Direct photons from relativistic heavy-ion collisions

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Abstract. We recall the seminal developments in the study of radiation of direct photons from relativistic heavy ion collisions, which have helped to enhance the scope of single photons as a probe of the quark gluon plasma considerably. There is a mounting evidence that in addition to providing information about the initial temperature of the plasma as envisaged originally, these radiations measure the momentum anisotropy of the deconfined quarks and gluons, energy loss of the quarks, the initial spatial asymmetry of the plasma, and the history of evolution of the system. After a brief description of the theoretical developments and results for direct photons at SPS energies, we discuss the expectations and findings at RHIC energies.

1. Introduction

Relativistic collisions of heavy nuclei are being studied with the aim of producing quark-gluon plasma, a deconfined state of strongly interacting matter, which populated the early universe a few micro-seconds after the big bang. Electromagnetic radiations in general, and direct photons in particular, from such collisions are expected to provide an accurate information about the initial conditions and the history of evolution of the plasma while it cools and hadronizes. This is possible because, the photons interact only electromagnetically and therefore they have a mean free path which is much larger than the size of the system. Thus once produced, they leave the system without any re-interaction and carry the information about the circumstances of their production. This expectation has led to an intense and concerted effort towards identification of various sources of such radiations- theoretically, and to their isolation from a background of intense radiations from the decay of hadrons- experimentally. While initially these studies were aimed at providing the initial temperature of the plasma, recent investigations have thrown open several new and unique possibilities. It is now known that single photons probe the evolution of the system size by intensity interferometry as well as the evolution of the momentum anisotropy of quarks and gluons by the elliptic flow.

A new and vastly clean source of photons, due to the passage of high energy quarks through the quark gluon plasma has also been suggested, which promises to provide an independent and accurate check on jet-quenching and several other aspects.
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Figure 1. World's inclusive and isolated direct photon production cross-section measured in ppi and pp collisions compared to NLO predictions, using JETPHOX. BFG II (CTEQ6M) fragmentation (structure) functions and a common scale $p_T/2$ were used. (Taken from Ref.[7]).

of the collision dynamics. It is not possible to cover the details of these developments in the limited space and time available to us, and the reader may consult several excellent reviews [2] available by now.

Direct photons or single photons are photons which do not have their origin in the decay of hadrons, e.g., $\pi^0 \rightarrow \gamma\gamma$ or $\eta \rightarrow \gamma\gamma$, which account for up to 90–98% of all the photons which are detected. These decays pose a serious experimental challenge to the detection of direct photons and several methods, basically employing invariant mass analysis along with statistical techniques of mixed-events, have been utilized to subtract the decay photons from the inclusive photon spectra. It should be recalled that suppression of high $p_T$ hadrons due to jet-quenching seen at higher centre of mass energies leads to an increased value for the ratio, $\gamma/\pi^0$. This considerably enhances the ease of detection of single photons at these momenta. Let us briefly recall the nodal theoretical developments in this field which have made these studies so very rewarding.
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Figure 2. Upper limits at the 90% confidence level on the invariant excess photon yield for the 7.4% $\sigma_{mb}$ most central collisions of 200A GeV $^{32}$S + Au. The solid and the dashed curves give the thermal photon production expected from hot hadron gas calculations\cite{20} while the dotted curve is the calculated thermal photon production expected in the case of a QGP formation\cite{20}. (Taken from Ref.\cite{19}.)

2. Recent Theoretical Developments

Theoretically, we need to identify various sources of direct photons and understand their relative importance and characteristics. One critically studied source is the radiation of prompt photons due to Compton scattering ($qg \rightarrow q\gamma$) and annihilation ($qq \rightarrow g\gamma$) of partons of the colliding nucleons. Perturbative QCD calculations at the NLO are available\cite{7,8} and all the available data for $pp$ and $p\bar{p}$ collisions have been analyzed, with the inclusion of the fragmentation off the final state quarks ($q \rightarrow q\gamma$), and a quantitative description is obtained by choosing a scale such that the scales for factorization, renormalization, and fragmentation are equal to $p_T/2$ (see Fig\[1\]). Extension of these results to the case of nucleus-nucleus collisions requires care. Early studies often obtained the prompt photon contribution for them by scaling the results for $pp$ collisions for the corresponding $\sqrt{s}$ with the number of nucleon-nucleon collisions. One immediately sees that this will over-estimate the prompt photon production for
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Figure 3. Single photon production in Pb+Pb collision at the CERN SPS. QM stands for radiations from the quark matter in the QGP phase and the mixed phase, HM denotes the radiation from the hadronic matter in the mixed phase and the hadronic phase. Prompt photons are estimated using pQCD (with a K-factor estimated using NLO calculations) and intrinsic $k_T$ of partons. (Taken from Ref.[26]).

nucleus-nucleus collisions as it ignores the iso-spin of the nucleons; protons ($uud$) and neutrons ($udd$) have different number of up and down valence quarks. Thus it will strongly affect the results for those values of $p_T$ which derive a large contribution from the valence quarks. On the other hand, there is no direct experimental method to get prompt photon contributions in $pn$ and $nn$ scatterings, though in principle one could estimate them by comparing results with scatterings involving deuterons. Secondly, one has to account for the effect of shadowing on structure functions. And lastly and equally importantly, one has to account for the energy loss suffered by final state quarks before they fragment into photons, if the collision leads to formation of a quark-gluon plasma [11, 12].

Of-course the importance of single photons having intermediate $p_T$ lies in their being dominated by thermal photons which have their origin in the Compton and annihilation processes in the quark-gluon plasma[9, 10] as well as in the reactions in the hadronic phase following the hadronization [9]. The calculations for radiation of photons from QGP have been extended up to two loops [13], which open up additional processes of bremsstrahlung and annihilation of a off-shell quark with an anti-quark following a scattering. In a very significant and novel development, complete leading order results are now available [14], which also properly account for the Landau Pomeranchuk Migdal (LPM) suppression in the plasma.

The production of photons due to hadronic reactions [9] has also been studied extensively, using field theoretical models along with an effective Lagrangian incorporating various mesonic fields and even baryons. Results are available which additionally account for the likely medium modification of hadronic properties [15]. The most recent calculations incorporate the strange mesons, using a Massive Yang-Mills theory, account for the form-factors, and include hitherto ignored $t$-channel exchange
of $\omega$ mesons which makes a large contribution at intermediate $p_T$ and explore the consequences of including photon producing reactions involving baryons \[16\]. In view of these developments, it is quite appropriate to suggest that the calculations of the rate of production of photons have reached an unprecedented level of sophistication.

The other significant development involves an enormous progress made towards the understanding of production of photons due to passage of jets through quark-gluon plasma, discovered recently \[5\]. These can make a large contribution at $p_T \approx 4$–8 GeV, at RHIC and LHC energies where jet-quenching appears. It has also been realized that there would be an additional contribution due to the jet-induced bremsstrahlung process \[6\] in the plasma. A high level of sophistication was introduced by treating jet-quenching and jet-induced photon production within the same treatment, which thus accounts for the energy loss (and flavour change) suffered by the jets as they traverse the plasma, and also treats the effect of this energy loss on the fragmentation contribution of the prompt photons as well as the jet-induced bremsstrahlung, with inclusion of LPM effects \[17, 18\].

3. Results at SPS energies

In order to get an idea of greatly increased insights provided by single photon production, let us briefly recall some of the important results from the SPS era, many of which preceded the large strides made in our theoretical understanding mentioned above. The first hint of single photon production, which later turned out to be the upper limit of their production came from the S+Au collisions studied at the SPS energies \[19\].

These results were analyzed in two different scenarios by authors of Ref. \[20\]. In the first scenario, a thermally and chemically equilibrated quark-gluon plasma was assumed to be formed at some initial time ($\tau_0 \approx 1$ fm/$c$), which expanded \[21\], cooled, and

![Figure 4. Yield of photons in central Au+Au collisions at $\sqrt{s} = 200$ AGeV. The primary hard photons, jet-photon conversion and the sum of the two can be seen here, indicating the presence of the later source. The thermal photon contribution is also given. Data are from the PHENIX collaboration \[30\]. (Taken from Ref. \[31\])](image-url)
converted into a mixed phase of hadrons and QGP at a phase-transition temperature, \( T_C \approx 160 \text{ MeV} \). When all the quark-matter was converted into a hadronic matter, the hot hadronic gas continued to cool and expand, and underwent a freeze-out at a temperature of about 140 MeV. The hadronic gas was assumed to consist of \( \pi, \rho, \omega, \) and \( \eta \) mesons, again in a thermal and chemical equilibrium. This was motivated by the fact that the included hadronic reactions involved \[9\] these mesons. This was already a considerable improvement over a gas of mass-less pions used in the literature at that time. In the second scenario, the collision was assumed to lead to a hot hadronic gas of the same composition. The initial temperature was determined by demanding that the entropy of the system be determined from the measured particle rapidity density \[22\]. It was found that the scenario which did not involve a formation of QGP led to a much larger initial temperature and a production of photons which was considerably larger than the upper limit of the photon production, and could be ruled out. The calculation assuming a quark-hadron phase transition yielded results which were consistent with the upper limit of the photon production. These results were confirmed \[23\] by several calculations exploring different models of expansion (see Fig.2).

It was soon realized that one may not limit the hadronic gas to contain just \( \pi, \rho, \omega, \) and \( \eta \) mesons, as there was increasing evidence that perhaps all the mesons and baryons were being produced in a thermal and chemical equilibrium in such collisions. Thus authors of Ref. \[24\] explored the consequences of using a hadronic gas consisting of essentially all the hadrons in the Particle Data Book, in a thermal and chemical equilibrium. This led to an interesting result for the Pb+Pb collision at SPS energies, for which experiments were in progress. It was found that with the rich hadronic gas, the results for the production of photons in the phase-transition and no phase transition models discussed above were quite similar, suggesting that measurement of photons at the SPS energy could perhaps not distinguish between the two cases. However, in a very
important observation, it was also noted that the calculations involving hot hadronic gas at the initial time would lead to hadronic densities of several hadron/fm$^3$, and while those involving a quark gluon plasma in the initial state would be free from this malady. Thus, it was concluded that the calculations involving a phase transition to QGP offered a more natural description.

The WA98 experiment \[25\], reported the first observation of direct photons in central 158A GeV Pb+Pb collisions studied at the CERN SPS. This was explained \[26\] in terms of formation of quark gluon plasma in the initial state (at $\tau_0 \approx 0.2$ fm/c), which expanded, cooled and hadronized as in Ref. \[24\] (see Fig.3). An independent confirmation of this approach was provided by an accurate description \[27\] of excess dilepton spectrum measured by the NA60 experiment for the same system.

Once again the results for single photons were analyzed by several authors using varying models of expansion as well as rates for production of photons; viz., with or without medium modification of hadronic properties (see, e.g.,Ref. \[28, 29, 16\]). The outcome of all these efforts can be summarized as follows: the single photon production in Pb+Pb collisions at SPS energies can be described either by assuming a formation of QGP in the initial state or by assuming the formation of a hot hadronic gas whose constituents have massively modified properties. The later description, however, involved a hadronic density of several hadrons/fm$^3$, which raises doubts about the applicability of a description in terms of hadrons, as suggested by Ref. \[24\].

4. Results at RHIC energies: The light from quarks

In view of the above, the results for single photon production from Au+Au collisions at the highest RHIC energy were eagerly awaited. The first to appear, courtesy the suppression of hadrons due to jet-quenching, was the centrality dependence of single photon production\[30\], where the single photons were clearly identified for $p_T > 4$ GeV for more central collisions and upper limits could be established for $p_T$ down to about 2 GeV. The authors compared these results with NLO pp values scaled by the number of collisions and reported a good agreement. This result is sometimes used to suggest an absence of new sources of single photons in this $p_T$ range. This approach, as discussed earlier, neglects the iso-spin of the nucleons, which leads to a reduction of single photon production at larger $p_T$, as well as the energy loss suffered by final state quarks, before they fragment. Thus the above agreement, in fact, points to the presence of additional sources of single photons!

A first attempt to understand these data was made by authors of Ref.\[31\], who included prompt photons, thermal photons- assuming a production of quark gluon plasma, and jet-conversion photons due to passage of jets through the QGP. The initial temperature (at $\tau_0 \approx 0.2$ fm/c) was obtained by relating the entropy to the multiplicity density, measured experimentally \[22\]. A good description of the data was obtained, providing the first indication of photons due to the mechanism of jet-photon conversion\[5\] (see Fig.4).
These results were next analyzed with jet-induced photons, first with a longitudinal expansion of the plasma [17] and next with transverse expansion of the plasma [18]. These results, along with clear direct photon excess measured at lower $p_T$ (Ref. [32]) are shown in Fig. 5 which also shows various components of the single photons at large $p_T$, viz., thermal, prompt-direct (i.e., Compton+ annihilation), prompt-fragmentation (corrected for the energy loss suffered by the quarks before they fragment), and the jet-conversion photons- both due to the Compton and annihilation processes and the jet-induced bremsstrahlung process, the later corrected for energy loss suffered by the jet. The iso-spin and shadowing effects were also properly accounted for. These results represent a very high level of sophistication reached in these studies. The studies also indicate a substantial production of photons due to these processes at LHC energies [5, 18] and have been extended to production of dileptons as well [33].

In a related and independent attempt, single photon production has been calculated using the parton cascade model. It has been found that large $p_T$ photon production at RHIC and even at SPS is quantitatively reproduced by these calculations provided the LPM effect on radiation of gluons is accounted for [34]. It has also been pointed out that the study of photon (or dilepton [35]) tagged jets can help us differentiate between different models for jet-quenching [36].

A very important and useful information about the evolution of the momentum anisotropy of deconfined quarks and gluons in such collisions can be obtained by the measurement of the effect of the elliptic flow on thermal photons or dileptons [4]. In a very interesting confirmation of our models for the evolution of the plasma [37], the $v_2$ for thermal photons rises with $p_T$, reaches a maximum, and then falls, when the contributions from the QGP phase dominate, where the temperatures are large but the flow is still building up (see Fig. 6). An experimental verification [38] of these results
would provide a direct confirmation of the production of QGP at very early times in such collisions. A small azimuthal anisotropy (with negative $v_2$) in the momentum distribution of photons at large $p_T$ is also expected, which reflects the spatial anisotropy of the plasma, at the earliest times in non-central collisions [18].

Before concluding, one may recall a very valuable comparison of several calculations describing the low $p_T$ single photon production from Au+Au collisions at 200A GeV, which all point, rather strongly, to the presence of a strong radiation from quark-gluon plasma produced very early in the collision[39], which has a temperature of about 300–500 MeV at $\tau_0$ of about 0.6–0.2 fm/c.

5. Summary

We conclude that the study of single photons has opened up very many interesting possibilities to explore the initial state of the quark-gluon plasma and its evolution. The light from quarks is clearly seen at RHIC energies!

These results hold out a promise [2] of a spectacular display of all the aspects discussed here at the LHC energies.

Acknowledgments

The author gratefully acknowledges a very enjoyable and rewarding collaboration spanning almost two decades with Terry Awes, Steffen Bass, Rupa Chatterjee, Jean Cleymans, Rainer Fries, Evan Frodermann, Charles Gale, Ulrich Heinz, Berndt Müller, Thorsten Renk, Krzysztof Redlich, Bikash Sinha, and Simon Turbide, and valuable discussions with countless colleagues.

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