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Photon production from quark gluon plasma at finite baryon density

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Abstract. The photon yield from a baryon-rich quark gluon plasma (QGP) at SPS energy has been estimated. In the QGP phase, rate of photon production is evaluated up to two-loop level. In the hadron phase, dominant contribution from π, ρ, ω mesons has been considered. The evolution of the plasma has been studied with appropriate equation of state in both QGP and hadron phase for a baryon-rich system. At SPS energy, the total photon yield is found to increase marginally in the presence of baryon density.

Keywords. Quark gluon plasma; photon; baryon density.

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1. Introduction

Photons are the promising signals of the quark gluon plasma (QGP). The experimental data on single photon from the Pb+Pb collision at CERN SPS (WA98 Collaboration [1]) suggests that final baryon multiplicity at freeze-out temperature, $\mathrm{d}N_{\mathrm{B}}/\mathrm{d}y \approx$80–90. The earlier studies of photon production [2,3] ignore the presence of baryon density. However, the presence of baryon density will affect the evolution of the plasma as well as the photon rate. In this work, we estimate the photon yield from a baryon-rich equilibrated quark gluon plasma undergoing first-order phase transition. We determine the photon production rate from the QGP phase, using effective field theory up to two-loop level. At one-loop level, the annihilation ($q\bar{q} \to g\gamma$) and the QCD Compton $(qg \to q\gamma, \bar{q}g \to \bar{q}\gamma)$ are the dominant processes, while at two-loop level bremsstrahlung and annihilation with scattering (AWS) contribute [4]. The total photon yield is calculated by integrating the rate over the plasma volume created by the expansion and consequent cooling of the plasma [5] and is compared with data.

2. Rate of photon production

Photon rate from Compton and annihilation processes for equilibrated plasma at finite baryon density is given by [6]

$$2E\frac{\mathrm{d}R}{\mathrm{d}^3q}=\frac{5\alpha\alpha_s \mathrm{e}^{-E/T}}{9\pi^2}\left(T^2+\frac{\mu_\mathrm{q}^2}{\pi^2}\right)\ln\left(\frac{2.91E}{g^2T}\right), \tag{1}$$

where quark chemical potential $\mu_\mathrm{q}=\mu/3$. The photon rate from bremsstrahlung and annihilation with scattering (AWS) processes is estimated by extending the formalism of Aurenche *et al* [4] for a baryon-rich plasma where the vertices in RA has been redefined for a baryon-rich system [5]. Hence the photon rate for the bremsstrahlung process are given by the following expression:

$$2E\frac{\mathrm{d}R}{\mathrm{d}^3q}\bigg|_{\mathrm{brem}}\approx 2\frac{NC_F\alpha\alpha_s}{\pi^5}\left(\sum_f e_\mathrm{f}^2\right)\frac{T}{E^2}(J_T-J_L)f_\mathrm{B}(E)$$
$$\times\int_0^\infty \mathrm{d}p(p^2+(p+E)^2)\{[f_F(p)-f_F(p+E)]$$
$$+[f_{\bar{F}}(p)-f_{\bar{F}}(p+E)]\}, \tag{2}$$

where f_F and $f_{\bar{F}}$ are quark and anti-quark distribution functions defined appropriately for a baryon-rich plasma [5]. Similarly, the photon rate for AWS process can be written as

$$2E\frac{\mathrm{d}R}{\mathrm{d}^3q}\bigg|_{\mathrm{AWS}}\approx 2\frac{NC_F\alpha\alpha_s}{\pi^5}\left(\sum_f e_\mathrm{f}^2\right)\frac{T}{E^2}(J_T-J_L)f_\mathrm{B}(E)$$
$$\times\int_0^E \mathrm{d}p(p^2+(E-p)^2)[1-f_{\bar{F}}(p)-f_F(E-p)]\,. \tag{3}$$

Here $J_T=1.108$ and $J_L=-1.064$ for $N_f=2$, and not sensitive to the baryo-chemical potential [5]. Photon emission from hadronic gas is estimated considering $\pi\pi\to\rho\gamma$, $\pi\rho\to\pi\gamma$ and decay processes $\rho\to\pi\pi\gamma$ and $\omega\to\pi\gamma$ which give the dominant contribution to the total photon production.

3. EOS of QGP and hadron phase

The equation of state (EOS) appropriate for a baryon-rich quark gluon plasma with massless u and d quarks and phenomenological bag constant B is given by

$$P_{\mathrm{QGP}}=\frac{T}{V}\ln Z_{\mathrm{QGP}}(\mu,T)=\frac{37\pi^2T^4}{90}+\frac{1}{9}\mu^2T^2+\frac{1}{162\pi^2}\mu^4-B, \tag{4}$$

where μ is the baryo-chemical potential and related to quark chemical potential $\mu_\mathrm{q}=\mu/3$. We consider nucleons and delta (Δ) particles and their resonances, and π, ρ, ω, η, a_1 among the mesons for the hadronic equation of state. The pressure in the hadron phase can be expressed as the sum of the contribution from mesons and baryons where the pressure for the mesons is

$$P_{\mathrm{meson}}=-T\sum_i\frac{g_i}{2\pi^2}\int p^2\mathrm{d}p\ln\{1-\exp[-\sqrt{p^2+m_i^2}/T]\}. \tag{5}$$

Here, the sum is over all the mesons under consideration. The pressure for the baryons can be written as

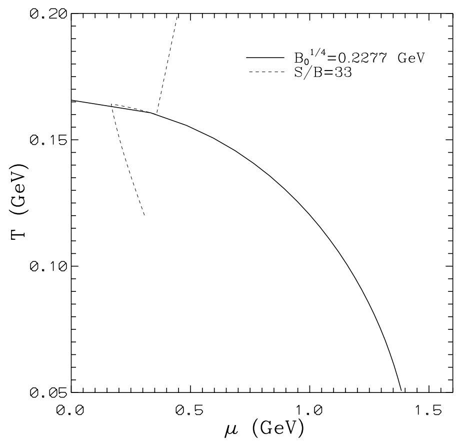

Figure 1. The phase boundary in T–μ plane (solid) and the path of evolution with constant entropy/baryon density $(S/B = 33)$ (dashed) obtained with constant bag pressure $B_0^{1/4} = 0.23$ GeV.

$$P_{\mathrm{B}} \approx \sum_i g_i \frac{m_i^2 T^2}{\pi^2} \cosh\left(\frac{\mu}{T}\right) K_2\left(\frac{m_i}{T}\right). \tag{6}$$

The phase transition between the hadron gas and the quark gluon plasma is considered with excluded volume correction and can be described through the first-order phase transition with Gibb's criteria. Figure 1 shows the phase boundary in (μ, T) plane obtained using the above equation of state for $B_0^{1/4} = 0.23$ GeV.

4. Evolution of QGP and hadronic gas

The space-time evolution of QGP and the hadronic matter has been studied in (1+1)-dimensional boost-invariant scenario. The energy–momentum and baryon number conservation laws require that $s\tau$ and $n_{\mathrm{B}}\tau$ are constant throughout the evolution, where s and n_{B} are entropy and baryon densities respectively. Hence, for isentropic expansion, entropy per baryon (S/B) should also remain constant. However, the entropy per baryon in QGP phase is considerably larger than the hadronic phase at any point on the phase boundary. To make S/B continuous across the phase boundary, T_{c} and μ_{c} are allowed to vary keeping $P_{\mathrm{QGP}} = P_H$. As a consequence T_{c} increases and μ_{c} decreases along the phase boundary as shown by the dashed line in figure 1 and phase transition occurs at varying T_{c} and μ_{c} where the mechanical stability ($P_{\mathrm{QGP}} = P_H$) is maintained [7].

5. Photon yield

Figure 2 shows total space-time integrated photon yield for SPS energy. Assuming entropy per particle ∼3.6, S/B is ∼33 at SPS energy. Each point in the μ–T curve in figure 1

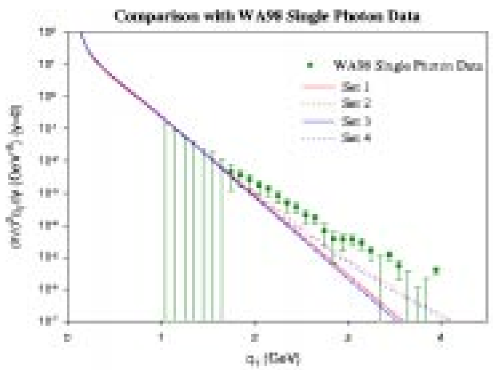

Figure 2. Data points are taken from WA98 measurements. Set 1: $T_0 = 0.2$ GeV, $\mu_0 = 0.447$ GeV and $\tau_0 = 1.0$ fm. Set 2: $T_0 = 0.3$ GeV, $\mu_0 = 0.67$ GeV and $\tau_0 = 0.3$ fm. Set 3: $T_0 = 0.2$ GeV, $\mu_0 = 0.0$ GeV and $\tau_0 = 1.0$ fm. Set 4: $T_0 = 0.3$ GeV, $\mu_0 = 0.0$ GeV and $\tau_0 = 0.3$ fm.

corresponds to a fixed S/B value which depends on the bag pressure B_0. We fix the freeze-out temperature $T_f = 0.12$ GeV and the bag constant $B_0^{-1/4} = 0.23$ GeV which gives $T_c = 0.16$ GeV and $\mu_c = 0.357$ GeV. Treating T_0 as a parameter, we get the curve set 2 which reproduces the photon spectrum quite well as shown in figure 2. The discrepancy at high p_T region can be accounted for by estimating the contributions from the prompt photon yields [8]. The curve set 1 is obtained with a different initial condition but same $S/B = 33$, which reproduces the spectrum at low p_T, but fails to give enhancement at higher photon momentum. The curves set 1 and set 2 are compared with set 3 and set 4 for baryon-free plasma. Presence of baryon density enhances the photon production marginally.

6. Conclusion

At SPS energy, the photon production from a baryon-rich QGP energy has been estimated up to two-loop level. Total space-time integrated photon yield is found not to be very sensitive to the presence of baryon density.

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