Electromagnetic emission from hot medium measured by the PHENIX experiment at RHIC

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Abstract. Electromagnetic radiation has been of interest in heavy ion collisions because it sheds light on early stages of the collisions where hadronic probes do not provide direct information since hadronization and hadronic interactions occur later. The latest results on photon measurement from the PHENIX experiment at RHIC reflect thermodynamic properties of the matter produced in the heavy ion collisions. An unexpectedly large positive elliptic flow measured for direct photons are hard to be explained by many models.

1. Introduction
The experiments utilizing relativistic heavy ion collisions have been aiming to find a new state of matter, quark-gluon plasma (QGP), that should have existed in the early stage of the Universe (Fig. 1). The QGP is an interesting state in the sense that it is not only a discovery subject, but also a unique place to understand the nature of QCD matter, such as quark confinement or the chiral symmetry restoration. The unique feature of the study at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory is that one can utilize the probe with high $Q^2$ (perturbative probe) to investigate the QCD matter in thermal region (low $Q^2$, non perturbative matter).

Figure 1. Phase diagram of the nuclear matter.

Figure 2. Photon emission in relativistic heavy ion collisions.
Many intriguing phenomena have been observed at RHIC since it started running in 2000. The high transverse momentum ($p_T$) hadron production from the initial hard scattering was observed, and the large suppression of their yields suggested that the matter is sufficiently dense to cause parton-energy loss prior to hadronization [1]. The large elliptic flow of particles and its scaling in terms of particle kinetic energy suggests that the system is locally in equilibrium as early as $0.3\text{fm}/c$, and the flow occurs already on the partonic level.

Because photons interact with the medium and other particles only electromagnetically and are largely unaffected by final state interactions, they serve as a direct and penetrating probe of the early stages at high temperature and high density [2]. At leading order, the production processes of photons are annihilation ($q\bar{q}\rightarrow\gamma g$) and Compton scattering ($qg\rightarrow\gamma q$) (Figure 3). Their yields are proportional to $\alpha\alpha_s$, where $\alpha$ is the electromagnetic coupling constant and $\alpha_s$ is the strong coupling constant, and are $\sim40$ times lower than those of hadrons from strong interactions ($\propto\alpha_s^2$).

![Figure 3. Photon production process.](image)

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![Figure 4. Sources of photons from various stages of collisions.](image)

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A calculation predicts that the photon contribution from the QGP state is predominant in the $p_T$ range of $1<p_T<3\text{GeV}/c$ [3]. For $p_T>3\text{GeV}/c$, the signal is dominated by a contribution from initial hard scattering, and $p_T<1\text{GeV}$, the signal is from hadron gas through processes of $\pi\pi(\rho)\rightarrow\gamma\rho(\pi)$, $\pi K^*\rightarrow K\gamma$ and etc. Figure 4 shows a landscape of photon sources as a function of the time they are produced. The vertical axis corresponds to transverse momenta of photons. We have one additional degree of freedom, virtual mass, in photon measurement, which will be explained in detail in a later section. These photons can be measured after a huge amount of background photons coming from hadron decays (\(\pi^0,\eta,\eta'\) and $\omega$, etc.) are subtracted off from inclusive photon distributions. The typical signal to background ratio is $\sim1\%$ at $2\text{GeV}$, and $\sim10\%$ at $5\text{GeV}$ in case of $p+p$ collisions. The signal from QGP is predicted to be $\sim10\%$ of the inclusive photons. For $Au+Au$ collisions, thanks to a large suppression of high $p_T$ hadrons, the ratio is enhanced by the same degree. PHENIX [4] has measured photons throughout the first decade of RHIC operations. We present here a review of the results.

2. Measurement of initial hard scattering photons in heavy ion collisions

One of the big successes by now in electromagnetic radiation measurements is the observation of high $p_T$ direct photons that are produced in initial hard scattering [5] in relativistic heavy ion collisions. Figure 5 shows the direct photon spectra in $Au+Au$ collisions at $\sqrt{s_{NN}}=200\text{GeV}$ for different centralities. The lines show the NLO pQCD calculations [6] scaled by the nuclear thickness function ($T_{AA}$). The fact that the data are well described by the lines show that the yields are following the $T_{AA}$ scaling and suggest that the source is the initial hard scattering.
3. Measurement of direct photons through its internal conversion

There is a huge background arising from \( \pi^0 \) decaying into two photons, which makes it very difficult to look at the direct photon signal at low \( p_T \), where thermal photons from QGP manifest, with traditional calorimetry of (real) photons. However, if we look at photons with a small mass (virtual photons) instead, we can select the mass region where \( \pi^0 \) contribution ceases (Fig 7). For the case of \( p_T \gg M \), the yield of virtual photons is expected to be dominated by internal conversion of real photons [8, 9]. For obtaining direct photon yield, we fit the measured invariant mass distribution with the function:

\[
F = (1 - r)f_c + rf_d,
\]

where \( f_c \) is the cocktail calculation (photons from various hadron decays), \( f_d \) is the mass distribution for direct photons, and \( r \) is the free parameter in the fit. Next, using the Kroll-Wada formula [10] to account for the Dalitz decays of \( \pi^0 \), \( \eta \) and direct photons, \( r \) is defined as the ratio of direct photons to inclusive photons:

\[
\frac{\gamma_{\text{dir}}(m_{ee} > 0.15)}{\gamma_{\text{inc}}(m_{ee} > 0.15)} \propto \frac{\gamma_{\text{dir}}^*(m_{ee} \approx 0)}{\gamma_{\text{inc}}^*(m_{ee} \approx 0)} = \frac{\gamma_{\text{dir}}}{\gamma_{\text{inc}}} \equiv r_\gamma
\]

Then, the invariant yield of direct photons is calculated as \( \gamma_{\text{inc}} \times r_\gamma \). As described in [9], the procedure is demonstrated in Fig 7 for \( 1.0 < p_T < 1.5 \text{ GeV/c} \). The dotted lines show the
contributions from various hadrons, the solid blue is the sum of these contributions, and the solid red line shows the distribution from direct photons converted internally. The $r$ value is determined by the fit to the data. The error of the fit corresponds to the statistical error. We applied the procedure as a function of $p_T$ for various centrality selections in p+p and Au+Au collisions, and obtained the $p_T$ spectra, as shown in Fig 8. The distributions are for 0–20%, 20–40% centrality and MB events for Au+Au collisions. For $p_T<2.5\ GeV/c$ the Au+Au yield is visibly higher than the scaled p+p yield. The distributions were then fitted with the p+p fit plus exponential function to obtain slopes and dN/dy for three centralities. The slopes are estimated to be $\sim 220\ MeV$. The lines show the theoretical expectation from a literature [3]. One may question whether or not the excess arises from a source that exists only in Au+Au collisions. For example, an effect that could increase the yield is cold-nuclear-matter (CNM) effect such as $k_T$ broadening (Cronin effect). To quantify the contribution we analyzed 2008 $d+Au$ data with the same procedure [11]. Figure 9 shows the Au+Au yield compared to the $d+Au$ yield scaled by $N_{coll}$. It clearly shows that there is an enhancement over CNM effects in Au+Au collisions.

4. Exploring new degree of freedom in direct photon measurement

On exploring the matter produced, one wants to explore a new degree of freedom of the observables. The angular dependence of the photon yield with respect to the plane defined by impact parameter (event plane) is one of the degrees that can be investigated. Rapidity dependence will be another degree of freedom, which may shed light to the pre-equilibrium state of the collisions. It is predicted that the second order of the Fourier transfer coefficient ($v_2$, elliptic flow) of angular distributions of photons show the different sign and/or magnitude, depending on the production processes [12] (Fig. 10). The observable is powerful to disentangle the contributions from various photon sources in the $p_T$ region where they intermix. The photons

Figure 7. Invariant mass distributions of electron-pairs and comparison with possible hadron sources of electron-pairs.
from hadron-gas interaction and thermal radiation may follow the collective expansion of a system, and give a positive $v_2$. The amount of photons produced by jet-photon conversion or in-medium bremsstrahlung increases as the medium to traverse increases. Therefore these photons show a negative $v_2$. The fragmentation photons will give positive $v_2$ since larger energy loss of jets is expected orthogonal to the event plane.

PHENIX has measured the $v_2$ of direct photons by subtracting the $v_2$ of hadron decay photons off from that of the inclusive photons, following the formula below:

$$v_2^{\text{dir.}} \equiv \frac{R \times v_2^{\text{incl.}} - v_2^{\text{bkgd.}}}{(R - 1)}, \quad R = \frac{\langle \gamma / \pi^0 \rangle_{\text{meas.}}}{\langle \gamma / \pi^0 \rangle_{\text{bkgd.}}}$$
The elliptic flow of $\pi^0$ and inclusive photons are shown in Fig. 12(a), and the one for direct photons is shown in Fig. 12(b). The $v_2$ of direct photons is large and positive, and comparable to the flow of hadrons for $p_T < 3 \text{GeV}/c$. This result is hard to be explained by many models. Several models qualitatively predicted the positive flow of the photons assuming the photons are boosted with hydrodynamic expansion of the system, but the amount is significantly lower than the measurement [13]. There is one model that gives relatively large flow by including hadron-gas interaction [14].

5. Summary
Direct photons are a powerful tool to investigate the collision dynamics. PHENIX has measured direct photons over wide $p_T$ ranges, including hard scattering and thermal photons, and extracted quantities, such as slope parameters, that reflect thermodynamic properties of the matter. An unexpectedly large positive elliptic measured for direct photons are hard to be explained by many models.

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