Photon production in heavy ion reactions

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Abstract. A review on experimental results of photon production in heavy ion reactions is given. Measurements using inclusive photons are discussed. Some developments in the theoretical description of direct photon production are reviewed. The measurement of direct photons in heavy ion reactions from the WA98 Collaboration is discussed and compared to theoretical calculations. First results on photon measurements at RHIC are also discussed.

1. Introduction

The major motivation to study relativistic heavy-ion collisions is the search for the Quark-Gluon Plasma (QGP), a potential new state of matter where colored quarks and gluons are no longer confined into hadrons and chiral symmetry is restored. To study such a complicated system one wishes for a probe that is not equally complicated in itself. The production of hadrons is governed by the strong interaction and therefore adds to the complication, as the probability of rescattering processes, which modify the properties at later stages is high. One possible way out might be the study of hard processes where QCD, the theory of strong interaction, enters the perturbative regime and is calculable. The other avenue involves a particle that suffers only electromagnetic interaction: Photons — both real and virtual — should be an ideal probe. For previous reviews on this topic see Refs. [1, 2, 3, 4].

While photon production may be less difficult to treat theoretically than some other processes in hadronic physics, an adequate treatment in heavy-ion collisions turns out to be far from trivial. Experimentally, high energy direct photon measurement has always been considered a challenge. This is true already in particle physics and even more in the environment of heavy-ion collisions. Nevertheless a lot of progress has been made and a large amount of experimental data is available, though mostly from particle physics. There exists only one published measurement of direct photons for heavy ion collisions [5]. Preliminary results on direct photons at RHIC have recently become available [6], and more results are expected to appear.

In the present report I attempt to provide a review of some interesting aspects of the study of direct photon production in heavy-ion collisions. I will discuss results from the CERN SPS fixed target program and comparisons to theoretical calculations and first results of direct photon measurements at RHIC.

2. Inclusive photons - multiplicity distributions and fluctuations

For the study of direct photons the decay photons from neutral pions and other hadrons with electromagnetic decays are considered a background which complicates the measurement. They do however themselves provide information on the production of neutral hadrons. This is
especially useful for event-by-event studies, as neutral hadrons can often not be identified on
an event-by-event basis. Moreover, the inclusive photon multiplicity, which is dominated by the
decay photons, can nicely complement the charged particle multiplicity measurement and thus
help to estimate the total multiplicity of produced particles.

The WA98 experiment has performed inclusive photon measurements \[7\] with its photon
multiplicity detector (PMD), which is a preshower detector covering the pseudorapidity range
3 < η < 4.3 \[8\]. Figure 1 shows examples of pseudorapidity distributions of photons obtained
with this detector. They are compared to distributions from VENUS simulations \[9\], which
are systematically lower than the data. The distributions can be reasonably well described by
Gaussians, the value at the maximum obtained from such fits are shown on the right hand side
of figure 1 as a function of the number of participants. To a good approximation the maximum
pseudorapidity density is a linear function of the number of participants.

Another example which makes use of the measurement of inclusive photons relates to the
search for a disoriented chiral condensate (DCC) \[10, 11, 12\]. Such a state might occur in
heavy ion reactions, when chiral symmetry is restored and then a sudden transition back to
the spontaneously broken phase happens. It was predicted that within domains of DCCs there
should be anomalously large fluctuations in the fraction of neutral pions to all pions:

\[ f \equiv \frac{N(π^0)}{N(π^+) + N(π^0) + N(π^-)}. \]  

This is illustrated in figure 2, which schematically shows on the left side probability distributions
\( p(f) \) for DCC events in comparison to normal events. In the WA98 experiment this was
studied \[13\] by looking at the joint distribution of charged particle multiplicity \( N_c \) and photon
multiplicity \( N_γ \). The dominant feature in these distributions is a correlation between \( N_c \) and
\( N_γ \), which originates from the variation of the centrality of the collision. Effects related to DCC-
like fluctuations would show up as a deviation from this major correlation feature in individual
events. This deviation is measured by the variable \( S_2 \) – distributions of this variable are shown
in figure 2 on the right. Here the data for central Pb + Pb reactions are compared to simulations
which assume that a certain fraction of the events contains DCC-like fluctuations. Although
the data appear to show slightly stronger fluctuations than the simulations without any DCC
contribution, systematic uncertainties only allow to extract an upper limit on the strength and size of DCC domains from this analysis [13].

Figure 2. Left: Illustration of the different probability distributions of the ratio $f$ for normal events (Generic) and for DCC events. Right: Frequency distribution of the variable $S_Z$ in central $Pb + Pb$ reactions for data (symbols) and simulations assuming different contributions of DCC events (for details see text and ref. [13]).

Figure 3. Lowest order processes for photon production in QCD. Left: quark-gluon Compton scattering; right: quark-antiquark annihilation.

3. Direct photons - theory
Direct photons, i.e. photons that are produced directly by an interaction and do not originate from decays of hadrons, can be either prompt or thermal. Both may be produced e.g. by processes like quark-gluon Compton scattering or quark-antiquark annihilation (see figure 3), which represent the lowest order diagrams in QCD. Prompt photons are produced in the primary hard parton collisions, their resulting momentum distributions therefore contains mainly information on the structure functions. Measurements of prompt photons in hadron-hadron collisions have been performed over a large range of beam energies. Next-to-leading-order perturbative QCD calculations describe data at the highest energies very well. At lower energies and especially at low transverse momenta the agreement between data and calculations is worse. The discrepancies are sometimes reduced by introducing phenomenological corrections as so-called $K$-factors or intrinsic transverse momentum of the partons. While this is not very satisfying theoretically, one should note that also the status of the experimental data is not ideal for the lowest energies. For the status of the theoretical description of prompt photons see e.g. the discussions in [14, 15].

The study of prompt photons in $p + A$ and $A + A$ collisions may shed more light on modifications of the parton distributions in nuclei, such as shadowing, initial state momentum...
Figure 4. Calculated photon and neutral pion yields as a function of transverse momentum for different scenarios including parton energy loss [16]. The two upper panels show results for RHIC energies, the lower panels for LHC. On the left side nuclear modification factors for photons and neutral pions are shown, on the right hand side ratios of $\gamma/\pi^0$ are displayed. For the $\gamma/\pi^0$ also estimates for $p + p$ collisions (i.e. no energy loss) are included.

broadening or the recently discussed gluon saturation. By determining the initial wave functions of the incoming partons one could better constrain the initial conditions which in turn would help to interpret other observables in heavy ion collisions. Modifications of prompt photon production in $A + A$ collisions due to parton energy loss have been discussed in [16]. The authors argue that direct photons are significantly less suppressed than neutral pions by the effects of parton energy loss. In fact only the photons produced via Bremsstrahlung should be affected by this mechanism. Figure 4 shows predictions of these calculations. One can see that for the (more realistic) scenario of energy dependent energy loss (labeled BH in the figure) the pions are suppressed by more than a factor of 5 for most of the $p_T$ range at RHIC, while the photons show a suppression of only about 20%. This would naturally lead to a strong enhancement in the $\gamma/\pi^0$ ratio relative to $p + p$ collisions by up to factor of 6 at high $p_T$ (right hand side of figure 4). At LHC the effects are not as striking - the enhancement in $\gamma/\pi^0$ is more on the order of a factor of 2 – 3. This is mainly due to the greater importance of Bremsstrahlung contributions at LHC. There are, however, other mechanisms, like medium-induced photon radiation from hard partons, which would enhance the photon yield [17].

Thermal photons are produced throughout the reaction out of the thermal system and thus
reflect thermal distributions, which contain information on the temperature. Predictions of the thermal photon momentum distributions require both the knowledge of in-medium rates and of the evolution of the system. Already the latter, which depends on the equation of state of the matter produced, is uncertain, but may contain important information on the matter properties. However, a lot of calculations have assumed a scaling scenario for the longitudinal degree of freedom and have used 1-dimensional hydrodynamics only, which may be a too simplistic assumption. Also the calculation of the rates has undergone a development. It was originally thought that the diagrams, which are lowest order in QCD (see figure 3) and thus dominant for vacuum production, would also be most important for heavy ion collisions.

![Figure 5. Two-loop photon production diagrams. Left: bremsstrahlung; right: annihilation with scattering.](image)

It was however shown, that at finite temperature the contribution of higher order (two-loop) diagrams may be significant and the contributions have been calculated [18, 19]. Such processes involve e.g. bremsstrahlung or the annihilation of an off-shell quark (from an earlier scattering) – these examples are displayed in figure 5. Also higher diagrams have to be included – this was investigated for the three loop case in [20] and they were found to be of similar magnitude. While there is in principle no limit to higher loops, coherence (the Landau-Pomeranchuk-Migdal effect) reduces the rates. It could be shown in [21] that this leads to a finite result in all orders.

4. Direct photon measurements

4.1. SPS experiments

In heavy-ion collisions the extraction of direct photons is extremely difficult due to the high particle multiplicity. In addition, measurements at the SPS suffer from the low expected rate at the relatively low beam energy. In fact the beam energy in heavy-ion collisions at the SPS is equivalent to the lowest energy where direct photons could be measured in \( pp \).

For \( Pb + Pb \) collisions at 158 A GeV (\( \sqrt{s_{NN}} = 17.3 \) GeV) the WA98 experiment has performed photon measurements [5] using a lead glass calorimeter for photon detection. The systematic errors are checked by performing the analysis with a number of different choices of experimental cuts. Inclusive photons and \( \pi^0 \) and \( \eta \) mesons have been measured in the same data samples, which helps to control the systematic errors. In peripheral collisions no significant direct photon excess was found. In central collisions the observed photons cannot entirely be explained by decay photons, implying the first observation of direct photons in high energy heavy-ion collisions. The extracted direct photon spectrum is shown in figure 6. The only other direct photon measurements at a similar energy are from \( p \)-induced reactions. Data from \( pp \) reactions by E704 [22] and from \( p+C \) reactions by E629 [23] and NA3 [24] at \( \sqrt{s} = 19.4 \) GeV.
have been converted to the lower energy $\sqrt{s} = 17.3$ GeV assuming a scaling according to [25]:

$$Ed^3N_e/dp^3 = f(x_T, \theta)/s^2,$$

where $x_T = 2p_T/\sqrt{s}$ and $\theta$ is the emission angle of the photon and have been multiplied with the average number of binary nucleon-nucleon collisions in the central $Pb + Pb$ reactions (660). These scaled $p$-induced results are included in figure 6 (left) for comparison. They are considerably below the heavy-ion results which indicates that a simple scaling of prompt photons as observed in $pp$ is not sufficient to explain the direct photons in central $Pb + Pb$ reactions.

Before attempting to address the thermal production of photons it is mandatory to understand the contribution from hard processes which are expected to dominate at high $p_T$. Wong and Wang have calculated this contribution [26] from a next-to-leading order perturbative QCD calculation, where an intrinsic parton momentum of $\langle k_T^2 \rangle = 0.9$ GeV$^2$ has been used. This $\langle k_T^2 \rangle$ is necessary to describe the $p$-induced reactions at a similar energy. The heavy ion data can, however, not be described by this calculation (see figure 6 left). Dumitru et al. [27] have followed up on this question. They showed that the WA98 photon spectrum above $p_T = 2.5$ GeV can be explained by prompt photons if an additional nuclear broadening of $\Delta k_T^2 = \langle k_T^2 \rangle_{AA} - \langle k_T^2 \rangle_{pp} \simeq 0.5$ - 1 GeV$^2$ is introduced. For low $p_T < 2.5$ GeV, however, prompt photons fail to reproduce the WA98 data regardless of the amount of nuclear broadening employed (see figure 6 right).

It is also instructive to compare the $\gamma/\pi^0$ ratio extracted from these heavy-ion data to those from $pp$ and $pC$ in figure 7. Such ratios are frequently used in direct photon analyses, as some of the systematic errors cancel. In fact $\gamma$ and $\pi^0$ produced in hard scatterings should also have
some of the theoretical uncertainties in common. The value of $\gamma/\pi^0$ in heavy-ion data is $\approx 3-5\%$ in most of the $p_T$ range, which is similar to the lowest values extracted in the proton data. This may be taken as a hint that such levels of direct photons approach the feasibility limit of such measurements. Still lower levels will be very hard or impossible to detect. Furthermore, while in this ratio the heavy ion data and the proton data agree for high transverse momenta, there is an indication of an additional component at intermediate $p_T$ in the heavy ion data.

Recently, the WA98 experiment has published additional results on direct photon production from central Pb + Pb collisions using interferometry methods [28]. Two-photon correlation functions have been studied in different bins of transverse momentum (see figure 8 left). These correlation functions show the familiar invariant mass peak of the $\pi^0$. In addition, for low values of $Q$ there is an enhancement qualitatively similar to usual interferometry measurements. As decay photons originate at a large distance from the original source (e.g. $c\tau(\pi^0) \approx 25$ nm) decay photons should not show any Bose-Einstein correlation with usual experimental resolutions. Any physics correlations must therefore come from direct photons - the observed signal at low $Q$ in figure 8 can be taken as evidence for this direct contribution. To be able to draw this conclusion one has to carefully investigate other sources of correlations, as e.g. imperfections of the detector response to close-by photons, or correlations induced by other particles misidentified as photons, e.g. neutrons or antineutrons. This has been done in [28], and the authors conclude that non-photon-HBT sources can not explain the observations.

While the width of the correlation does contain information on the effective size of the source, the strength does directly depend on the relative amount of direct photons in the inclusive photon sample. Naively, the true correlation strength would be related to the relative yield of direct photons as:

$$\lambda(k_T) = \frac{1}{2} \left( \frac{N_{direct}^2(k_T)}{N_{total}^2(k_T)} \right),$$  \hspace{1cm} (3)$$

where the factor 1/2 is due to the polarization average. It turns out that the effective correlation strength when measured in $Q_{inv}$ is smaller than the ideal value of $\lambda$, and the necessary correction depends on the source size. The correction has been performed in [28] for the extreme
assumptions of $R = 0$ and $R = 6$ fm and the authors obtain estimates for two $k_T$ bins below 300 MeV/c, which are added to the previously obtained direct photon spectra in figure 8 on the right. Here the estimate for $R = 0$ (open circles) is more unrealistic and should be seen as the lowest estimate possible. The most probable values using the measured radii are given as triangles.

A number of groups [29, 30, 31, 32, 33, 34, 19] have compared their hydrodynamical calculations with the data of WA98. For a detailed discussion see e.g. [35]. Summarizing, the WA98 result requires either a high initial temperature, a large prompt photon contribution, an initial radial velocity, in-medium modifications of the hadron masses and/or a strong flow at later stages. At the moment, it is fair to say that the uncertainties and ambiguities in the hydrodynamical models and in the rates do not allow to decide from the WA98 photon spectra about the presence of a QCD phase transition in SPS heavy-ion collisions. However, most calculations do require a thermal source with an initial temperature of $T_i \approx 250$ MeV or higher.

As one example figure 8 includes results of a calculation given in [36]. The authors are able to describe the WA98 spectrum with a moderately high initial temperature or an additional nuclear $k_T$ for the prompt contribution. However, they are not able to describe the yield at low $p_T$ obtained from the HBT measurement. Here the photon yield is dominated by the hadron gas contribution, but in the calculation this is significantly lower than the observed yield.

4.2. RHIC experiments

In summer 2000 experiments at the Relativistic Heavy Ion Collider (RHIC) at BNL started to take data in collisions of Au nuclei at $\sqrt{s_{NN}} = 130$ GeV, continuing with a beam energy
Figure 9. Direct photon yield as a function of transverse momentum in p+p collision at 200 GeV. The solid circles show the experimental results from PHENIX [6]. Included for comparison is a NLO-pQCD calculations (solid line), and estimates for decay photons from a similar pQCD calculation and from DPMJET [4].

Preliminary PHENIX data.
is displayed. This ratio should reduce to 1 if no direct photons are measured. While it is close to the value of 1 at low transverse momenta, the experimentally measured values increase dramatically reaching values of \( \approx 3 \) for \( p_T > 8 \text{ GeV/c} \), revealing a significant direct photon component. The strong increase in the ratio can in fact be explained by a suppressed background photon yield due to the suppression of neutral pions as discussed above, while the direct photons remain almost unmodified. This is demonstrated by the NLO pQCD calculations included. The ratio of the photon yields for unsuppressed \( \pi^0 \) production (thin dashed line) fails to describe the data, while the calculations using the suppressed neutral pion yield as obtained experimentally (thin solid line) are in good agreement. The additional dotted lines have been obtained for other choices of the factorization scale and demonstrate part of the uncertainty in the calculation.

The thick lines in figure 10 show calculations from [4]. A pure pQCD calculation is shown as a dashed line. The obtained double ratio differs from the above pQCD calculation – part of this discrepancy may be due to the fact that this calculation does not use the experimentally measured hadron decay background but calculates this background independently. The calculation has also been done adding a thermal contribution from a hydrodynamic source (solid line). One can see that the thermal contribution adds only a very small fraction of photons essentially below \( p_T = 6 \text{ GeV/c} \). It is clear that with the current systematical errors a statement about thermal photons is not possible from the RHIC data.

In figure 11 predictions for direct photon production at RHIC and LHC [36] are shown. As already seen from figure 10, the prompt photon component dominates the direct photon yield...
Figure 11. Predictions for direct photon production at RHIC (left) and LHC (right) as a function of transverse momentum [36]. The contributions from prompt and thermal production are shown separately.

at high $p_T$. As dashed and dash-dotted lines the thermal contributions from the hadron gas and the QGP are displayed separately. One can easily see that the most interesting thermal QGP contribution dominates the photon production only in a small window between 1 and 3 GeV/c. At LHC, however, due to the higher initial temperature and the longer life time of the QGP phase the plasma contribution is expected to dominate in this calculation at least up 5 GeV/c. Still it will be difficult to measure the thermal direct photons in these reactions, because they are expected to contribute of the order of 10% to the total photon yield.

5. Summary and outlook
Inclusive photons have been demonstrated to be a useful tool to complement hadron measurements, e.g. for multiplicity and fluctuations. The first direct photon measurement in heavy ion reactions has been successfully performed by the WA98 experiment. The direct photon yield is higher than expected from simple extrapolations of earlier p-induced reactions. The results may be partially explained by an increased hard photon production in nuclei, i.e. $k_T$ broadening. The yield at intermediate $p_T$ seems to require a thermal source with a moderately high initial temperature.

Preliminary RHIC results in central Au+Au collisions show a strong direct photon component at high transverse momentum. This is in line with pQCD calculations scaled with the number of collisions, and thus demonstrates that, unlike high $p_T$ hadrons, photons are not suppressed in heavy ion collisions at RHIC. Current systematical errors do not allow any conclusion on a thermal component in the direct photon spectrum.

References
[1] Alam J, Sinha B and Raha S 1996 Phys. Rep. 273 243
[2] Alam J, Sarkar S, Roy P, Hatsuda T and Sinha B 2001 Ann. Phys. 286 159
[3] Peitzmann T and Thoma M H 2002 Phys. Rep. 364 175-246
[4] Aurenche P (Editor) Photon Physics in Heavy Ion Collisions at the LHC CERN Yellow Report 2004 Preprint hep-ph/0311131
[5] Aggarwal M M et al (WA98 Collaboration) 2000 Phys. Rev. Lett. 85 3595
[6] Frantz J et al (PHENIX Collaboration) Quark Matter 2004, Proceedings of the Seventeenth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Oakland, USA, 2004 J. Phys. G 30 S1003-S1006
[7] Aggarwal M M et al (WA98 Collaboration) 1999 Phys. Lett. B 458 422
[8] Aggarwal M M 1999 Nucl. Instr. and Meth. A 424 395
[9] Werner K 1993 Phys. Rep. 232 87
[10] Bjorken J D, Kowalski K L and Taylor C C 1993 SLAC-PUB-6109
[11] Rajagopal K and Wilczek F 1993 Nucl. Phys. B 399 395
[12] Rajagopal K and Wilczek F 1993 Nucl. Phys. B 404 577
[13] Aggarwal M M et al (WA98 Collaboration) 1998 Phys. Lett. B 420 169
[14] Vogelsang W and Whalley M R A 1997 J. Phys. G 23 A1
[15] Aurenche P et al 1999 Eur. Phys. J. C 9 107
[16] Jeon S, Jalilian-Marian J and Sarcevic I 2003 Nucl. Phys. A 715 795
[17] Fries R J, Mueller B and Srivastava D K 2003 Phys. Rev. Lett. 90 132301
[18] Aurenche P, Gelis F, Kobes R and Zaraket H 1998 Phys. Rev. D 58 085003
[19] Steffen F D and Thoma M H 2001 Phys. Lett. B 510 98
[20] Aurenche P, Gelis F and Zaraket H 2000 Phys. Rev. D 61 116001
[21] Arnold P, Moore G D and Yaffe L G 2001 JHEP 0111 057
   Arnold P, Moore G D and Yaffe L G 2001 JHEP 0112 009
[22] Adams D et al (E704 Collaboration) 1995 Phys. Lett. B 345 569
[23] McLaughlin M et al (E629 Collaboration) 1983 Phys. Rev. Lett. 51 971
[24] Badier J et al (NA3 Collaboration) 1986 Z. Phys. C 31 341
[25] Owens J F 1987 Rev. Mod. Phys. 59 465
[26] Wong C Y and Wang H 1998 Phys. Rev. C 58 376
[27] Dumitru A, Frankfurt L, Gerland L, Stöcker H and Strickman M 2001 Phys. Rev. C 64 054909
[28] Aggarwal M M et al (WA98 Collaboration) 2004 Phys. Rev. Lett. 93 022301
[29] Srivastava D K and Sinha B 2001 Phys. Rev. C 64 034902
[30] Alam J, Sarkar S, Hatsuda T, Nayak T K and Sinha B 2001 Phys. Rev. C 63 021901
[31] Peressounko D Y and Pokrovsky Y E 2000 Preprint hep-ph/0009025
[32] Gallmeister K, Kämpfer B and Pavlenko O P 2000 Phys. Rev. C 62 057901.
[33] Huovinen P, Ruuskanen P V and Räsänen J S 2002 Phys. Lett. B 535 109
[34] Chaudhuri A K 2003 J. Phys. G 29 235
[35] Alam J 2003, proceedings of ICPA-QGP, Jaipur, World Scientific
[36] Turbide S, Rapp R and Gale C 2004 Phys. Rev. C 69 014903