanding and cooling, which will minimize the Landau-Pomeranchuk suppression. This will ensure that our results will not be drastically altered by the inclusion of this effect.

In brief we have obtained the bremsstrahlung production of low energy photons within a soft photon approximation for quark matter and hadronic matter. The contributions of pionic processes is found to be large and sensitive to the freeze-out temperature. The sensitivity of these results to the last stages of the evolution holds out the promise that it may be possible to utilize soft photons as chroniclers of the final moments of the evolution of the relativistic heavy ion collisions. If observed, these radiations will further confirm the emergence of a hot and dense charged medium, as a sequel to the collision.

It is rather tempting to imagine a more optimistic scenario where we shall have access to measurements of soft photons and transverse mass distribution of soft dileptons. These could then be compared in a model independent fashion, somewhat in the manner of universal signals of QGP proposed by one of the authors [32] quite some time ago. This may be of considerable interest.

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[1] J. D. Bjorken and L. McLerran, Phys. Rev. D **31**, 63 (1985); A. Dumitru, L. McLerran, H. Stöcker, and W. Greiner, Phys. Lett. B **318**, 583 (1993).
[2] M. Neubert, Z. Phys. C **45**, 231 (1988).
[3] J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1965), p. 725.
[4] See, e.g., D. Lissauer, H. Takai, C. Woody, J. Gomez del Campo, A. Ray, D. Shapira, M. Tincknell, R. Clark, C. Erd, J. Schukraft, and W. Willis, Nucl. Phys. **A566**, 451c (1994).
[5] P. Lichard and L. Van Hove, Phys. Lett. B **245**, 605 (1990).
[6] See, e.g., V. Balek, N. Pišútowá, and J. Pišút, Acta Phys. Pol. B **21**, 149 (1990), for a general review.
[7] See, e.g., F. Botterweck *et al.*, Z. Phys. C **51**, 541 (1991); J. Antos *et al.*, *ibid.* **59**, 547 (1993); S. Banerjee, Phys. Lett. B **305**, 182 (1993).
[8] P. Braun-Munzinger, J. Stachel, J. P. Wessels, and N. Xu, Phys. Lett. B **344**, 43 (1995).
[9] J. Kapusta, Phys. Rev. C **24**, 2545 (1991).
[10] K. Haglin, C. Gale, and V. Emel'yanov, Phys. Rev. D **47**, 973 (1993).
[11] R. Rückl, Phys. Lett. **64B**, 39 (1976).
[12] P. Lichard, Phys. Rev. D **51**, 6107 (1995).
[13] J. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D **44**, 2774 (1991); **47**, 4771(E) (1993); H. Nadeau, J. Kapusta, and P. Lichard, Phys. Rev C **45**, 3034 (1992).
[14] R. Baier, H. Nakkagawa, A. Niegawa, and K. Redlich, Z. Phys. C **53**, 433 (1992).
[15] C. T. Traxler, H. Vija, and M. H. Thoma, Phys. Lett. B **346**, 329 (1995).
[16] P. Henning and E. Quack, Phys. Rev. Lett. **75**, 2811 (1995).
[17] P. Danielewicz and M. Gyulassy, Phys. Rev. D **31**, 53 (1985).
[18] D. Pal, K. Haglin, and D. K. Srivastava, ''Bremsstrahlung production of low mass dielectrons in relativistic heavy ion collisions,'' V. E. C. Centre Calcutta Report, 1995 and Michigan State University Report No. MSUCL-998; submitted to Phys. Rev. D.
[19] K. Kajantie, J. Kapusta, L. McLerran, and A. Mekijan, Phys. Rev. D **34**, 2746 (1986).
[20] J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).
[21] R. C. Hwa and K. Kajantie, Phys. Rev. D **32**, 1109 (1985).
[22] D. K. Srivastava and B. Sinha, J. Phys. G **18**, 146 (1992); D. K. Srivastava, B. Sinha, M. Gyulassy, and X. N. Wang, Phys. Lett. B **276**, 145 (1992); S. Chakrabarty, J. Alam, D. K. Srivastava, B. Sinha, and S. Raha, Phys. Rev. D **46**, 3802 (1992); J. Alam, D. K. Srivastava, B. Sinha, and D. N. Basu, *ibid.* **48**, 1117 (1993); D. K. Srivastava and B. Sinha, Phys. Rev. Lett. **73**, 2421 (1994).
[23] R. D. Pisarski, Nucl. Phys. **B309**, 476 (1988); Phys. Rev. Lett. **63**, 1129 (1989); E. Braaten and R. D. Pisarski, Nucl. Phys. **B337**, 569 (1990).
[24] V. V. Goloviznin and K. Redlich, Phys. Lett. B **319**, 520 (1993). It should be added here that this paper has many typographical errors. However, using the results of Refs. [25,26], with the limit $M \rightarrow 0$, etc., we can get the correct expressions. The numerical results given in the paper are, however, correct and our computer programs correctly reproduced all of them.
[25] J. Cleymans, K. Redlich, and H. Satz, Z. Phys. C **53**, 517 (1991).
[26] J. Cleymans, V. V. Goloviznin, and K. Redlich, Phys. Rev. D **47**, 173 (1993); **47**, 989 (1993); Z. Phys. C **59**, 459 (1993).
[27] Li Xiong, E. Shuryak, and G. E. Brown, Phys. Rev. D **46**, 3798 (1992); C. S. Song, Phys. Rev. C **47**, 2861 (1993).
[28] C. Gale and J. Kapusta, Phys. Rev. C **35**, 2107 (1987).
[29] P. Koch, Z. Phys. C **57**, 283 (1993).
[30] K. Haglin and S. Pratt, Phys. Lett. B **328**, 255 (1994).
[31] M. Gyulassi and T. Matsui, Phys. Rev. D **29**, 419 (1984).
[32] B. Sinha, Phys. Lett. **128B**, 91 (1983).