Flash of Prompt Photons from the Early Stage of Heavy-Ion Collisions

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Abstract. We briefly recall the tremendous strides in the studies of the parton cascade model made by Klaus Geiger. Next, we argue that photons may provide confirmation of several of these ideas. Thus we know that, copious interwoven partonic cascades may develop in the wake of relativistic collisions of nuclei at CERN SPS and BNL RHIC energies. We use the parton cascade model to estimate the emission of single photons generated from such cascades due to the branching of quarks \( q \rightarrow q \gamma \), scattering of quarks and gluons, and annihilation of quarks. The formation of a hot and dense partonic matter is shown to be preceded by an intense radiation of photons from the QED branching of quarks. This is similar to the QCD branching \( q \rightarrow qg \) which along with the gluon multiplication (\( g \rightarrow gg \)) which is known to play a crucial role in the formation of the dense partonic plasma.

FROM PCM TO VNI; AN ODE TO KKG

It is incumbent on us to provide a comprehensive and accurate description of relativistic collision of nuclei from the instant of nuclear contact to the formation of hadronic states which are ultimately detected in experiments. Such collisions are expected to create: a) the conditions which prevailed at the time of early universe a few micro-seconds after the big-bang, and thus, b) a strongly interacting matter under conditions of extreme temperatures and densities which would throw light on the “hallowed” quark-hadron phase transition.

A significant step in this direction was provided by the parton cascade model (PCM) [1] which was proposed to study the time evolution of the parton phase space distribution in relativistic nuclear collisions. In this approach the space-time

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description is formulated within renormalization group-improved QCD perturbation theory embedded in the framework of relativistic transport theory. The dynamics of the dissipative processes during the early stage of the nuclear reactions is thus simulated as the evolution of multiple interwoven parton cascades associated with quark and gluon interactions. The model was considerably improved and extended [2] to include a number of new effects like individual time scale of each parton-parton collision, formation time of parton radiation, effective suppression of radiative emissions from virtual partons due to enhanced absorption probability of others in regions of dense phase space occupation and the effects of soft gluon interference for low energy gluon emissions, which all become important in nuclear collisions. With these improvements the model was used [3] to study the dynamics of partons in relativistic collision of gold nuclei at BNL RHIC and CERN LHC energies. In particular very useful information about the evolution of partons from pre-equilibrium to a thermalized quark-gluon plasma was obtained along with the temperature, energy-density, and entropy-density etc. It was demonstrated that energy densities in excess of an order of magnitude of the critical energy-density when a quark-hadron phase transition is expected, could be attained in such collisions. The model was further used to study the evolution of chemical evolution [4], the production of strangeness, charm, and bottom [5], dileptons [6], and very recently single photons [7] in such collisions.

The next important step [8] involved combining the above parton cascade model with a phenomenological cluster hadronization model [9–11] which is motivated by the “preconfinement” property [12] of partons which is seen from the tendency of quarks and gluons produced in parton cascades to arrange themselves in colour neutral clusters, already at the perturbative level [13]. This approach provided a decent description of the experimentally measured momentum and multiplicity distributions for \(pp\) collisions at \(\sqrt{s} = 200 – 1800\) GeV, and was further used to predict the multiplicity distributions likely to be attained in relativistic heavy ion collisions at BNL RHIC and CERN LHC. A critical review of these developments along with details can be found in [14].

However, the above description of hadron formation [8] did not explicitly account for the colour degree of freedom of the partons, which is, after-all, at the origin of confinement. To be specific, the “ansatz” for the confinement picture was based exclusively on the dynamically evolving space-time separations of nearest-neighbour colour charges in the parton cascade, rather than on the details of the colour structure of produced gluons, quarks, and anti-quarks. Thus, it was assumed that due to the above mentioned “pre-confinement” property of QCD, the partons which are close in colour (in particular minimal colour singlets) are also close in phase space. In other words, instead of using a colour flow description, the colour structure during the development of the cascade was ignored and at the end of perturbative evolution, colour neutral clusters were formed from partons which had a minimal separation in coordinate and momentum space.

It is known that this correspondence between the colour and space-time structures of a parton cascade is not an equivalence, but holds only in the average [15].
Thus, it has been argued that the colour structure of the cascade tree provides in principle, exact microscopic information about the flow of colour charges, whereas the space-time structure is based on our model for the statistical kinetic description of parton emission and the nearest-neighbour search, which may be subject to fluctuations that deviate from the exact colour-flow [16]. This issue is expected to become increasingly important when more particles populate a phase-space region, e.g. for small $x$ region in deep inelastic collisions and in hadron-nucleus and nucleus-nucleus collisions. Thus it is expected that in such cases, it is increasingly likely that the nearest neighbours in momentum and phase space would not necessarily form a colour singlet. It is also likely that the “natural” colour-singlet partner for a given parton within the same cascade (its “endogamous” partner) might actually be disfavoured in comparison with a colour singlet partner from a different but overlapping cascade (an “exogamous” partner). These consideration were incorporated in the hadronization scheme with colour flow discussed in Ref. [16], where it is provided that if the space-time separation of two nearest-neighbour partons allows coalescence, they can always produce one or two color-singlet clusters, accompanied, if necessary, by the emission of a gluon or a quark that carries away any unbalanced net colour (see fig.5, Ref. [16]).

This parton cascade -cluster hadronization model with colour flow is now available in the form of a fortran programme- VNI [17], and has already formed basis for some interesting studies at SPS energies [18], and also to investigate the effect of the hadronic cascades at the end of the hadronization [19].

There are very few examples in recent times, where one person has contributed so much in such a short time.

**PHOTONS FROM CASCADING PARTONS**

Photons, either radiated or scattered, have remained one of the most effective probes of every kind of terrestrial or celestial matter over the ages. Thus, it is only befitting that the speculation of the formation of deconfined strongly interacting matter - some form of the notorious quark-gluon plasma (QGP) - in relativistic heavy ion collisions, was soon followed by a suggestion [20] that it should be accompanied by a characteristic radiation of photons. The effectiveness of photons in probing the history of such a hot and dense matter stems from the fact that, after production, they leave the system without any further interaction and thus carry unscathed information about the circumstances of their birth. This is a very important consideration indeed, as the formation of a QGP is likely to proceed from a hard-scattering of initial partons, through a pre-equilibrium stage, to perhaps a thermally and chemically equilibrated state of hot and dense partonic matter. This matter will hadronize and interaction among hadrons will also give rise to photons. In this letter we concentrate on photons coming from the early partonic stage in such collisions.

During the partonic stage, photons emerge from two different mechanisms: firstly,
from collisions between partons, i.e., Compton scattering of quarks and gluons and
annihilation of quarks and antiquarks; secondly, from radiation of excited partons,
i.e. electromagnetic bremsstrahlung of time-like cascading partons. Whereas the
former mechanism has been studied in various contexts [21,22], the latter source
of photons is less explored [23], although, as we shall show, it is potentially much
richer both in magnitude and complexity.

The *Parton Cascade Model* (PCM) [14], provides a fully dynamical description
of relativistic heavy ion collisions. It is based on the parton picture of hadronic
interactions and describes the nuclear dynamics in terms of the interaction of quarks
and gluons within the perturbative quantum chromodynamics, embedded in the
framework of relativistic transport theory. The time evolution of the system is
simulated by solving an appropriate transport equation in a six-dimensional phase-
pace using Monte Carlo methods. The procedure implemented in the computer
code VNI [17] follows the dynamic evolution of scattering, radiating, fusing, and
clusterizing partons till they are all converted into hadrons. VNI, the Monte Carlo
implementation of the PCM, has been adjusted on the basis of experimental data
from $e^+e^-$ annihilation and $pp$ ($p\bar{p}$) collisions.

As recounted earlier, the PCM has been extensively used to provide valuable
insight into conditions likely to be achieved at RHIC and LHC energies [14]. Very
recently, it has been found [18] to provide reasonable description to a large body of
particle spectra from $Pb + Pb$ and $S + S$ collisions at CERN-SPS energies as well.

Prompt photons are ideally suited to test the evolution of the partonic matter as
described by the PCM. They would accompany the early hard scatterings and the
approach to the thermal and chemical equilibration. Most importantly, the PCM
is free of assumptions of any type about the initial conditions, since the space-time
evolution of the matter is calculated causally from the moment of collision onwards
and at any point the state of the matter is determined by the preceding space-time
history.

$$Q \rightarrow Q\gamma \text{ \ AND \ } Q \rightarrow QG$$

There are some important and interesting differences between a scattering or a
branching leading to production of photons and gluons, as has been pointed out
nicely by Sjöstrand [23].

(i) Consider an energetic quark produced in a hard scattering. It will radiate
gluons and photons till its virtuality drops to some cut-off value $\mu_0$. The
branchings $q \rightarrow q\gamma$ and $q \rightarrow qg$ appear in the PCM on an equal footing and
as competing processes with similar structures. The probability, for a quark
to branch at some given virtuality scale $Q^2$, with the daughter quark retaining
a fraction $z$ of the energy of the mother quark, is given by:

$$dP = \left(\frac{\alpha_s}{2\pi} C_F + \frac{\alpha_{em}}{2\pi} e_q^2\right) \frac{dQ^2}{Q^2} \frac{1 + z^2}{1 - z} dz \quad (1)$$
where the first term corresponds to gluon emission and the second to photon emission. Thus, the relative probability for the two processes is,

\[
\frac{P_{q\rightarrow q\gamma}}{P_{q\rightarrow qg}} \propto \frac{\alpha_{em} \langle e_q^2 \rangle}{\alpha_s C_F} \approx \frac{1}{200},
\]

for \( \alpha_{em} = 1/137, \alpha_s = 0.25, \langle e_q^2 \rangle = 0.22 \) and \( C_F = 4/3 \). This does not mean, though, that we can simulate emission of photons in a QCD shower by simply replacing the strong coupling constant \( \alpha_s \) with the electromagnetic \( \alpha_{em} \) and the QCD colour Casimir factor \( C_F \) by \( e_q^2 \). One has to keep in mind that the gluon, thus emitted, may branch further, either as \( g \rightarrow gg \), or as \( g \rightarrow q\bar{q} \); implying that the emitted gluon has an effective non-zero mass. As the corresponding probability for the photon to branch into a quark or a lepton pair is very small, this process is neglected and we take the photon to have a zero mass. (However, if we wish to study the dilepton production from the collision, this may become an important contribution [6]; see later.)

(ii) Secondly, the radiation of gluons from the quarks is subject to soft-gluon interference which is enacted by imposing an angular ordering of the emitted gluons. This is not needed for the emitted photons. To recognize this aspect, consider a quark which has ‘already’ radiated a number of ‘hard’ gluons. The probability to radiate an additional ‘softer’ gluon will get contributions from each of the existing partons which may further branch as \( q \rightarrow qg \) or \( g \rightarrow gg \). It is well-known (see e.g.; Ref. [13]) that if such a soft gluon is radiated at a large angle with respect to all the other partons and one adds the individual contributions incoherently, the emission rate would be overestimated, as the interference is destructive. This happens as a soft gluon of a long wavelength is not able to resolve the individual colour charges and sees only the net charge. The probabilistic picture of PCM is then recovered by demanding that emissions are ordered in terms of decreasing opening angle between the two daughter partons at each branching, i.e., restricting the phase-space allowed for the successive branchings. The photons, on the other hand, do not carry any charge and only the quarks radiate. Thus this angular ordering is not needed for them.

(iii) Finally, the parton emission probabilities in the QCD showers contain soft and collinear singularities, which are regulated by introducing a cut-off scale \( \mu_0 \). This regularization procedure implies effective masses for quarks and gluons,

\[
m^{(q)}_{\text{eff}} = \sqrt{\frac{\mu_0^2}{4} + m_q^2} \quad m^{(g)}_{\text{eff}} = \frac{\mu_0}{2},
\]

where \( m_q \) is the current quark mass. Thus the gluons cannot branch unless their mass is more than \( 2m^{(q)}_{\text{eff}} = \mu_0 \), while a quark cannot branch unless its mass is more than \( m^{(q)}_{\text{eff}} + m^{(g)}_{\text{eff}} \). An appropriate value for \( \mu_0 \) is about 1 GeV [14];
a larger value is not favoured by the data, and a smaller value will cause the perturbative expression to blow up. These arguments, however, do not apply for photon emission, since QED perturbation theory does not break-down and photons are not affected by confinement forces. Thus, in principle quarks can go on emitting photons till their mass reduces to current quark mass. One may further argue that if the confinement forces screen the "bare" quarks the effective cut-off can be of the order of a GeV. Thus we can choose the cut-off scale $\mu_0$ separately for the emission of photons and get valuable insight about confinement at work.

The discussion above was focused on the production of photons from the branching of quarks. We also include the parton scattering processes in the PCM which yield photons: $q + \bar{q} \rightarrow g + \gamma$, $q + g \rightarrow q + \gamma$, from annihilation and Compton processes, the perturbative cross-sections of which are well-known. In the PCM approach we treat these processes within a perturbative QCD if the transverse momentum of the process ($p_T$) is larger than some cut-off $p_T^0$; see [24]. Thus our results for these contributions will be strictly valid only for $p_T > p_T^0$. (This cut-off is introduced in the collision frame of the partons, and thus we shall have contributions even for smaller $p_T$ in the nucleus-nucleus c.m. frame.)

RESULTS

We study four examples: $S + S$ and $Pb + Pb$ collisions at SPS energies and $S + S$ and $Au + Au$ collisions at RHIC energies.

In Fig. 1 we have plotted the production of single photons from such a partonic matter in the central rapidity region for $Pb + Pb$ system at SPS energies. The dot-dashed histogram shows the contribution of Compton and annihilation processes mentioned above. The dashed and the solid histograms show the total contributions (i.e., including the branchings $q \rightarrow q\gamma$) when the virtuality cut-offs for the photon production is taken respectively as 0.01 and 1 GeV.

We see that prompt photons from the quark branching completely dominate the yield for $p_T \leq 3$ GeV, whereas at larger transverse momenta the photons coming from the collision processes dominate. The reduction of the virtuality cut-off for the $q \rightarrow q\gamma$ branching is seen to enhance the production of photons having lower transverse momenta as one expects.

We have also shown the production of single photons from $pp$ collisions for $\sqrt{s} \approx 24$ GeV, obtained by WA70 [28], NA24 [29], and UA6 [30] collaborations scaled by the nuclear thickness for zero impact parameter for the collision of lead nuclei. The solid curve gives the perturbative QCD results [27] for the $pp$ collisions scaled similarly. The dashed curve is a direct extrapolation of these results to lower $p_T$.

In Fig. 2 we have plotted the transverse momenta of the single photons in several rapidity bins for $Pb + Pb$ and $S + S$ systems at SPS energies. We see that the transverse spectra scale reasonably well with the ratio of the nuclear overlap for
central collisions for the two systems $T_{\text{Pb-Pb}}/T_{\text{S-S}} \approx 15.4$, which is indicative of the origin of these photons basically from a collision mechanism. (Note that the time-

**FIGURE 1.**

The radiation of prompt photons from partonic matter in central collision of Pb (158 GeV/nucleon)+Pb nuclei at CERN SPS. The dot-dashed histogram gives the contribution of only the collision processes. The dashed and the solid histograms give the contribution of the collision plus branchings when the $\mu_0$ for the $q \rightarrow q\gamma$ branching is taken as 1 and 0.01 GeV respectively. The $pp$ data at $\sqrt{s} \approx 24$ GeV scaled by the nuclear overlap function for the central collision of lead nuclei and the corresponding QCD prediction (solid curve, arbitrarily extended to lower $p_T$) is also shown for a comparison. $p_T^0$ denotes the momentum cutoff above which the hard scatterings are included in the PCM.
like partons are generated only if there is a collision.) The slight deviation from this scaling seen at lower \( p_T \) results in a \( \approx 20\% \) increase in the integrated yield at central rapidities. This is a good measure of the multiple scatterings in the PCM. In fact we have found that the number of hard scatterings in the Pb+Pb system is \( \approx 17 \) times more than that for the S+S system which also essentially determines the ratio of the number of the photons produced in the two cases. We also note

![Figure 2.](image)

he radiation of single photons from S+S (200 GeV/Nucleon) and Pb+Pb (158 GeV/Nucleon) collisions in different rapidity bins. The inset shows the rapidity distribution of the radiated photons. The results for the S+S collisions have been scaled by the ratio \( T_{Pb-Pb}/T_{S-S} \approx 15.4 \) for central collisions. \( \mu_0 \) for the quark branching \( q \to q\gamma \) is taken as 0.01 GeV.
that the inverse slope of the $p_T$ distribution decreases at larger rapidities, which is suggestive of the fact that the “hottest” partonic system is formed at central rapidities.

In Fig. 3 we have plotted our results for $S+S$ and $Au+Au$ systems at RHIC energies in the same fashion as Fig. 2 above. We see that the inverse slope of the $p_T$ distribution is now larger and drops only marginally at larger rapidities, indicating

![Graph of photon radiation from S+S and Au+Au collisions](image)

**FIGURE 3.**

![Caption](image)

The radiation of single photons from S+S and Au+Au collisions in different rapidity bins at RHIC energy, $\sqrt{s} = 200$ GeV/nucleon. The inset shows the rapidity distribution of the radiated photons. The results for the S+S collisions have been scaled by the ratio $T_{Au-Au}/T_{S-S} \approx 14.2$ for central collisions. $\mu_0$ for the quark branching $q \rightarrow q\gamma$ is taken as 0.01 GeV.
that the partonic system is now “hotter” and spread over a larger range of rapidity.

Even though the $p_T$ distribution of the photons is seen to roughly scale with the ratio of the nuclear overlap functions for central collisions $T_{Au-Au}/T_{S-S} \approx 14.2$, the integrated yield of photons for the $Au + Au$ is seen to be only about 12 times that for the $S + S$ system at the RHIC energies. We have again checked that the number of hard scatterings for the $Au + Au$ system is also only about 12 times that for the $S + S$ system. (Again note that we have switched off soft-scatterings completely, and the hard scatterings are permitted only if the $p_T$ is more than $p_T^0$ which is taken to be larger at higher energies; see \cite{24}.)

This contrasting behaviour at SPS and RHIC energies seen in our work has a very interesting physical origin. At the SPS energies, the partonic system begins to get dense and multiple scatterings increase; specially for heavier colliding nuclei. At RHIC energies, the partonic system gets quite dense, and then the Landau Pomeranchuk effect starts playing an important role. We have implemented this in the PCM semi-phenomenologically; by inhibiting a new scattering of partons till the passage of their formation time after a given scattering. In a separate publication we have demonstrated that these competitive mechanisms can be seen at work by comparing results for zero impact parameter for different colliding nuclei.

**DISCUSSIONS AND SUMMARY**

Before concluding, we would like to make some other observations.

Firstly, recall such branchings of the partons produced in hard collisions correspond to a next-to-leading-order correction in $\alpha_s$. These are known to be considerably enhanced for collinear emissions. The parton shower mechanism incorporated in the PCM amounts to including these enhanced contributions to all orders, instead of including all the terms for a given order \cite{25}.

It may also be added that the first-order corrections to the Compton and annihilation processes in the plasma have been studied by a number of authors \cite{26}; however in the plasma the $Q^2 \approx (2T)^2$, thus their contribution is limited to very low $p_T$. $Q^2$ is obviously much larger in the early hard scatterings, and thus the radiations from the emerging partons are much more intense and also populate higher transverse momenta, as seen in the present work.

The large yield of photons from the branching of energetic quarks preceding the formation of dense partonic matter opens an interesting possibility to look for a similar contribution to dilepton (virtual photon) production in such collisions. In fact a large yield of low-mass dileptons was reported from $q \to q\ell\ell$ processes in PCM \cite{6} calculations at RHIC energies. It is quite likely that this process also makes a substantial contribution to the “excess” low mass dileptons observed in sulfur and lead induced collisions studied at SPS energies.

Recall again that we have only included the contribution of photons from the partonic interactions in this work. It is quite likely that the hadrons produced at the end will also interact and produce photons which has been extensively studied...
in recent times (see, e.g. Ref. [22]). A comparison of typical results from, say, Ref. [22] with the present work shows that at the SPS energies the emission from

![Graph](image-url)

**FIGURE 4.** A comparison of the radiation of single photons from Pb+Pb collision at SPS energies with various predictions. The (preliminary) data are from the WA98 collaboration. The histogram shows the radiations from the partonic matter (only) evaluated in this work. The solid curve gives the predictions of Cleymans, Redlich, and Srivastava [22] when a hot hadronic matter is assumed to be formed at $1 \text{ fm}/c$ evaluated within a hydrodynamic model. The dashed curve gives their prediction when a thermalized and chemically equilibrated quark gluon plasma is assumed to be formed at $1 \text{ fm}/c$. While the PCM predictions do not account for the hadronic contributions to single photons, the hydrodynamic predictions do not account for the contributions before the time $\tau = 1 \text{ fm}/c$. 
the early hard partonic scatterings is of the same order as the photon production from later hadronic reactions, for $p_T \leq 2–3$ GeV, and dominates considerably over the same at higher transverse momenta. A comparison of our predictions (Fig.4) with the preliminary results reported by the WA98 collaboration [31] in fact clearly demonstrates that the pre-equilibrium contributions evaluated in the present work will play a very important role in providing a proper description to the single photon data at larger $p_T$ from such collisions.

We conclude that the formation of a hot and dense partonic system in relativistic heavy ion collisions may be preceded by a strong flash of photons following the early hard scatterings. Their yield will, among several other interesting aspects, also throw light on the extent of multiple scattering encountered in these collisions.

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Most of this work was done when I visited Klaus at the Brookhaven National Laboratory during December 15, 1997 to March 15, 1998. Little did I know that I would not see Klaus again. I was in e-mail contact with him till a day before he departed. I wondered what should I write, having done several things and having planned several things in collaboration with him and yet not being able to attend the workshop in his memory. The choice was not easy. This work appeared in print [7] in the September 1998 issue of the Physical Review C; with Klaus going away in a ‘flash’ just when these issues were perhaps being mailed. Yes Klaus;

The world was listening
With so much attention,
Alas! you dozed off
While telling your tales..

Boss!, I will always miss you, remember you, and endeavour to complete all that we planned.

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