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Photoproduction of Light Vector Meson in Heavy Ion Collisions

YU Gongming, LI Yunde

(*Department of Physics, Yunnan University, Kunming 650091, China*)

Abstract: We calculate the photoproduction processes of light vector meson(ρ, ω and ϕ) in heavy ion collisions. Based on the narrow-width approximation, we rigorously derive the exclusive and inclusive cross sections of ρ, ω and ϕ produced by the semielastic and inelastic photoproduction processes in relativistic heavy ion collisions. The numerical results indicate that contribution of photoproduction processes of light vector meson is not prominent for p-p collisions, but the contribution becomes evident for $p_{\rm T} > 2.5$ GeV in Au-Au collisions and $p_{\rm T} > 3$ GeV in Pb-Pb collisions.

Key words: photoproduction process; light vector meson; relativistic heavy ion collision

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1 Introduction

Recently, the ALICE collaboration[1–3] has performed the data of light vector meson(ρ, ω and ϕ) for $2.5 < y < 4.0$ in p-p collisions with $\sqrt{s} = 7.0$ TeV and $y = 0$ in Pb-Pb collisions with $\sqrt{s} = 2.76$ TeV. The differential cross section of ρ, ω and ϕ production was measured. Furthermore, ϕ production was also measured by the STAR collaboration[4] in Au-Au collisions with $\sqrt{s} = 200$ GeV. Moreover, the results indicated that the ϕ mesons are not produced predominantly by kaon coalescence. The light vector meson can be produced from various processes in relativistic nucleus-nucleus collisions: The purely diffractive mechanism[5–11] that a real or virtual photon fluctuates into a vector meson through the exchange of the pomeron; the double diffractive process(BFKL effects)[12–14] $\gamma^*\gamma^* \to$VV, through the scattering of two virtual photons; the recombination of thermal partons[15]; dynamical quark coalescence based on multiphase transport model[16]; the underlying-event model in PYTHIA 6.4[17].

In the present work, we extend the vector-dominance two-photon exchange model[18] that has been used to calculate $e^+e^- \to \gamma^*\gamma^* \to$VV exclusive differential cross section with each virtual photon converting to a light vector meson in e^+e^- annihilation to the Drell-Yan type process $q\bar{q} \to \gamma^*\gamma^* \to$VV in relativistic nucleus-nucleus collisions. However, we also consider the photoproduction mechanism[19–24] which appears to be the dominant mechanism for light vector meson production in relativistic heavy-ion collisions. In the semielastic photoproduction processes, the low energy quasireal photon emitted from the incident nucleus interacts with the parton of another incident nucleus by the interaction of $q\gamma \to q$V and γ-g fusion. In the inelastic photoproduction processes, the charged parton of the incident nucleus can emit a high energy photon that can interact with the parton of another incident nucleus by the interaction of $q\gamma \to q$V and γ-g fusion. Through perturbative quantum chromodynamics (pQCD) calculation, we determine the in-

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Biography: Yu Gongming(1985–), male(Bouyei Nationality), Kunming, Yunnan, China, PHD student, working on the field of Quark-Gluon plasma; E-mail: ygmanan@163.com
Corresponding author: LI Yunde, E-mail: yndxlyd@163.com.

clusive differential cross section of semielastic photoproduction processes and inelastic photoproduction processes of light vector meson.

This paper is organized as follows. In Sec. 2, we present the production for Drell-Yan type process and photoproduction processes of light vector meson based on the vector-dominance two-photon exchange model in relativistic nucleus-nucleus collisions. Finally, the conclusion is given in Sec. 3.

2 General formalism

The light vector meson can be produced by Drell-Yan type initial parton annihilation $\mathrm{q\bar{q}} \to \gamma^*\gamma^* \to \mathrm{VV}$ with each virtual photon converting to a light vector meson based on the vector-dominance two-photon exchange model. The exclusive cross section for Drell-Yan type process of light vector meson production in relativistic nucleus-nucleus is given by

$$\frac{\mathrm{d}\sigma^{\mathrm{DY.exclusive}}_{\mathrm{AB\to VV}}}{\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y} = \int \mathrm{d}x_{\mathrm{a}} x_{\mathrm{a}} G^a_{\mathrm{A}}(x_{\mathrm{a}},Q^2) G^{\mathrm{b}}_{\mathrm{B}}(x_{\mathrm{b}},Q^2) \times \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\left(\mathrm{q\bar{q}} \to \gamma^*\gamma^* \to \mathrm{VV}\right), \quad (1)$$

where x_{a} and x_{b} is the parton's momentum fraction. $G^i_{\mathrm{A}}(x_i,Q^2)$ is the parton distribution function of the nucleus[25].

The cross section of subprocess $\mathrm{q\bar{q}} \to \gamma^*\gamma^* \to \mathrm{VV}$ in the narrow-width approximation[18] can be written as

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\left(\mathrm{q\bar{q}} \to \gamma^*\gamma^* \to \mathrm{VV}\right) = \frac{1}{3} f^{\mathrm{V}}_1 f^{\mathrm{V}}_2 \frac{\pi\alpha^2 e^4_{\mathrm{q}}}{\hat{s}} \frac{2|\boldsymbol{p}|}{\sqrt{\hat{s}}} \times \frac{2(m^2_1+m^2_2)\hat{s}\hat{u}\hat{t} + (\hat{t}^2+\hat{u}^2)(\hat{u}\hat{t}-m^2_1 m^2_2)}{\hat{u}^2\hat{t}^2}, \quad (2)$$

where m_i is the mass of light vector meson, $|\boldsymbol{p}|$ is the momenta of light vector meson, $\hat{s}$, $\hat{t}$ and $\hat{u}$ are the Mandelstam variables of subprocess. We choose the momentum scale as $Q^2 = 4p^2_{\mathrm{T}}$.

The effective coupling coefficient f^{V}_i for photon-to-V is given by[18]

$$f^{\mathrm{V}}_i = \frac{3\Gamma^{\mathrm{e^+e^-}}_{\mathrm{V}}}{\alpha m_i}, \quad (3)$$

where $\Gamma^{\mathrm{e^+e^-}}_{\mathrm{V}}$ is the electronic width of light vector meson, α is the electromagnetic coupling constant.

Furthermore, the inclusive cross section for light vector meson produced by the inclusive Drell-Yan type processes is given by

$$\frac{\mathrm{d}\sigma^{\mathrm{DY.inclusive}}_{\mathrm{AB\to VX}}}{\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y} = \int \mathrm{d}x_{\mathrm{a}} G^a_{\mathrm{A}}(x_{\mathrm{a}},Q^2) G^{\mathrm{a}}_{\mathrm{B}}(x_{\mathrm{b}},Q^2) \times \frac{x_{\mathrm{a}}x_{\mathrm{b}}}{x_{\mathrm{a}}-x_1} \cdot \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}(\mathrm{q\bar{q}} \to \mathrm{VX}), \quad (4)$$

where $\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}(\mathrm{q\bar{q}} \to \mathrm{VX})$ is the cross section of subprocesses($\mathrm{q\bar{q}} \to \mathrm{Vg}$, q-g Compton process and g-g fusion) based on narrow-width approximation[18].

In semielastic photoproduction process, the incident nucleus can emit a quasireal photon, then photon interacts with the parton of another incident nucleus by the interaction of $\mathrm{q}\gamma \to \mathrm{q}\gamma^*(\gamma^* \to \mathrm{V})$ and γ-g fusion. The invariant cross section of light vector meson produced by semielastic photoproduction processes can be written as

$$\frac{\mathrm{d}\sigma^{\mathrm{semi}}_{\mathrm{AB\to VX}}}{\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y} = 2\int \mathrm{d}x_{\mathrm{a}} f_{\gamma/\mathrm{N}}(x_{\mathrm{a}}) G^{\mathrm{b}}_{\mathrm{B}}(x_{\mathrm{b}},Q^2) \times \frac{x_{\mathrm{a}}x_{\mathrm{b}}}{x_{\mathrm{a}}-x_1} \cdot \frac{\mathrm{d}\hat{\sigma}(\mathrm{q}\gamma \to \mathrm{qV})}{\mathrm{d}\hat{t}}, \quad (5)$$

where x_{a} is the low energy photon's momentum fraction, x_{b} is the parton's momentum fraction. $f_{\gamma/\mathrm{N}}(x_{\mathrm{a}})$ is the equivalent photon spectrum function of nucleus.

For the p-p collisions, the low energy equivalent photon spectrum function of proton in the Weizsäcker-Williams approximation can be written as[26]

$$f_{\gamma/\mathrm{p}}(x) = \frac{\alpha\left[1+(1-x)^2\right]}{2\pi x} \times \left[\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right], \quad (6)$$

where x is the photon's momentum fraction, m_{p} is the mass of proton, $A = 1 + 0.71\ \mathrm{GeV}^2/Q^2_{\min}$ with

$$Q^2_{\min} = -2m^2_{\mathrm{p}} + \frac{1}{2s}[(s+m^2_{\mathrm{p}})(s-xs+m^2_{\mathrm{p}}) - (s-m^2_{\mathrm{p}})\sqrt{(s-xs-m^2_{\mathrm{p}})^2 - 4m^2_{\mathrm{p}}xs}, \quad (7)$$

at high energies $Q^2_{\min}$ is given to a very good approximation by $m^2_{\mathrm{p}}x^2/(1-x)$.

For the nucleus-nucleus collisions, The equivalent photon spectrum function for the nucleus can be obtained from a semiclassical description of high energy electromagnetic collisions. A relativistic nucleus with Z times the electric charge moving with a relativistic factor $\gamma \gg 1$ with respect to some observer develops an equally strong magnetic field component; hence, it resembles a beam of real photons, where the photon spectrum function of low photon energies can be written as[27−28],

$$f_{\gamma/\mathrm{N}}(\omega)=\frac{2Z^2\alpha}{\pi\omega}\ln(\frac{\gamma}{\omega R}) , \tag{8}$$

where ω is the energy of photon, $R = b_{\min}$ is the radius of nucleus ($b_{\min}$ is the cut-off of impact).

In the inelastic photoproduction processes, the parton of the incident nucleus can emit a high energy photon, then the high energy photon interacts with the parton of another incident nucleus by the interaction of $q\gamma \to q\gamma^*(\gamma^* \to V)$ and γ-g fusion. The invariant cross section of light vector meson produced by inelastic photoproduction processes is given by

$$\frac{\mathrm{d}\sigma^{\mathrm{inel}}_{\mathrm{AB}\to\mathrm{VX}}}{\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y}=2\int \mathrm{d}x_{\mathrm{a}}\mathrm{d}x_{\mathrm{b}}G^{\mathrm{a}}_{\mathrm{A}}(x_{\mathrm{a}},Q^2)G^{\mathrm{b}}_{\mathrm{B}}(x_{\mathrm{b}},Q^2)\times f_{\gamma/\mathrm{q}}(z_{\mathrm{a}})\frac{x_{\mathrm{a}}x_{\mathrm{b}}z_{\mathrm{a}}}{x_{\mathrm{a}}x_b-x_{\mathrm{a}}x_1}\cdot\frac{\mathrm{d}\hat{\sigma}(\mathrm{q}\gamma\to\mathrm{qV})}{\mathrm{d}\hat{t}} , \tag{9}$$

where x_{a} and x_{b} are the parton's momentum fraction, z_{a} is the photon's momentum fraction. $\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}$ is the invariant cross section of subprocesses $q\gamma \to q\gamma^*(\gamma^* \to V)$ and γ-g fusion based on narrow-width approximation[18].

The photon spectrum function from the quark in the Weizsäcker-Williams approximation can be written as[29]

$$f_{\gamma/\mathrm{q}}(x)=\frac{\alpha}{\pi}Q^2\left\{\frac{1+(1+x)^2}{x}\left(\ln\frac{E}{m}-\frac{1}{2}\right)+\frac{x}{2}\left[\ln\left(\frac{2}{x}-2\right)+1\right]+\frac{(2-x)^2}{2x}\ln\left(\frac{2-2x}{2-x}\right)\right\}, \tag{10}$$

where E, m and Q is the energy, mass and charge of ultrarelativistic fermion, respectively.

The numerical results of light vector meson(ρ, ω and ϕ) production for our calculation in relativistic nucleus-nucleus collisions are plotted in Fig. 1, Fig. 2 and Fig. 3. In comparison with the ALICE data[2−3], the STAR data[4], the results from the recombination model[15], the result fitting by Boltzmann-Gibbs Blast Wave functions[3] and the underlying-event model in PYTHIA 6.4[17], we find that the modification for ϕ meson production of the photoproduction process is evident for $p_{\mathrm{T}} > 2.5$ GeV in Au-Au collisions(Fig. 3(a)) and $p_{\mathrm{T}} > 3$ GeV in Pb-Pb collisions(Fig. 3(b)), but for p-p collisions with $\sqrt{s} = 7$ TeV is not prominent(Fig. 3(c)).

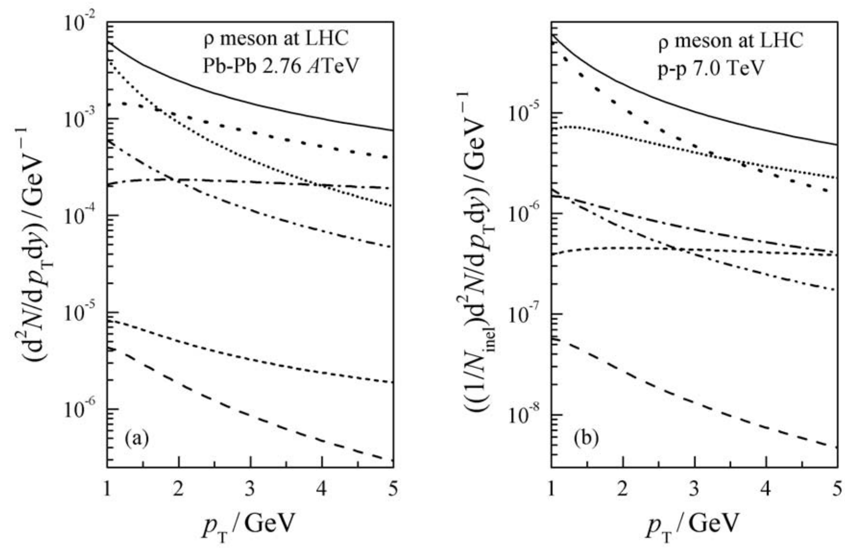

Fig. 1　The invariant yields of ρ meson production for $y=0$ in Pb-Pb collisions($\sqrt{s}=2.76$ TeV) and $2.5<y<4.0$ in p-p collisions($\sqrt{s}=7.0$ TeV)

The dash line is for the exclusive Drell-Yan type process($q\bar{q} \to VV$), the dot line for the inclusive Drell-Yan type process($q\bar{q} \to gV$), the dash-dot line for the q-g Compton process, the dash-dot-dot line for the g-g fusion processes, the short-dash line for the semielastic photoproduction processes, the short-dot line for the inelastic photoproduction processes, the solid line is the total of all above.

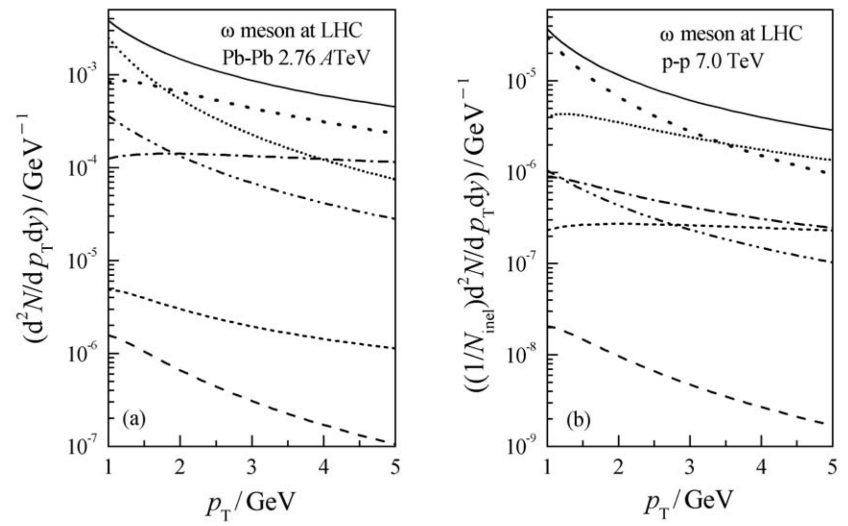

Fig. 2　The invariant yields of ω meson production for $y=0$ in Pb-Pb collisions($\sqrt{s}=2.76$ TeV) and $2.5<y<4.0$ in p-p collisions($\sqrt{s}=7.0$ TeV).

Same as Fig. 1.

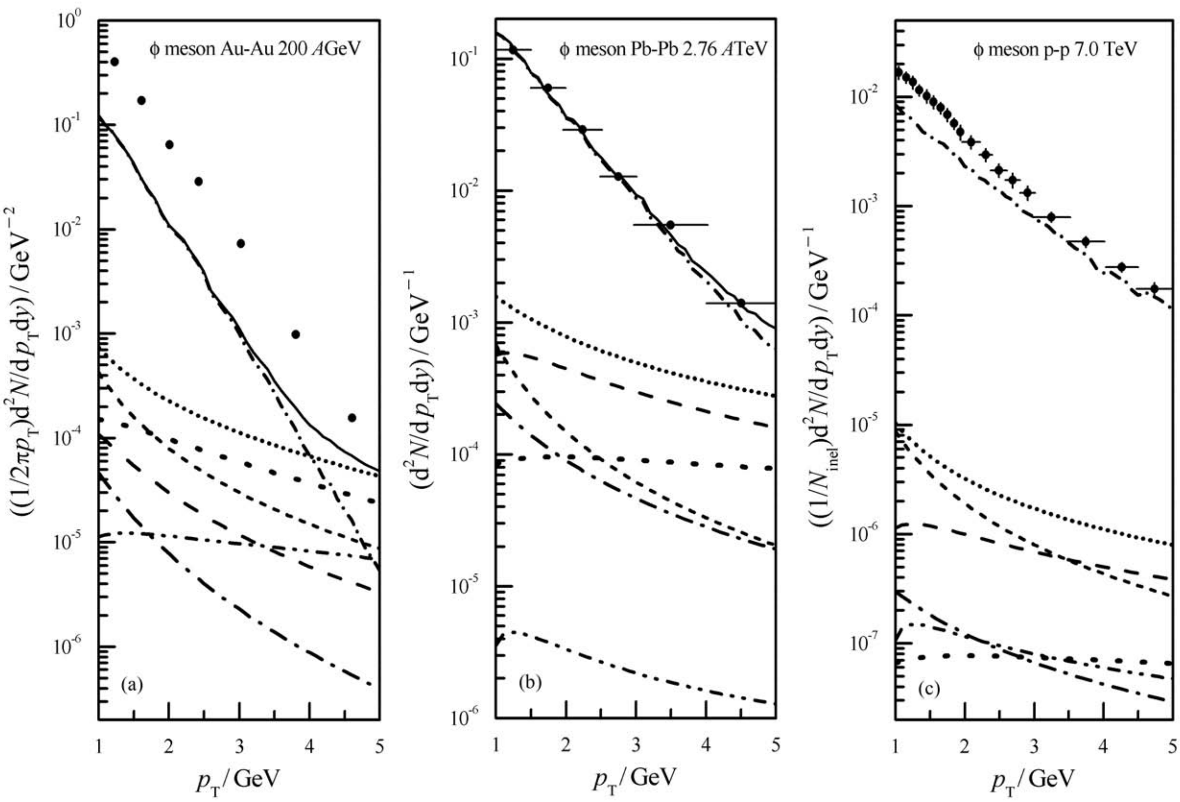

Fig. 3　The invariant yields of ϕ meson production for $y=0$ in AA collisions($\sqrt{s}=200$ GeV and $\sqrt{s}=2.76$ TeV) and $2.5<y<4.0$ in p-p collisions($\sqrt{s}=7.0$ TeV).

The data points are from STAR and ALICE, respectively. The dash line is for the inclusive Drell-Yan type process($q\bar{q}\rightarrow gV$), the dot line for the the q-g Compton process, dash-dot line for the g-g fusion processes, the dash-dot-dot line for the semielastic photoproduction processes, the short-dash line the inelastic photoproduction processes, the short-dot line for the sum of leading order(LO) and photoproduction processes, the short-dash-dot line are the results from the recombination model, Boltzmann-Gibbs Blast Wave functions and underlying-event model in PYTHIA 6.4, respectively. The solid line is the total of all above.

3 Conclusion

Based on the narrow-width approximation, we have investigated the photoproduction processes of light vector meson(ρ, ω and ϕ) in relativistic pp and AA collisions. In semielastic and inelastic photoproduction process, the photons from the early stage of relativistic heavy ion collisions can interact with the parton from the incident nucleus via γ-q Compton scattering and γ-g fusion. The numerical results indicate that the contribution of the vector-dominance two-photon exchange process is negligible. However, the modification for photoproduction processes of ϕ meson becomes evident for $p_T > 2.5$ GeV in Au-Au collisions and $p_T > 3$ GeV in Pb-Pb collisions. The modification for photoproduction processes of light vector meson is not prominent in pp collisions, but can not be negligible for nucleus-nucleus collisions.

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重离子碰撞中的轻矢量介子光生过程

余功明，李云德

(云南大学物理系，昆明 650091)

摘要： 计算了相对论重离子碰撞中轻矢量介子(ρ，ω和ϕ)的光生过程。基于窄-宽近似，严格推导了相对论重离子碰撞中ρ，ω和ϕ半弹性和非弹性光生过程的遍举和单举横截面。从数值结果可以看出对于p-p碰撞，光生过程的贡献是不重要的，但是对于$p_T > 2.5$ GeV Au-Au碰撞和$p_T > 3$ GeV Pb-Pb碰撞，轻矢量介子光生过程的贡献是明显的。

关键词： 光生过程；轻矢量介子；相对论重离子碰撞

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通信作者： 李云德，E-mail: yndxlyd@163.com。