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Soft Dilepton Production in Au-Au Collisions by Two-photon Processes

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Abstract: The production of the low transverse momentum (P_T) dileptons induced by semi-coherent two-photon interaction is calculated. The numerical results are compared with the experimental data from the PHENIX, the modification of the semi-coherent two-photon interaction is remarkable in the low transverse momentum region for different mass bins. We find that the contribution of semi-coherent two-photon processes is more evident in the large dilepton mass region.

Key words: two-photon interaction; relativistic heavy ion collision; dilepton production

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1 Introduction

The observation of the quark-gluon plasma (QGP) is the main goal in the study of the relativistic heavy ion collisions. Because the mean free path of photons (and virtual photons) is larger than the size of the QGP, the photons and dileptons emitted from the QGP can escape from dense medium without strong interactions[1−11]. The contribution of thermal dileptons in the low mass region is covered by the cocktail of hadron decays because the vector meson peaks are more pronounced than the thermal spectrum. The thermal information is dominant in the intermediate mass region between the ϕ and J/ψ vector meson for the phase transition theory, but the contribution of dileptons in this region also can be explained by the decays of charmed mesons. The NA60 collaboration has observed an enhancement in intermediate mass region. The data suggests that such an enhancement may include a thermal information and not just charm decays[12]. However, so far no evident experiments show that some information are exactly produced from the thermalized medium[13−23].

Besides, some experimental data at Relativistic Heavy Ion Collider (RHIC) remain puzzling. The experimental dilepton data show that the production rate of low mass dileptons is few times of the theory predictions. The scenario of the mass dropping in a hot medium successfully interprets the dilepton yield enhancement in the low mass region at Super Proton Synchrotron (SPS) energies for 158 *A*GeV Pb-Au collisions[24−30]. The ρ meson strongly couples to the $\pi^+\pi^-$ channel, and the lifetime of the ρ meson is short compared with the ω and ϕ meson. The ρ meson spectrum may be modified in hot medium due to the chiral symmetry restoration. The measurement of the dilepton continuum at RHIC energies has been performed by the PHENIX experiments for 200 *A*GeV Au-Au collisions[31−32]. The dilepton yield in the low mass range between 0.2～0.8 GeV is enhanced by a fac-

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tor of 2 ~ 3 compared with the expectation from hadron decays. However, such a modified scenario can not completely explain the enhancement in the Au-Au collisions at RHIC.

Except the above problems, another puzzle was presented by PHENIX experiments[33]. The P_T data of dileptons in pp collisions for different mass bins agree with the expectation of the cocktail, charm decays and direct dilepton contributions. The agreement also exists in the Au-Au collisions at high P_T (P_T>1 GeV). In the soft region of P_T< 1 GeV, pQCD is useless, the experimental data from the Au-Au collisions are still higher than the expectation of the cocktail and charm decays. If fitted with exponential in this soft window, the data have a slope T_{eff} ~ 100 MeV, which is smaller than the typical slope of the standard thermal component. Another candidate in the soft window is the new cold component which is still valid in the low P_T region. In Ref. [34] Shuryak et al. suggest a new cold dilepton production mechanism (semi-coherent two-photon interaction) which is not discussed in the standard theory list before.

In the present work, we discuss the soft dileptons produced by the semi-coherent two-photon processes ($\gamma\gamma \to l^+l^-$) at small impact parameters. We find that the contribution of the soft dileptons can partly explain the PHENIX data in the region of P_T<1 GeV. The two-photon processes are the well-known source of small mass and low P_T dileptons. Shuryak et al. use the equivalent photon approximation to determine the differential cross section of the $\gamma\gamma$ processes in Au-Au collisions, and they conclude that the semi-coherent two-photon processes of dilepton production do not contribute significantly to the PHENIX data[34]. We investigate the dilepton production for $\gamma\gamma$ processes with the restriction $b < R_T$, and we find that the dilepton production of the semi-coherent two-photon interaction has a positive contribution to the cocktail and charm decays in the soft region. In the next section we focus on the semi-coherent two-photon processes. The thermal dilepton production is also mentioned in this section. The numerical results are plotted in third section. The conclusion is given in fourth section.

2 General formalism

The equivalent photon spectrum corresponding to a point charge Ze, moving with a velocity v is given by

$$n(\omega) = Z^2 \frac{2\alpha}{\pi v^2}\left[\xi K_0 K_1 - \frac{v^2\xi^2}{2}(K_1^2 - K_0^2)\right] , \quad (1)$$

where the argument of the modified Bessel functions is $\xi = (\omega R_{\min})/(\gamma v)$, and $R_{\min}$ corresponds to the radius of the radiation system with the maximum energy of the photons. The cross section of the semi-coherent two-photon interaction for Au-Au collisions is given by

$$d\sigma = \sigma_{\gamma\gamma} dn(\omega_1) dn(\omega_2) , \quad (2)$$

where

$$dn(\omega) = \frac{d^3 q}{q_T^2 \omega} n(\omega) , \quad (3)$$

and the mean cross section of $\gamma\gamma \to l^+l^-$ interaction is[35]

$$\sigma_{\gamma\gamma} = \frac{4\pi\alpha^2}{M^2}\hat{\beta}_L\left[\frac{3-\hat{\beta}_L^4}{2\hat{\beta}_L}\ln\frac{1+\hat{\beta}_L}{1-\hat{\beta}_L} - (2-\hat{\beta}_L^2)\right] , \quad (4)$$

here the parameter

$$\hat{\beta}_L = \left(1 - \frac{4m_l^2}{M^2}\right)^{1/2} , \quad (5)$$

where m_l is the lepton mass. In the semi-coherent case [$q_1 = (\omega_1, q_{1T}, q_{1z})$ and $q_2 = (\omega_2, \vec{0}, -q_{2z})$], a photon with a large transverse momentum (q_{1T}) is radiated from a proton of a incident nucleus, and a photon with a small transverse momentum (q_{2T}) is radiated from another incident nucleus in the relativistic heavy ion collisions. If $q_{1T} >> q_{2T}$, the total transverse momentum of the dilepton is $P_T = q_{1T} + q_{2T} \sim q_{1T}$, where q_{iT} is the transverse momentum of a photon. In the MacDonald approximation[36-37] the cross section as a function of the transverse momentum and invariant mass can be written as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 P_{\mathrm{T}}\mathrm{d}M\mathrm{d}y} = 2\pi Z^3 \left(\frac{2\alpha}{\pi}\right)^2 \ln \frac{\gamma}{P_{\mathrm{T}} R_{\min}} \times \frac{\sigma_{\gamma\gamma}}{P_{\mathrm{T}}^3}\int_{q_{2\mathrm{T}\min}}^{\gamma/R_{\min}} \ln \frac{\gamma}{q_{2\mathrm{T}} R_{\min}} \frac{1}{q_{2\mathrm{T}}} \mathrm{d}q_{2\mathrm{T}}, \quad (6)$$

where the minimum transverse momentum of the photon q_2 is $q_{2\mathrm{T}\min} \sim 0.2$ GeV due to the single track acceptance condition[34], and $R_{\min} \sim 7$ fm and $\gamma = 106$ for 200 AGeV Au-Au collisions at RHIC. In this article we use the natural units, namely $h = c = 1$. In the above integral we have

$$\omega_1 + \omega_2 = M_{\mathrm{T}} \cosh y , \quad (7)$$

and

$$q_{1z} + q_{2z} = M_{\mathrm{T}} \sinh y , \quad (8)$$

where $\omega_1 = (P_{\mathrm{T}}^2 + q_{1z}^2)^{1/2}$, $\omega_2 = q_{2z}$, here $M_{\mathrm{T}}^2 = M^2 + P_{\mathrm{T}}^2$.

In the QGP phase the leading order production of thermal dileptons is $q\bar{q} \rightarrow \gamma^* \rightarrow l^+ l^-$. The yield of the thermal dileptons (th. $l^+ l^-$) with low dilepton mass and large transverse momentum can be written as[1, 38]

$$\frac{\mathrm{d}N_{\mathrm{th.}\, l^+ l^-}}{\mathrm{d}^2 P_{\mathrm{T}}\mathrm{d}M\mathrm{d}y} = R_{\mathrm{A}}^2 \frac{\sigma_{q\bar{q}}(M)}{2(2\pi)^4} M^3 \times \sqrt{1-\frac{4M_{\mathrm{q}}^2}{M^2}} \frac{3\tau_0^2 T_0^6}{P_{\mathrm{T}}^6} \left[G\left(\frac{P_{\mathrm{T}}}{T_0}\right) - G\left(\frac{P_{\mathrm{T}}}{T_{\mathrm{c}}}\right)\right], \quad (9)$$

where R_{A} is the nuclear radius, m_{q} is the quark mass. τ_0 and T_0 are the initial time and the initial temperature of the system, respectively. We use $\tau_0 = 0.26$ fm/c for RHIC. The initial temperature of the QGP is chosen as $T_0 = 370$ MeV for Au-Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. T_{c} (= 160 MeV) is the critical temperature of the phase transition[11]. Here $\sigma_{q\bar{q}} = (4\pi\alpha^2 N_{\mathrm{c}} N_{\mathrm{s}}^2 e_{\mathrm{q}}^2)/3M^2$ is the cross section of the process $q\bar{q} \rightarrow \gamma^* \rightarrow l^+ l^-$, N_{c} (= 3) is the color number, N_{s} (= 2) is the spin number. The function $G(z)$ is given by $G(z) = z^3(8+z^2)K_3(z)$.

In order to compare with the data from PHENIX, the yield for producing dileptons in a mass range between M_1 and M_2 is given by

$$\frac{\mathrm{d}N}{\mathrm{d}^2 P_{\mathrm{T}}\mathrm{d}y} = \int_{M_1}^{M_2} \frac{\mathrm{d}N}{\mathrm{d}^2 P_{\mathrm{T}}\mathrm{d}M\mathrm{d}y} \mathrm{d}M , \quad (10)$$

the relation between the differential cross section $\mathrm{d}\sigma/(\mathrm{d}^2 p_{\mathrm{T}}\mathrm{d}M\mathrm{d}y)$ and the yield is[34]

$$\frac{\mathrm{d}N}{\mathrm{d}^2 P_{\mathrm{T}}\mathrm{d}M\mathrm{d}y} = \frac{1}{\sigma_{\mathrm{tot}}} \frac{\mathrm{d}\sigma}{\mathrm{d}^2 P_{\mathrm{T}}\mathrm{d}M\mathrm{d}y} , \quad (11)$$

where σ_{tot} is the total cross section of the collisions. The authors in Ref. [34] use $\sigma_{\mathrm{tot}} \sim 1.4 \times 10^4$ GeV^{-2} for the 200 AGeV Au-Au collisions at RHIC.

3 Numerical results

From Fig. 1 one can see that in the soft region of $P_{\mathrm{T}} < 1$ GeV the experimental dilepton data for different mass bins are still higher than the expectation of the cocktail and charm decays[33]. The spectra of direct dileptons have been calculated in our previous works[38]. Shuryak et al. have discussed the semi-coherent two-photon processes in the soft region by using the charge distribution form factors[34]. In the semi-coherent approach, the soft photons see the nucleus as a uniform charge distribution (with the Woods-Saxon shape), the hard photons see the nucleus as the dispersedly individual protons (the point charge distribution). In the small momentum region the Woods-Saxon form factor is $|F_{\mathrm{soft}\,\gamma}|^2 \sim 1$, but as the momentum is increasing the form factor goes to zero ($|F_{\mathrm{soft}\,\gamma}|^2 \rightarrow 0$). Therefore the Woods-Saxon form factor depresses the value of the soft spectra of dileptons for the semi-coherent two-photon processes when the momentum is increasing. In this article we consider that the form factor of the soft photons is only localized in the small momentum region, which means that the soft photons only act coherently, and we find that the contribution of the semi-coherent two-photon interaction is remarkable. The contribution of the semi-coherent two-photon processes is only valid in the low P_{T} region due to the radiation limit condition $q_{2\mathrm{T}} < \gamma/R_{\min}$ of the MacDonald approximation. The restriction also implies that the spectra of the two-photon interaction depend on the radiation energies of the nucleus. In Ref. [34] the authors choose the radiation limit as $q \leqslant 1/R$ by considering the Heisenberg's uncertainty principle.

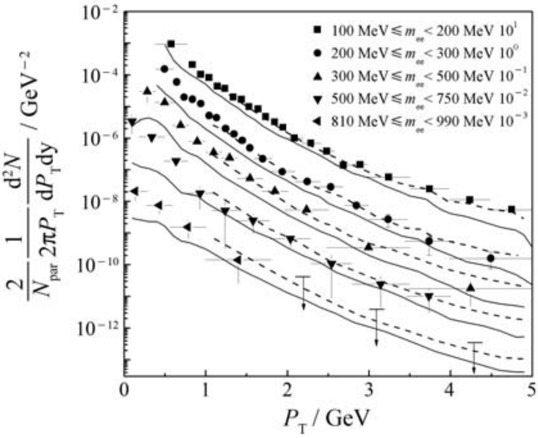

Fig. 1 The dilepton production for different mass bins. The solid line is the sum of cocktail and charm decays, the dash line is the sum of cocktail, charm decays, and the contribution of direct dileptons (data from Ref. [33]).

At low mass, $m_{ee} < 200$ MeV, the contribution of cocktail and charm decays agrees with the PHENIX data. However, in the soft region ($P_T <$ 1 GeV) the data are still higher than the expectation of cocktail and charm decays at $m_{ee} > 200$ MeV. The yield enhancement is more evident withincreasing dilepton invariant mass. In order to avoid the influence of e^+e^- decays of narrow vector mesons, the mass regions around the ω meson [(0.78 ± 0.03) GeV] and ϕ meson [(0.102 ± 0.030) GeV] are excluded by PHENIX experiments.

In Fig. 2 we plot the calculation result of semi-coherent $\gamma\gamma \to e^+e^-$ interactions [Eq. (6)] with the transverse momentum for different mass bins. Like the above discussion the yield enhancement is not evident in the mass range of 100 MeV $\leqslant m_{ee} <$ 200 MeV, so the modification of the cold component (semi-coherent two-photon interaction) is weak. In the mass range of 200 MeV $\leqslant m_{ee} <$ 300 MeV, 300 MeV $\leqslant m_{ee} <$ 500 MeV, 500 MeV $\leqslant m_{ee} <$ 750 MeV and 810 MeV $\leqslant m_{ee} <$ 990 MeV the data are almost one order higher than the expectation of cocktail and charm decays, and the modification of the γγ reaction is remarkable now. Therefore the semi-coherent two-photon interaction plays an important role in the soft P_T dilepton production. The contribution of the thermal dileptons [Eq. (9)] is also plotted in Fig. 2. If the system temperature of the QGP created in the Au-Au collisions at RHIC is $T_0 = 370$ MeV, the numerical results show that the thermal yield is increasing with the rising invariant mass. However, the modification of thermal component is weak.

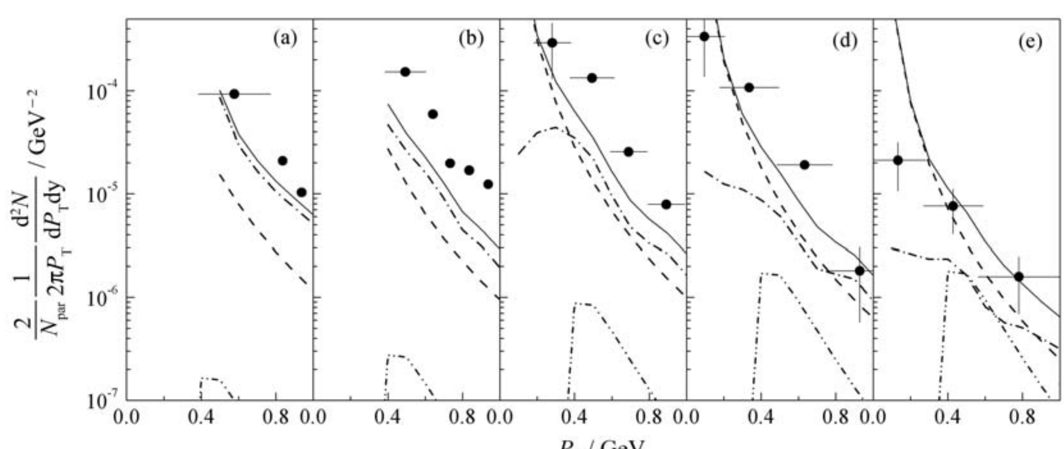

Fig. 2 The dilepton spectra of semi-coherent two-photon processes in different mass bins. The dilepton transverse momentum is in the soft region $P_T <$ 1 GeV. The dash-dot line is the contribution of the cocktail and charm decays, the dash line is the semi-coherent two-photon processes, the dash-dot-dot line is the thermal contribution, the solid line is the total contribution.

(a) 100 MeV $\leqslant m_{ee} <$ 200 MeV, (b) 200 MeV $\leqslant m_{ee} <$ 300 MeV, (c) 300 MeV $\leqslant m_{ee} <$ 500 MeV, (d) 500 MeV $\leqslant m_{ee} <$ 750 MeV, (e) 810 MeV $\leqslant m_{ee} <$ 990 MeV.

4 Conclusion

We investigated the semi-coherent two-photon processes from the passage of $\gamma\gamma \rightarrow e^+ e^-$. The dileptons with the soft transverse momentum can be produced in the semi-coherent two-photon interaction. The energy of the radiated photon is limited in the region of $\omega < \gamma/R_{\rm min}$, therefore the cold dilepton component of semi-coherent two-photon processes is still valid in the soft $P_{\rm T}$ region. The $\gamma\gamma$ process is an important complement to the standard cold dilepton production. The numerical results show that the modification of semi-coherent two-photon processes is evident with rising dilepton mass, especially in the mass range of 300 MeV $\leqslant m_{\rm ee} <$ 500 MeV, 500 MeV $\leqslant m_{\rm ee} <$ 750 MeV and 810 MeV $\leqslant m_{\rm ee} <$ 990 MeV. We also consider the thermal contribution to the dilepton production, but the modification of the thermal component is weak.

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金-金碰撞中由双光子过程产生的软双轻子

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摘要：计算了由准相干双光子相互作用导致的低横动量双轻子产生。对于不同的质量范围，准相干双光子相互作用在低横动量区域都很重要。将计算结果与相对论重离子对撞机 RHIC 的 PHENIX 实验数据进行比较，发现随着双轻子不变质量的增加，准相干双光子过程的修正作用会更加明显。

关键词：双光子相互作用；相对论重离子碰撞；双轻子产生

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