Direct photon production in d+A and A+A collisions at RHIC

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Direct photon production in minimum bias d+Cu and d+Au and central Cu+Cu and Au+Au collisions at center of mass energies $\sqrt{s} = 62.4$ GeV and 200GeV at RHIC is systematically investigated. We study the jet quenching effect, the medium-induced photon bremsstrahlung and jet-photon conversion in the hot QGP. We account for known cold nuclear matter effects, such as the isospin effect, the Cronin effect, shadowing and cold nuclear matter energy loss. It is shown that at high $p_T$ the nuclear modification factor for direct photons $R_{\gamma AA}(p_T) < 1$ is dominated by cold nuclear matter effects and there is no evidence for large cross section amplification due to medium-induced photon bremsstrahlung and jet-photon conversion in the medium. Comparison of numerical simulations to experimental data also rules out large Cronin enhancement and incoherent photon emission in the QGP but the error bars in the current experimental data cannot provide further constraints on the magnitudes of other nuclear matter effects.

Keywords: direct photon; jet quenching; QGP.

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1. Introduction

In relativistic heavy-ion collisions a large amount of energy is deposited in the interaction region over a very short time interval $\tau \approx 2R_A/\gamma$. An excited state of matter, the quark-gluon plasma (QGP), is expected to be formed and its properties are subject to intense theoretical and experimental investigation. From SPS to RHIC and to the LHC, with increasing $\sqrt{s}$, hard probes \cite{1,2} have become increasingly more important as tomographic tools in the study of the QGP. Their perturbative QCD (pQCD) calculation is based on the factorization theorem, which separates the hard partonic part from the soft, non-perturbative part. For a physics observable $dF/dy d^2p_T$ in p+p collisions we have:

$$\frac{dF}{dy d^2p_T} \propto \phi_{a/A}(\xi_A, \mu_f)\phi_{b/B}(\xi_B, \mu_f) \otimes \frac{dF^{a+b\rightarrow c+X}}{dy d^2p_T} \otimes D_{h/c}(z, \mu_f).$$

(1)
Here, $dF_{a+b\rightarrow c+X}/dyd^2p_T$ represents the partonic cross section, while $\phi_{a/A}(\xi_A, \mu_f)$ and $D_{h/c}(z, \mu_f)$ are the non-perturbative parton distribution functions (PDF) and parton fragmentation functions (FF), respectively. In nucleus-nucleus (A+A) collisions, the result of final-state interactions can often be represented as effective modifications of the FFs. Similarly, cold nuclear matter (CNM) effects resulting from the initial-state interactions in cold nuclei can be absorbed in effective modifications of the PDFs. The latter will also be present in A+A collisions and a robust calculation of QGP signatures needs reliable understanding of initial-state interactions.

Since the photon couples to the partons in the collision region only through electromagnetic interactions ($\alpha_{em} \ll \alpha_s$) its mean free path is very large. Hard photons leave the medium without rescattering and their production can provide valuable information to help constrain initial-state CNM effects. The study of $\gamma$ production in A+A has so far been centered on its QGP-specific components, in particular medium-induced photon emission in the QGP and jet-photon conversion. The predicted consequential large enhancement of the direct photon production cross section in central heavy-ion collisions appears to be incompatible with recent data. Our paper addresses the need for a systematic study of direct photon production in both p+A and A+A reactions by taking consistently into account all relevant hot and cold nuclear matter effects. We concentrate on the intermediate and large transverse momentum regions ($p_T > 2$ GeV) in minimum bias d+Cu and d+Au and central Cu+Cu and Au+Au heavy ion collisions at RHIC with center of mass energies of $\sqrt{s} = 62$ GeV and 200 GeV. We also provide the theoretical derivation of the medium-induced radiative $\gamma$ spectrum for a quark emerging out of a large $Q^2$ process.

2. Direct photon production in p+p collisions

In "elementary" p+p collisions direct photons can be produced, at leading-order in perturbation theory, by quark-antiquark annihilation ($q + \bar{q} \rightarrow \gamma g$) and Compton scattering ($q+g \rightarrow \gamma q$), see LHS of Fig.1. One should also include the contribution of the bremsstrahlung/fragmentation process illustrated in the RHS of Fig.1. Naively, it seems that $\gamma$ radiation gives a higher-order contribution ($\alpha_{em} \alpha_s^2$) when compared to annihilation and Compton scattering ($\alpha_{em} \alpha_s$). However, noticing the logarithmic growth with the hard scale $Q^2$ of the photon fragmentation function $D_{\gamma/c}(z, Q^2)$, parametrically we have:

$$\alpha_s(Q) \propto \ln^{-1}(\frac{Q^2}{\Lambda^2}), \quad D_{\gamma/c}(z, Q^2) \propto \ln(\frac{Q^2}{\Lambda^2})$$

$$\alpha_{em} \alpha_s^2(Q^2) D_{\gamma/c}(z, Q^2) \propto \alpha_{em} \alpha_s(Q^2). \quad (2)$$

The convenience of a particular mathematical representation of nuclear matter effects on the observable cross section should not be confused with genuine universal modification (which may also be present) of the parton distribution and fragmentation functions.
Fig. 1. Direct photon production from the $q + \bar{q}$ annihilation process + Compton scattering (left panel) and bremsstrahlung/fragmentation (right panel).

Fig. 2. Cross sections for direct $\gamma$ production in p+p collisions at $\sqrt{s} = 62.4$ GeV and 200 GeV. Data at $\sqrt{s} = 200$ GeV is taken from PHENIX\cite{PHENIX2}. Insert gives the ratio of bremsstrahlung photons to all direct photons.

Hence the contribution of the bremsstrahlung process is effectively the same order as the prompt production processes and should be taken into account even in LO calculations.

In our leading-order pQCD model, the cross section of direct photon production in p+p collision is given by Eq. (1), where we also allow for possible deviations from collinearity for the incoming partons:

$$\propto \int d^2k_a d^2k_b f(k_a) f(k_b) (\cdots) .$$

Further technical details are given in\cite{5} and we emphasize that any overall scale factor (e.g. the process-dependent NLO K-factor) will cancel when we calculate the nuclear modification ratio $R_{AB}(p_T)$.

In Fig. 2 we show our numerical results for the differential cross sections for direct photons in p+p collisions at $\sqrt{s} = 62.4$ GeV and $\sqrt{s} = 200$ GeV. The power-law $p_T$ dependence of the data at 200 GeV, measured by PHENIX\cite{PHENIX7} is well described by the pQCD calculation. The insert in Fig. 2 gives the fraction of bremsstrahlung (fragmentation) photons to all direct photons. We note that at very high $p_T$ the fragmentation $\gamma$ yield $\sim 25\% - 30\%$ of all direct photons in p+p collisions.
3. Direct photon production in heavy-ion collisions: hot nuclear matter effects

We first discuss final-state QGP-induced modifications to $d\sigma/2d^2p_T$.

- **Jet quenching in the QGP**
  It is well established that when an energetic parton propagates in a hot/dense nuclear medium, it will suffer multiple scattering and lose a fraction of its energy via induced gluon radiation\cite{1}. This jet quenching effect will reduce the contribution of the fragmentation photons due to the attenuation of the flux of energetic quarks. We calculate the parton energy loss using the GLV formalism and represent the effective fragmentation functions into photons as follows:

$$D_{\gamma/c}(z) \Rightarrow \int_0^{1-z} d\epsilon P(\epsilon) \frac{1}{1-\epsilon} D_{\gamma/c} \left( \frac{z}{1-\epsilon} \right). \quad (4)$$

Here, $P(\epsilon)$ is the probability distribution of the fractional jet energy loss $\epsilon = \Delta E/E$\cite{8}.

- **Medium-induced photon radiation**
  In the hot QGP, a propagating jet may also radiate photons due to multiple scattering in the medium\cite{5,9}. Because there is no gauge-boson self-interactions in $\gamma$ bremsstrahlung, one may expect that the $d\Gamma/d\omega$ evaluation is a trivial simplification of the gluon intensity calculation. This naive expectation is not true. Consider the radiative amplitude for single scattering of a fast on-shell quark (there are 3 diagrams in QCD, while 2 diagrams in QED as shown in Fig. 3):

$$\mathcal{M}_{rad}^\gamma(k) \propto 2ig_s\epsilon_{\perp} \cdot \left( \frac{k_{\perp}}{k_{\perp}^2 - (k - q_{\perp})_{\perp}^2} \right) e^{i2k_{\perp}z^+} \left[ T^c, T^a \right]. \quad (5)$$

In the QED limit $T^c \rightarrow 1$ and we obtain $\mathcal{M}_{rad}^\gamma(k) \rightarrow 0$. Thus, a theoretical approach optimized for medium-induced gluon radiation cannot be directly applied to photon bremsstrahlung in the medium and one should be careful in identifying the correct kinematic approximations in evaluating $\gamma$ emission\cite{5,9}.

![Fig. 3. Single-Born diagrams for medium-induced $\gamma$ emission.](image-url)
Meaningful direct photon phenomenology requires theoretical advances in understanding the medium-induced $\gamma$ radiation off of quarks produced inside the plasma in large $Q^2$ processes. We derive this contribution to the $\gamma$ spectrum using the Reaction Operator approach. For the single-Born scattering diagrams, illustrated in Fig. 3, we obtain:

$$M_{\text{rad}}(k,\{i\}) = e \left( \frac{\varepsilon \cdot p_f}{k \cdot p_f} - \frac{\varepsilon \cdot p_i}{k \cdot p_i} \right) e^{iz^+ k^-},$$

where the collisional part of the amplitude is not shown. The contribution of Double-Born diagram is found to be negligible:

$$M_{V\text{rad}}(k) \approx 0.$$ Extend-}

ing the above calculations to higher orders in the correlation between the multiple scattering centers we demonstrate that contributions to $dI^\gamma/d\omega$ vanish beyond second order in opacity:

$$k^+ \frac{dN^\gamma(k)}{dk^+d\mathbf{k}_\perp} = \frac{\alpha_{\text{em}}}{\pi^2} \left\{ \int \frac{d\Delta z_1}{\lambda_q(z_1)} \int d^2\mathbf{q}_{\perp 1} \frac{1}{\sigma_{\text{el}}} \frac{d^2\sigma_{\text{el}}}{d^2\mathbf{q}_{\perp 1}} \right. \times \left[ |M_{\text{rad}}(\{1\})|^2 + 2M^\dagger_{\text{rad}}(\{1\})M_{\text{rad}}(\{0\}) \cos(k^-\Delta z_1^+) \right]$$

+ corrections.

Here $\Delta z_1^+ = z_1^+ - z_{i-1}^+$, and $\lambda_q$ is the quark mean free path. We define the inverse photon formation time as $\tau_f^{-1} = k^2/(2\omega) \approx \sqrt{2} k^-$. There are two well-defined limits in Eq. (7): when $\tau_f^{-1} \lambda_q \gg 1$, the term $\propto \cos(k^-\Delta z_1^+)$ vanishes due to oscillation and we recover incoherent $\gamma$ emission. In the opposite case, $\tau_f^{-1} \lambda_q \leq 1$, interference between the vacuum and medium-induced photons becomes critical.

In Fig. 4 we show numerical results for the scaled medium-induced photon number spectrum $dN^\gamma/d\omega = (e/e_q)^2 dN^\gamma/dx$, $x = k^+/E^+$ for a quark jet.
propagating outwards from the center of the medium created in Au+Au collisions at RHIC with the impact parameter $b = 3$ fm. It is apparent that interference effect strongly suppresses stimulated photon emission when compared to the incoherent scenario. This reduction in emission strength, which is relevant for photon production in heavy ion reactions, differs significantly from the argued small LPM effect for on-shell quarks, see e.g. [310]. In our detailed numerical simulations [518] we also find that the average number of jet interactions in the medium is never large, $\langle n \rangle = L/\lambda_q = 2 - 3$.

- **Jet-photon conversion**

  In the hot/dense medium, a possible new source of direct $\gamma$ is jet-photon conversion [63], see e.g. Fig. 5. Making the approximation that $p_\gamma \approx p_c$ in the forward scattering process, we can derive the additional differential photon multiplicity as follows:

$$N_{\text{conv}}^\gamma (c) = \int_{t_0}^{t_L} dt \rho(T)\sigma_{\text{tot}}^{qg\rightarrow \gamma q}(T),$$

where the cross section is given by

$$\sigma^{qg\rightarrow \gamma q} = \frac{\pi\alpha_s\alpha_{\text{em}}}{6m_DE} \ln \frac{E}{2m_D},$$

with $s \approx 2m_D E$ and $t \in (m_D^2, s/4)$. Here $m_D = g_s T$ is the Debye screen mass.

- **Total QGP contribution to direct photons**

  Combining our results, we obtain the net effect on direct $\gamma$ productions from the final-state jet-medium interactions in the QGP:

$$D_{\gamma/c}(z) \Rightarrow \int_0^{1-z} d\epsilon P(\epsilon) \frac{1}{1-\epsilon}D_{\gamma/c} \left( \frac{z}{1-\epsilon} \right) + \frac{dN_{\text{med}}^\gamma}{dz}(c) + N_{\text{conv}}^\gamma (c) \delta(1-z),$$

where the first term takes into account the jet quenching effect on fragmentation photons, the second term $\frac{dN_{\text{med}}^\gamma}{dz}(c)$ stands for the additional contribution from medium-induced photons which can be derived from Eq. (7), and the last term gives the correction from the inverse Compton scattering of the fast quark in the QGP.

![Fig. 5. A fast quark jet is converted into a high energy photon jet via an interaction with a thermal gluon in the hot QGP.](image-url)
4. Direct photon production in heavy-ion collisions: cold nuclear matter effects

Even though in p+A collisions there are no final-state hot nuclear medium effects, these still cannot be regarded as a simple superposition of p+p scatterings. There are different types of CNM interactions that will manifest themselves in the cross section for direct photon production in p+A and A+A reactions.

- **Isospin effect**
  The cross sections for direct photon production for p+p, p+n and n+n collisions are different because they depend on the electric charges of the quarks ($\sigma \propto \sum q e_q^2$). The different quark composition of p and n will have a significant impact on the nuclear modification factor of direct photon production $R_{AB}^{\gamma}(p_T)$ if the large $x_B$ region in the PDFs is probed.

- **Initial-state energy loss in cold nuclei**
  A fast parton passing through cold nuclear matter may also lose energy before the hard scattering. There is plentiful evidence that this initial-state energy loss is important for heavy ion phenomenology but only recently has it been calculated\[11\]. Its effect can be modeled as:
  \[ \phi_{a,b/N}(x_{a,b}, Q^2) \to \phi_{a,b/N} \left( \frac{x_{a,b}}{1 - \epsilon_{a,b}}, Q^2 \right), \]
  where $\epsilon_{a,b}$ are the fractional energy losses for the incoming partons $a, b$ evaluated in the rest frame of the corresponding target nucleus with, typically, $\epsilon_{a,b} \ll 1$.

- **Cronin effect**
  Initial-state multiple scattering in cold nuclear matter will broaden the transverse momenta of incoming partons before the hard scattering. The Cronin effect, in our calculation, is modeled via such $k_T$ diffusion, $\langle k_T^2 \rangle = \langle k_T^2 \rangle_{pp} + \langle k_T^2 \rangle_{med}$\[1\],
  \[ \langle k_T^2 \rangle_{med} = \left( \frac{2 \mu^2 L}{\lambda} \right)_{q,g} \zeta, \]
  where $\mu^2 = 0.12$ GeV$^2$, $\lambda_g = (C_F/C_A)\lambda_q = 1$ fm, $L$ denotes the length of the nuclear medium and $\zeta$ accounts for the logarithmic dependence arising from large-angle scattering. Eq. \[3\] allows one to incorporate easily such transverse momentum broadening into the pQCD calculation.

- **Shadowing and EMC effect**
  In our model shadowing was calculated from the coherent final-state parton interactions within the pQCD higher-twist collinear factorization approach\[5\]. The scale of power correction $\xi^2$ is the only parameter constrained by the mean squared momentum transfer per unit length $\mu^2/\lambda$, $\langle (\xi^2 A^{1/3})_{q,g} \rangle \approx (2\mu^2 L/\lambda)_{q,g}$ in minimum bias collisions, and by the world’s data on DIS on nuclei. Only the EMC effect is parametrized in our numerical simulations.
Fig. 6. Nuclear modification factors $R_{\gamma}^{dA}(p_T)$ for direct $\gamma$ production in minimum bias d+Au (solid lines) and d+Cu (dashed lines) collisions at $\sqrt{s} = 62.4$ GeV (bottom panel) and 200 GeV (top panel). Preliminary $\sqrt{s} = 200$ GeV minimum bias d+Au data is from PHENIX [12].

5. Numerical results

With the leading-order pQCD improved parton model in Eqs. (1) and (3), augmented by including all QGP effects, calculated in Sect. 3, and CNM effects, discussed in Sect. 4, we can evaluate numerically the nuclear modification factor

$$R_{\gamma}^{AB}(p_T, b) = \frac{d\sigma_{AB}}{dyd^2p_T} / N_{coll}^{AB}(b) \frac{d\sigma_{pp}}{dyd^2p_T},$$

and compare to available experimental data at RHIC. Since we focus on hard photon production with $p_T > 2 - 3$ GeV, the contribution from thermal photons is very small and thus neglected in the current study.

Figure 6 shows numerical results of direct photon production for minimum-bias d+Au and d+Cu collisions at different colliding energies $\sqrt{s} = 62.4, 200$ GeV by taking into account all relevant CNM effects, which has not yet been done before in the literature according to our knowledge. Here to demonstrate the relative importance of different CNM effects, we calculated $R_{\gamma}^{dA}(p_T)$ under different theoretical assumptions, namely, $R_{\gamma}^{dA}(p_T)$ with isospin and Cronin effects, $R_{\gamma}^{dA}(p_T)$ with isospin, Cronin effect and shadowing effects, and $R_{\gamma}^{dA}(p_T)$ with the initial-state energy loss as well as isospin, Cronin and shadowing effects. And in all numerical simulations the EMC effect is already included. We note that when $p_T < 6$ GeV, the Cronin effect is dominant and leads to cross section enhancement. For $p_T > 6$ GeV, the isospin effect becomes important and $R_{\gamma}^{dA}(p_T) < 1$. The effect of initial-state energy loss on direct $\gamma$ attenuation is substantial but the EMC effect is small and
noticeable only at the low colliding energy and at the largest transverse momenta. It is interesting to note that CNM effects have reduced direct photon production at $p_T \sim 15$ GeV by about 25% for d+A collisions at $\sqrt{s} = 200$ GeV, and by about 40% for reactions at $\sqrt{s} = 62.4$ GeV. Due to large error bars in the data, current experimental measurements in d+A cannot constrain more quantitatively parton dynamics in large nuclei and progress in this area is urgently needed.

Next, we show results of direct photon production in central Au+Au and Cu+Cu collisions at $\sqrt{s} = 62.4$ GeV and 200 GeV in Fig. 7. Similar to calculations for $R_{dA}^\gamma(p_T)$, in Fig. 7 we demonstrate the relative strength of different nuclear matter effects by giving three curves of $R_{AA}^\gamma(p_T)$: one stands for $R_{AA}^\gamma(p_T)$ with coherent medium-induced photon bremsstrahlung and jet-photon conversion as well as initial-state energy loss; another curve represents $R_{AA}^\gamma(p_T)$ with jet-photon conversion and initial-state energy loss; and the third curve denotes $R_{AA}^\gamma(p_T)$ with only incoherent photon radiation and jet-photon conversion in the QGP. By comparing Fig. 7 to Fig. 6 one can see that in A+A collisions $R_{AA}^\gamma(p_T)$ for direct photon production is dominated by cold nuclear matter effects, amplified by the presence of two large nuclei. We note that in our treatment of photon bremsstrahlung in the QGP we have considered the coherent interference of medium-induced photon radiation with the hard emission from the large $Q^2$ scattering of the parent quark, which effect, as well as the initial-state energy loss effect, has been ignored in a previous study [10]. Experimental data clearly exclude both large Cronin enhancement and incoherent photon emission, thereby providing support for the new theoretical developments reported in [5, 11]. Copious jet-photon conversion [9] is also ruled out. In fact, in contrast to early speculations we find that $p_T < 5$ GeV medium-induced photons contribute $\sim 10\%$ to the observed cross section and inverse Compton scattering of energetic quarks in the QGP is a $< 25\%$ correction. In the high $p_T$ region, the two enhancement contributions are very small and $R_{AA}^\gamma(p_T) < 1$.

6. Conclusions

By taking into account all relevant cold nuclear matter effects and the hot QGP effects we carried out the first systematic study of direct photon production in p+A and A+A collisions at RHIC [5]. After consistent modeling of initial- and final-state parton propagation in the medium we did not find theoretical justification for the previously argued large QGP-induced enhancement of the direct photon cross section. In fact, our results suggest that in both proton-nucleus and nucleus-nucleus reactions cold nuclear matter effects are dominant. Experimental data is compatible with such an interpretation ($R_{AB}^\gamma(p_T) \sim 1$) and provides support for the theoretical underpinnings [11] of our numerical results.

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Fig. 7. $R_{AA}(p_T)$ for direct photon in central Au+Au and Cu+Cu collisions at $\sqrt{s} = 62.4$ GeV (bottom panel) and $\sqrt{s} = 200$ GeV (top panel) calculated including cold and hot nuclear matter effects. Data are taken from Refs. 4, 7.

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