Direct Photons in Heavy-Ion Collisions

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Abstract. A brief overview of direct-photon measurements in ultra-relativistic nucleus-nucleus collisions is given. The results for Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV and for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are compared to estimates of the direct-photon yield from hard scattering. Both results leave room for a significant thermal photon component. A description purely based on hard scattering processes, however, is not ruled out so far.

Keywords: Direct Photons, Heavy-Ion Collisions, CERN SPS, RHIC
PACS: 13.85.Qk, 25.75.-q

INTRODUCTION

In ultra-relativistic heavy-ion collisions it is expected that for a brief period of several fm/$c$ a thermalized medium is created whose relevant degrees of freedom are quarks and gluons. It has long been suggested that the initial temperature of this quark-gluon plasma (QGP) can be determined via the measurement of direct photons, i.e., photons not coming from late hadron decays like $\pi^0 \rightarrow \gamma\gamma$ [1]. The virtue of direct photons is that they escape the hot and dense medium unscathed. The experimental challenge is to extract a direct-photon signal above the large decay-photon background and to identify other sources of direct photons which are not of thermal origin.

A brief summary of known and presumed photon sources in nucleus-nucleus collisions is given in Fig. 1 [6]. Photons from hard scattering of quarks and gluons, analogous to the production mechanisms in p+p-collisions, dominate the direct-photon spectrum at high transverse momenta ($p_T$). The main motivation for the measurement of high-$p_T$ photons in heavy-ion collisions is to test perturbative QCD models and to measure the rate of initial hard scatterings.

The QGP expands and cools and at a temperature of $T_c \approx 190$ MeV a phase transition to a hadron gas takes place [5]. During the entire evolution of the QGP and the hadron gas thermal direct photon are produced. The shape of their $p_T$ spectra reflects the temperature of the medium. Thermal photon are expected to contribute to the direct photon spectrum significantly at low $p_T$ ($\lesssim 3$ GeV/$c$). For model comparisons and the extraction of the initial temperature model calculations need to convolve photon rates for the QGP and the hadron gas with realistic scenarios of the space-time evolution of the fireball. Initial temperatures $T_i > T_c$ would provide evidence for the creation of a QGP.

Direct photons might furthermore be produced in interactions of quarks or gluons from early hard scattering processes with soft quarks and gluons from the QGP. One suggested mechanism is jet-photon conversion in processes like $q_{\text{hard}} + g_{\text{QGP}} \rightarrow \gamma + q$ and $q_{\text{hard}} + \bar{q}_{\text{QGP}} \rightarrow \gamma + g$ in which the photon obtains a large fraction of the momentum...
Photons in A+A

Direct Photons

Decay Photons

hard

thermal

hard+thermal

QGP
Hadron gas

jet-γ -conv.

Medium induced γ bremsstr.

FIGURE 1. Known and presumed photon sources in nucleus-nucleus collisions.

of $q_{\text{hard}}$ [7]. In Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV jet-photon conversion might be a significant direct-photon source for $p_T \lesssim 6$ GeV/c. Direct photons might furthermore be produced due to multiple scattering of quarks in the medium. These interesting ideas, however, still require a experimental verification.

MEASUREMENTS: WA98 AND PHENIX

Direct photons were measured by the fixed-target experiment WA98 at the CERN SPS in central Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 17.3$ GeV [4] and by the PHENIX experiment at the Relativistic Heavy-Ion Collider (RHIC) in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV [2, 3] (see Fig. 2). One of the basic questions in both cases is whether thermal photons or photons from jet-plasma interactions are needed on top of the hard direct-photon component in order to explain the data.

In both experiments the direct-photon spectra are determined by a statistical subtraction of the calculated yield of photons from hadron decays from the total photon yield. The WA98 measurement was made with a highly segmented lead-glass calorimeter. PHENIX measured high-$p_T$ direct photons ($p_T \gtrsim 4$ GeV/c) in a similar way with its electromagnetic calorimeters (see Fig. 3). The preliminary low-$p_T$ direct-photon spectrum shown in Fig. 2b was obtained by measuring virtual photons via their decay into $e^+ e^-$ pairs with the aid of a Ring Imaging Cherenkov Detector. The spectrum of real direct photons can then be obtained under the assumption that the fraction $\gamma^{\text{direct}}/\gamma^{\text{all}}$ of real direct photons is identical to the fraction $\gamma^{\ast}_{\text{direct}}/\gamma^{\ast}_{\text{all}}$ of virtual direct photons with small mass ($\lesssim 30$ MeV) [3].

The spectrum of direct photons in central Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 17.3$ GeV in Fig. 2a is compared to p+p and p+A direct-photon data measured at slightly higher $\sqrt{s_{\text{NN}}}$. These data sets have been scaled to $\sqrt{s_{\text{NN}}} = 17.3$ GeV and furthermore scaled by the respective number of nucleon-nucleon collisions in p+A and central Pb+Pb [4]. The underlying assumption in both cases is that direct photons in p+p and p+A are produced in hard scattering processes. This comparison shows that for $p_T \gtrsim 2.5$ GeV/c the direct-photon yield in central Pb+Pb collisions is consistent with the expected yield from hard scattering. Another possibility to pin down the hard scattering contribution is a comparison to a perturbative QCD (pQCD) calculation and to a parameterization of p+p direct-photon data. Fig. 2a indicates that a thermal photon signal might be present
FIGURE 2. Direct-photon spectra measured in Pb+Pb collisions at the CERN SPS (WA98 experiment) and in Au+Au collisions at RHIC (PHENIX experiment). Both spectra are compared to estimates of the contribution of hard scattering processes in order determine whether an additional thermal photon contribution is needed.

below $p_T \approx 2.5$ GeV/$c$. However, a solid estimate of the hard scattering contribution at CERN SPS energies remains difficult. Firm conclusions can only be drawn if, e.g., a better understanding of the modification of the hard scattering yield in Pb+Pb due to multiple soft scattering of the incoming partons prior to the hard process ("Cronin" or "nuclear $k_T$" effect) can be achieved.

The PHENIX low-$p_T$ direct-photon spectrum in Fig. 2b is compared to a next-to-leading-order p+p pQCD calculation scaled by the number of nucleon-nucleon collisions. The three different pQCD curves correspond to different scales used in the calculation and reflect theoretical uncertainties. An advantage at RHIC energies is that the modification of the hard scattering yield due to the Cronin effect is expected to be small \cite{9}. The difference between the data and the hard scattering yield as estimated by the pQCD calculation hints at the presence of significant thermal photon signal. This will be confirmed or disproved with forthcoming low-$p_T$ direct-photon measurements in p+p and d+Au at the same energy.

Despite these difficulties several attempts have been made to describe the WA98 and PHENIX direct-photon spectra with a combination of a hard and a thermal component and to extract the initial temperature of the thermalized fireball. Both measurements are consistent with a QGP scenario. Initial temperatures for central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV roughly range from $200 \lesssim T_i \lesssim 370$ MeV. For central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV the extracted initial temperatures tend to be higher and cover the range $370 \lesssim T_i \lesssim 570$ MeV \cite{8}.

The high-$p_T$ direct-photon measurement in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is presented in Fig. 3 in terms of the nuclear modification factor

$$R_{AA}(p_T) = \frac{dN/dp_T|_{A+A}}{(T_{AA}) \times d\sigma/dp_T|_{p+p}} .$$

(1)
FIGURE 3. Nuclear modification factor $R_{AA}$ for direct-photons, neutral pions, and \( \eta \) mesons in central Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). Pions and \( \eta \)-mesons are suppressed whereas direct photons are not. The cartoon illustrates the most popular explanation: energetic quarks and gluons which fragment into hadrons suffer energy loss in the medium, direct photons don’t.

The nuclear overlap function $T_{AA}$ is related to the number of inelastic nucleon-nucleon collisions according to $\langle T_{AA} \rangle = \langle N_{\text{coll}} \rangle / \sigma_{\text{inel}}^{NN}$. Fig. 3 shows that unlike pions and \( \eta \)-mesons high-$p_T$ direct photons are not suppressed, \textit{i.e.}, they follow $N_{\text{coll}}$ scaling as expected for hard processes. This is in line with jet-quenching models which attribute the hadron suppression to energy loss of highly-energetic quarks and gluons from initial hard scattering processes in the QGP.

CONCLUSIONS

Direct-photon measurements in nucleus-nucleus collisions from WA98 (Pb+Pb at \( \sqrt{s_{NN}} = 17.3 \text{ GeV} \)) and PHENIX (Au+Au at \( \sqrt{s_{NN}} = 200 \text{ GeV} \)) have been discussed. Both measurements are consistent with a thermal photon signal and initial temperatures \( T_i > T_c \). A description purely based on hard scattering processes, however, is not ruled out so far. The observation that hadrons at high-$p_T$ are suppressed whereas direct photons are not supports jet-quenching models.

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