原 子 核 物 理 评 论
Nuclear Physics Review

Article ID：1007－4627(2010)01－0016－06

Jet-photon Conversion in Expanding Quark-gluon Plasma*

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Abstract：We develop a jet-photon conversion mechanism in the expanding quark-gluon plasma. The jet-photon conversion in hot quark-gluon medium is a vital source of the thermal photon production. The jet converts into photons via the secondary Compton and annihilation processes in the quark-gluon plasma. The gluon-photons are also considered in the calculation of prompt photons which includes the effect of the shadowing and isospin of nucleus. We find that the prompt gluon-photons are also an important modification to prompt photons.

Key words：quark-gluon plasma；jet-photon conversion；photon production

CLC number：O572.31 **Document code**：A

1 Introduction

Quark-gluon plasma(QGP) has become the most important issue in the study of relativistic heavy ion collisions. The novel deconfined state of strong interacting matter can be created by relativistic heavy ion collisions[1—12]. From the earlier Relativistic Heavy Ion Collider(RHIC) to the accomplished Large Hadron Collider(LHC), many efforts try to probe the properties of the hot quark-gluon matter[13—15]. The collision energy could be several TeV per nucleon in Pb-Pb collisions at LHC, one may hope for using the novel experimental data of Pb-Pb collisions to examine the correctness of the quark-gluon plasma theory at such high temperature. Because of the short lifetime of the quark-gluon plasma, it is difficult to probe the information of the hot quark-gluon plasma[16—20]. Fortunately, the mean free path of the electromagnetic radiation is much larger than the size of the quark-gluon plasma, so a possible way is available to probe the photon information emitted from the plasma. Theoretical efforts aim to identify various sources of the electromagnetic radiation including prompt and thermal photons, and then one can distinguish the information of quark-gluon plasma from hard photons produced in initial nucleon-nucleon collisions[21—24].

The jet-photon fragmentation only exists in the out side of the quark-gluon plasma, and the jet is highly suppressed in the quark-gluon medium due to the jet quenching effect. The jet-photon conversion turns into an important photon production source in the quark-gluon plasma[25—31]. We consider that jet-photons are produced by the jet-photon conversion mechanism in the quark-gluon medium. The jet-photon conversion is defined as the secondary Compton and annihilation processes. The contribution of jet-photons plays a vital role in the traditional thermal Compton and annihilation photon spectrum at the low transverse momentum region.

Gluon-photons are produced by finite contri-

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* **Received date**：26 Mar. 2009；**Revised date**：27 May 2009

* **Foundation item**：National Natural Science Foundation of China(10665003)

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butions of the quark one-loop($gg \to g\gamma$, $gg \to \gamma\gamma$) which represent the effect of the hot gluon medium. Previous studies often neglect the contribution of gluon-photons, because the strong coupling parameters of the quark one-loop are relatively smaller than the parameters of direct photon processes. We examine the gluon-photon spectrum with the direct photon and fragmentation photon processes, and find that the production of gluon-photons is also an important source of prompt photons in low transverse momentum region. The EMC shadowing and isospin of the nucleus which can avoid overestimating the prompt photon production in nucleus-nucleus collisions are also considered in the calculation of the prompt photons[18, 21, 32].

This article is organized as follows. In Sec. 2, we discuss the prompt photon production including the modification of gluon-photons. The EMC shadowing and isospin effect are introduced in the parton model. The thermal direct photons and thermal gluon-photons are discussed in Sec. 3. In Sec. 4, the mechanism of the jet-photon conversion is discussed. Finally, a conclusion is contained in Sec. 5.

2 Prompt Photon Production in Relativistic Heavy Ion Collisions

The prompt photons are produced by the hard scattering of high energy parton collisions. The prompt photons can be defined into three categories. They are direct photons, fragmentation photons and gluon-photons. The direct photons are produced by the Compton and annihilation processes. The fragmentation photons are those produced by jet-photon fragmentation from final state partons. The gluon-photons are produced by finite contributions of the quark one-loop($gg \to g\gamma$, $gg \to \gamma\gamma$) which represent the photon modification of the hot gluon medium. The production rate of direct photons was discussed extensively by previous studies, but the radiation source of gluon-photons is to be neglected for the reason that the strong coupling parameters of quark one-loop ($gg \to \gamma\gamma$ ($\alpha^2\alpha_s^2$) and $gg \to g\gamma$ ($\alpha\alpha_s^3$)) are relatively smaller than the parameters of direct photon processes ($\alpha\alpha_s$). However, because of the abundance of gluons at the low transverse momentum region, the contributions of QCD single and double gluon-photons are not negligible in relativistic heavy ion collisions[24].

The direct photons and gluon-photons emitted from the hard scattering of high energy partons satisfy the cross section in the following[24]

$$E\frac{d\sigma}{d^3p} = \frac{1}{\pi}\int_{x_a^{\min}}^{1} dx_a G_{A/a}(x_a, Q^2) G_{B/b}(x_b, Q^2) \times \frac{x_a x_b}{x_a - x_1}\frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) , \qquad (1)$$

where the subprocess of parton scatterings is $d\hat{\sigma}/d\hat{t}$ [24,31]. For the rapidity y is zero, we have the Mandelstam variables in the cross section as $\hat{s} = x_a x_b s$, $\hat{u} = -x_b x_T s/2$ and $\hat{t} = -x_a x_T s/2$, where $x_T = 2P_T/\sqrt{s}$, $x_b = x_a x_2/(x_a - x_1)$, here s is the square of the total energy of nucleon-nucleon collisions and P_T is the transverse momentum of the photon. The minimum momentum fraction in the integral is $x_a^{\min} = x_1/(1-x_2)$, where $x_1 = x_2 = x_T/2$. These subprocesses are given by the leading order (direct photons) and quark one-loop (gluon-photons) QCD calculation. To consider the higher order contribution, we take the K correction factor as $K \approx 1.5$[17].

The cross section of fragmentation photons can be estimated from parton fragmentation in the following[29]

$$E\frac{d\sigma}{d^3p} = \frac{1}{\pi}\int_{x_a^{\min}}^{1} dx_a \int_{x_b^{\min}}^{1} dx_b G_{A/a}(x_a, Q^2) \times G_{B/b}(x_b, Q^2) D_q^{\gamma}(z_c, Q^2)\frac{1}{z_c}\frac{d\hat{\sigma}}{d\hat{t}}(ab \to cd) , \qquad (2)$$

where $z_c = x_1/x_a + x_2/x_b$, and $d\hat{\sigma}/d\hat{t}$ represent the subprocess cross section of parton + parton → parton + parton collisions, here the photon is smashed from the final state of the jet quark by introducing a photon fragmentation function $D_q^{\gamma}(z_c, Q^2)$. The photon fragmentation function can be estimated from the Born approximation of the photon bremsstrahlung($q \rightarrow q\gamma$) processes[24]. The momentum fractions in the integral are $x_a^{\min}=x_1/(1-x_2)$ and $x_b^{\min}=x_a x_2/(x_a-x_1)$. The fragmentation function of photons is given by the following

$$D_q^\gamma(z_c, Q^2)=\frac{\alpha_s e_q^2}{2\pi z_c}\ln\frac{Q^2}{\Lambda^2}[1+(1-z_c)^2] \quad , \tag{3}$$

and one should note that $D_g^\gamma(z_c, Q^2)=0$. Here the strong running coupling constant is

$$\alpha_s=\frac{4\pi}{\beta_0\ln(Q^2/\Lambda^2)} \quad , \tag{4}$$

where the QCD scale parameter $\Lambda=200$ MeV, $\beta_0=11-(2n_f/3)$, and n_f is the flavor number of quarks.

For the nucleus-nucleus collisions, we choose the parton distribution $G(x, Q^2)$ of the nucleus from M. Gluck et al[25] in the following

$$G(x, Q^2)=R(x, Q^2, A)[ZP(x, Q^2)+(A-Z)N(x, Q^2)], \tag{5}$$

where $R(x, Q^2, A)$ is the EMC shadowing factor[26], Z is the proton number of the nucleus, A is the nucleon number, $P(x, Q^2)$ is the proton distribution and $N(x, Q^2)$ is the neutron distribution. Since protons and neutrons have different up and down valence quark distribution, the isospin of the nucleus can be represented by the sum of the proton and neutron distribution. In Fig. 1 one can see that the theoretical results of prompt photons with our measurements are in good agreement with the experimental data in proton-proton collisions at different energies[28]. The EMC shadowing and isospin effect are not included in the proton distribution due to the nucleon-nucleon collisions. The comparison between the theory and experimental data of the nucleus-nucleus collisions is shown in Fig. 2. One can see that the prompt photon spectrum of the Au-Au collisions which contains the shadowing and isospin effect fits the RHIC PHENIX data[21] in the region of $P_T>4.5$ GeV quite-well. Previous studies treat the production rate of prompt photons in nucleus-nucleus collisions by scaling the results for proton-proton collisions with the number of nucleon-nucleon collisions. The treatment without the shadowing and isospin effect will overestimate the prompt photon spectrum in the large P_T region[14, 17, 27] . In Ref . [32], the

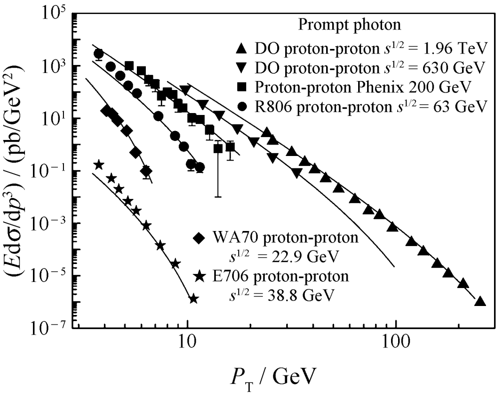

Fig. 1 Prompt photons produced from proton-proton collisions at different energies with experimental data. The solid line is the prompt photon contribution (Data from Ref. [28]).

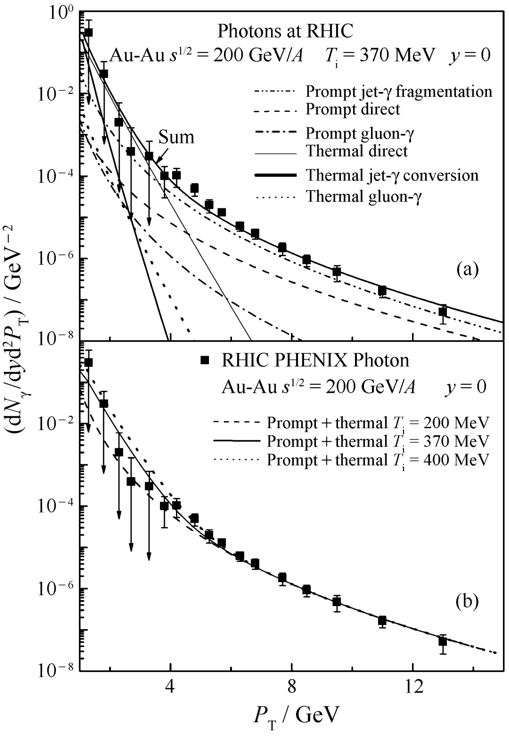

Fig. 2 The photons production sources in the Au-Au collisions at RHIC energy, the data from Ref. [21] (a). Theoretical results fit the PHENIX data quife well at the initial temperature 200 MeV $<T_i<$400 MeV and formation time $\tau_i\approx 0.2$ fm/c (a).

authors discussed the effect of the isospin and shadowing in the prompt photon production, their results have a satisfied agreement with the Super Proton Synchrotron(SPS) WA98 experimental data in the region of 2.0 GeV $< P_T <$ 4.0 GeV. It means that in the higher collision energies such as the case at RHIC and LHC one can not ignore the effect of the isospin and shadowing in the parton model.

In Figs. 2 and 3, the contribution of prompt gluon-photons is shown by comparing with the prompt direct photons and prompt fragmentation photons. The prompt gluon-photon spectrum is higher than that of the prompt direct production in the region of $P_T <$ 1.5 GeV (RHIC) and $P_T <$ 7 GeV(LHC). Especially, the prompt gluon-photon spectrum is higher than that of the prompt fragmentation photon at LHC in the region of $P_T <$ 2 GeV. Although the low P_T region is dominated by the thermal photons, one can not neglect the modification of prompt gluon-photons. Fig. 3 shows that in Pb-Pb collisions at $\sqrt{s} =$ 5.5 TeV and $P_T =$ 1.0 GeV the contributions of gg→gγ and gg→γγ are almost 62% of the total photon spectrum. In the region of 1.1 $P_T <$ 2.0 GeV such contribution is almost 6.2%—0.3% of the total photon production at LHC. Therefore, the production of prompt gluon-photons is an important modification to prompt photons in the low P_T region.

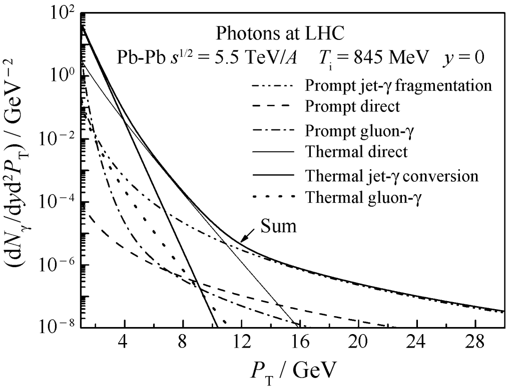

Fig. 3 The production of prompt and thermal photons at LHC energy.

3 Thermal Photon Production in the Quark-gluon Plasma

The thermal photons also can be defined into three categories: thermal direct photons, thermal jet-photons and thermal gluon-photons. After the QGP formation time τ_i the thermal emission rate of direct photons can be written in the form[8]

$$\frac{\mathrm{d}N_\gamma^{\text{th-direct}}}{\mathrm{d}y\mathrm{d}^2P_T} = \int_{\tau_i}^{\tau_h} \mathrm{d}\tau \int_0^{V(\tau)} \mathrm{d}V f_F(T) T^2 M_q(T), \quad (6)$$

where τ_h represents the hadronic time when the mixed phase transfers into the hadronic phase. The bulk correlates with time as $V(\tau) = \pi R_{QGP}^2 \tau$, and the Compton integral factor is

$$M_q^{\text{Com.}}(T) = \frac{5}{9}\,\frac{4\alpha\alpha_s}{96(2\pi)^2}\left[\ln\left(\frac{6P_T}{\pi\alpha_s T}\right) + C_{\text{Com.}}\right], \quad (7)$$

the one of annihilation is

$$M_q^{\text{ann.}}(T) = \frac{5}{9}\,\frac{4\alpha\alpha_s}{18(2\pi)^2}\left[\ln\left(\frac{6P_T}{\pi\alpha_s T}\right) + C_{\text{ann.}}\right], \quad (8)$$

where the parameter $C_{\text{Com.}} = -0.42$ and $C_{\text{ann.}} = -1.92$. Here α is the electromagnetic coupling constant and $f_F(T)$ is the Fermi-Dirac distribution. Similarly, the cross section of the gluon-photons can be written in the form

$$\frac{\mathrm{d}N_\gamma^{\text{th-gluon}}}{\mathrm{d}y\mathrm{d}^2P_T} = \int_{\tau_i}^{\tau_h} \mathrm{d}\tau \int_0^{V(\tau)} \mathrm{d}V f_B(T) T^2 M_g(T), \quad (9)$$

where $f_B(T)$ is the Bose-Einstein distribution for gluons, and the integral factors of gluon-photons are

$$M_g^{gg\to\gamma\gamma}(T) = \frac{25}{81}\,\frac{4\alpha^2\alpha_s^2}{192(2\pi)^3}\left[\ln\left(\frac{6P_T}{\pi\alpha_s T}\right) + C_g\right], \quad (10)$$

and

$$M_g^{gg\to g\gamma}(T) = \frac{5}{12}\,\frac{4\alpha\alpha_s^3}{192(2\pi)^3}\left[\ln\left(\frac{6P_T}{\pi\alpha_s T}\right) + C_g\right], \quad (11)$$

here the parameter C_g is given by the following

$$C_g = 29.76 - C_{\text{Euler}} - \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{\ln n}{n^2} = 28.61, \quad (12)$$

where the parameter 29.76 comes from the integral of the mean cross section of gg→γγ and gg→gγ in the following

$$\sigma(\mathrm{gg}\rightarrow\gamma\gamma)=2\int\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}(\mathrm{gg}\rightarrow\gamma\gamma)\times$$
$$\delta\left(P_\gamma-\frac{\sqrt{\hat{s}}}{2}\right)P_\gamma\mathrm{d}P_\gamma\mathrm{d}\cos\theta,$$

and

$$\sigma(\mathrm{gg}\rightarrow\gamma\gamma)=2\int\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}(\mathrm{gg}\rightarrow\mathrm{g}\gamma)\times$$
$$\delta\left(P_\gamma-\frac{\sqrt{\hat{s}}}{2}\right)P_\gamma\mathrm{d}P_\gamma\mathrm{d}\cos\theta, \qquad (13)$$

where the scattering angle θ correlates to the rapidity, and the Mandelstam variables correlate with θ in the form $\hat{u}=-(\hat{s}/2)(1+\cos\theta)$, $\hat{t}=-(\hat{s}/2)(1-\cos\theta)$. The differential cross section $\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}(\mathrm{gg}\rightarrow\gamma\gamma)$ and $\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}(\mathrm{gg}\rightarrow\mathrm{g}\gamma)$ come from Ref. [24]. After the integral, the mean cross sections of gluon-photons can be written in the form

$$\sigma(\mathrm{gg}\rightarrow\gamma\gamma)=\frac{25}{81}\frac{\alpha^2\alpha_\mathrm{s}^2}{16\hat{s}}\left[\ln\left(\frac{\hat{s}}{k_\mathrm{g}^2}\right)+29.76\right], \qquad (14)$$

and

$$\sigma(\mathrm{gg}\rightarrow\mathrm{g}\gamma)=\frac{5}{12}\frac{\alpha\alpha_\mathrm{s}^3}{16\hat{s}}\left[\ln\left(\frac{\hat{s}}{k_\mathrm{g}^2}\right)+29.76\right]. \qquad (15)$$

In the integral, k_g is the infrared cutoff for the integral divergence [8].

At RHIC energy, we assume the initial temperature $T_\mathrm{i}=370$ MeV and the formation time $\tau_\mathrm{i}\approx0.2$ fm/c. We take the radius of the QGP as $R_\mathrm{QGP}\approx4$—8 fm(RHIC) and $R_\mathrm{QGP}\approx6$—11 fm(LHC) in the bulk integral of the quark-gluon matter[17]. From Fig. 2 one can see that thermal direct photons dominate in the region of $P_\mathrm{T}<3.7$ GeV at RHIC energy[21, 22]. The results of the thermal photon spectrum are comsistent with the data at the initial temperature of 200 MeV $<T_\mathrm{i}<400$ MeV. The result for the larger energy case $T_\mathrm{i}=845$ MeV[17] of LHC is shown in Fig. 3, the thermal direct spectrum dominates in the region of $P_\mathrm{T}<11$ GeV. The thermal gluon-photons make a faint contribution to total thermal photons in the QGP.

4 Jet-photon Conversion in Quark-gluon Plasma

For the fragmentation photons, one can estimate the jet-photon fragmentation by introducing a photon fragmentation function into the Parton+Parton→Parton+Parton processes, and the photon fragmentation function is estimated from the Born approximation of the photon bremsstrahlung. The QED bremsstrahlung $\mathrm{q}\rightarrow\mathrm{q}\gamma$ processes play an essential role in the jet-photon fragmentation. However, because of the jet quenching effect, the jet process in the hot quark-gluon medium is extremely suppressed. The QED bremsstrahlung processes is also suppressed in the quark-gluon medium by the QCD bremsstrahlung processes $\mathrm{q}\rightarrow\mathrm{qg}$, and then a jet quark can not smash into a photon directly. We define that the jet-photon conversion satisfies to the secondary processes of Compton ($\mathrm{q}'\mathrm{g}\rightarrow\mathrm{q}'\gamma$) and annihilation ($\mathrm{q}'\bar{\mathrm{q}}'\rightarrow\mathrm{g}\gamma$) in the medium with the jet-conversion coefficients $\xi(P_\mathrm{T})_{\text{jet-Com.}}$ and $\xi(P_\mathrm{T})_{\text{jet-ann.}}$, where $\mathrm{q}'/\bar{\mathrm{q}}'$ represents the final state of the hard scattering $\mathrm{q}'\mathrm{q}'\rightarrow\mathrm{q}'\mathrm{q}'$ or $\mathrm{q}'\bar{\mathrm{q}}'\rightarrow\mathrm{q}'\bar{\mathrm{q}}'$ in the quark-gluon medium.

The expressions of the production rate of jet-photons in the quark-gluon medium are

$$\frac{\mathrm{d}N_\gamma^{\text{jet-Com.}}}{\mathrm{d}y\mathrm{d}^2P_\mathrm{T}}=\xi(P_\mathrm{T})_{\text{jet-Com.}}\frac{\mathrm{d}N_\gamma^{\text{th-Com.}}}{\mathrm{d}y\mathrm{d}^2P_\mathrm{T}}, \qquad (16)$$

and

$$\frac{\mathrm{d}N_\gamma^{\text{jet-ann.}}}{\mathrm{d}y\mathrm{d}^2P_\mathrm{T}}=\xi(P_\mathrm{T})_{\text{jet-ann.}}\frac{\mathrm{d}N_\gamma^{\text{jet-ann.}}}{\mathrm{d}y\mathrm{d}^2P_\mathrm{T}}, \qquad (17)$$

where the jet-conversion coefficients of the Compton and annihilation processes are given by the following

$$\xi(P_\mathrm{T})_{\text{jet-Com.}}=P_\mathrm{T}^2\frac{\mathrm{d}N_\text{jet}^{\mathrm{qq}/\mathrm{q}\bar{\mathrm{q}}\rightarrow\mathrm{qq}/\mathrm{q}\bar{\mathrm{q}}}}{\mathrm{d}y\mathrm{d}^2P_\mathrm{T}}, \qquad (18)$$

and

$$\xi(P_\mathrm{T})_{\text{jet-ann.}}=\xi(P_\mathrm{T})_{\text{jet-Com.}}^2. \qquad (19)$$

The production rate of the jet quark can be written in the form

$$\frac{\mathrm{d}N_\text{jet}^{\mathrm{qq}/\mathrm{q}\bar{\mathrm{q}}\rightarrow\mathrm{qq}/\mathrm{q}\bar{\mathrm{q}}}}{\mathrm{d}y\mathrm{d}^2P_\mathrm{T}}=\frac{1}{P_\mathrm{T}^2}\int_{\tau_\mathrm{i}}^{\tau_\mathrm{h}}\mathrm{d}\tau\int_0^{V(\tau)}\mathrm{d}VE_\mathrm{q}^2\times$$
$$f_\mathrm{F}(T)T^2M_\text{jet}(T), \qquad (20)$$

where the integral factor is

$$M_\text{jet}(T)=\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n^2}\frac{16\pi\alpha_\mathrm{s}^2}{9(2\pi)^5}\times$$

$$\left[\ln\left(\frac{6P_{\mathrm{T}}}{\pi\alpha_{\mathrm{s}}T}\right)^{1/2}-C_{\mathrm{qq}}\right], \qquad (21)$$

here the parameter C_{qq} is given by the following

$$C_{\mathrm{qq}}=0.773+\ln\frac{1}{2}-\frac{C_{\mathrm{Euler}}}{2}+\frac{\sum_{n=1}^{\infty}\frac{(-1)^{n+2}}{n^2}\ln n}{\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n^2}}=-0.085\ , \qquad (22)$$

and the parameter 0.773 comes from the integral of the mean cross section $\sigma(\mathrm{qq}\rightarrow\mathrm{qq})$ or $\sigma(\mathrm{q\bar{q}}\rightarrow\mathrm{q\bar{q}})$ by using the same procedure in Eq. (13). The differential cross section of the jet quark/antiquark scattering comes from Ref. [24], the final results of the mean cross section of the jet quark scattering can be written in the following

$$\sigma(\mathrm{qq/q\bar{q}}\rightarrow\mathrm{qq/q\bar{q}})=\frac{2}{9}\frac{\pi\alpha_{\mathrm{s}}^2}{\hat{s}^2}\left[\frac{1}{2}\ln\frac{\hat{s}}{m_{\mathrm{q}}^2}+0.773\right]\ , \qquad (23)$$

Numerical results of the thermal jet-photon conversion are also shown in Figs. 2 and 3 at the RHIC and LHC energy. The jet-conversion coefficients depend on the system temperature sensitively, the thermal jet-photon spectrum can vary extremely at the different collision temperature. At the RHIC temperature, the jet-conversion coefficients $\xi(P_{\mathrm{T}})_{\mathrm{jet}}<1$, the thermal jet-photon spectrum gives an important modification to the QGP thermal spectrum. The thermal jet-photons enhance the total thermal spectrum in the region of $P_{\mathrm{T}}<2$ GeV. The thermal jet-photons are even brighter than the traditional thermal direct photons in low P_{T} region when the jet-conversion coefficients $\xi(P_{\mathrm{T}})_{\mathrm{jet}}>1$ ot higher temperature such as the LHC energy $T_{\mathrm{i}}=845$ MeV. In the LHC case the thermal jet-photon conversion plays a vital role in the thermal photon spectrum at the novel shining window of 1 GeV$<P_{\mathrm{T}}<$4 GeV which could be a good expectation for the LHC experimental data.

5 Conclusion

A jet-photon conversion mechanism for thermal photons is developed. We obtain the satisfied agreement between theory results and the RHIC PHENIX data. The jet-photons represent an important contribution to QGP thermal photons based on the secondary Compton and annihilation processes. Especially, at LHC energy the jet-conversion coefficients rise rapidly for the higher temperature, and then the jet-photons become a novel shining source in the interesting window of 1 GeV $<P_{\mathrm{T}}<4$ GeV which could be a good expectation for the LHC experimental data.

The prompt gluon-photons which include the effect of the shadowing and isospin are also considered. In the Pb-Pb collisions the modification of prompt gluon-photons is almost 62% of the total photon spectrum. In the region of 1.1 GeV$<P_{\mathrm{T}}<$ 2.0 GeV the contribution of prompt gluon-photons is almost 6.2%—0.3% of the total photon production at LHC.

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夸克-胶子等离子体中的喷注-光子转换机制[*]

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摘　要：提出了一种夸克-胶子等离子体中的喷注-光子转换机制。对于热光子而言，在热夸克-胶子媒介中的喷注-光子转换是一个非常重要的热光子来源。喷注可以通过次级康普顿散射和湮灭过程来实现喷注-光子转换。此外，还考虑了在快光子产生过程中起重要修正作用的胶子-光子贡献，其中，核遮蔽效应和同位旋效应也被引入到了部分子模型中。

关 键 词：夸克-胶子等离子体；喷注-光子转换；光子产生

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[*] **收稿日期**：2009－03－26；**修改日期**：2009－05－27

[*] **基金项目**：国家自然科学基金资助项目(10665003)

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