Inclusive and Direct Photons in S + Au Central Collisions at 200A GeV/c

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A hadron and string cascade model, JPCIAE, which is based on LUND string model, PYTHIA event generator especially, is used to study both inclusive photon production and direct photon production in 200A GeV S + Au central collisions. The model takes into account the photon production from the partonic QCD scattering process, the hadronic final-state interaction, and the hadronic decay and deals with them consistently. The results of JPCIAE model reproduce successfully both the WA93 data of low \( p_T \) inclusive photon distribution and the WA80 data of transverse momentum dependent upper limit of direct photon. The photon production from different decay channels is investigated for both direct and inclusive photons. We have discussed the effects of the partonic QCD scattering and the hadronic final-state interaction on direct photon production as well.

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I. INTRODUCTION

Currently, relativistic nucleus-nucleus collisions are used to study the characteristics of nuclear matter under extreme conditions. One of the goals in this study is to search for the quark-gluon plasma (QGP), which is believed to be formed at high temperature and/or density during a nucleus-nucleus collision at high energies. Photons arising from the electromagnetic interactions of the constituents of the plasma will provide information on the properties of the plasma at the time of their production. Since photons hardly reinteract in the produced medium, they form a relatively ‘clean’ probe to study a QGP state. The possible detection, in near future, of the photon produced in the QGP phase in relativistic heavy-ion collider (RHIC) and/or large hadron collider (LHC) will be of great interest in probing such a QGP state, but presently that might not be the case at CERN SPS energies.

Photons measured after the subtraction of the photons from meson decays are usually called “direct photon.” The direct photons could be produced from the interaction of matter in the QGP phase, a mixed QGP and hadron phase, and a pure hadron phase. The thermal direct photon and prompt direct photon are referred to the photons produced from the partonic QCD processes in the QGP phase and in the hadron phase, respectively. However, the photons produced in the hadronic interactions are sorted into hadronic direct photon, although the prompt direct photon is also originated from hadrons. Different processes give rise to photons in different (transverse) momentum regions. Of course, photons, which might show up in the low transverse momentum region, extending to the region of intermediate transverse momentum of 1–3 GeV/c, from a QGP are specially important. Photons with energies up to 2 GeV can come from the decay of \( \pi^0 \) and \( \eta \) resonances as well as from \( \rho, \omega, \eta', \) and \( \phi, \) and from the interaction of hadron matter via \( \pi \rho \rightarrow \gamma \pi \) and \( \pi \pi \rightarrow \gamma \rho \) reactions (i.e., hadronic direct photons). If a hot quark-gluon plasma is formed initially, clear signal of photon from the plasma could be visible by examining photons with \( p_T \) in the region of 2–3 GeV/c. However, photons in this transverse momentum region could also be produced in the collision of a parton from the projectile nucleon with another parton from the target nucleon, i.e., prompt direct photon. Such a contribution must be subtracted in order to infer the net photons from the QGP source, i.e., thermal direct photon.

WA80 experimental data of transverse momentum dependent upper limits of direct photon in 200A GeV/c S + Au central collisions initiate theoretical interests extensively. Refs. 15 and 16 concluded that WA80 data can only be understood if a scenario with QGP phase transition is assumed. However, in Ref. 17 the single photon production has been calculated using relativistic hadronic transport model and taking into account self-consistently the change of hadron mass in dense matter. It was found there that the spectra with either free or in-medium meson mass do not exceed the WA80 upper limits, although the experimental transverse momentum distribution in low \( p_T \) region was not repro-

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duced quite well. Ref. [15] calculated the direct photon production using the rate theory (thermal model) and the hydrodynamical model for space-time evolution of temperature, their results were below WA80 upper limits.

Recently, WA93 measured the invariant differential cross section distribution of inclusive photons at low transverse momentum in S + Au central collisions at 200A GeV/c [23]. The results indicated that the photon yields at low transverse momentum are much enhanced in comparing with the results of photons from hadron decays measured by WA80 and with the VENUS 4.12 calculations.

We have already studied in details the photon production from QCD hard processes in high transverse momentum region in nucleon-nucleon, nucleon-nucleus, and nucleus-nucleus collisions with the effects of parton intrinsic transverse momentum and the contributions of next-to-leading-order Feynman diagram corrections [24]. The results show that the inclusion of intrinsic transverse momentum of parton leads to an enhancement of photon production cross section and the enhancement increases as $\sqrt{s}$ decrease. Such an enhancement is an important consideration in the region of photon momenta under investigation in high energy heavy-ion collisions.

In this paper, we study the low transverse momentum distribution of both inclusive photons and direct photons produced in S + Au central collisions at 200A GeV/c using a hadron and string cascade model, JPCIAE [25,26]. We have considered consistently the photons from different sources, such as the partonic QCD scattering, the hadronic final-state interaction, and the hadron decay. Our results reproduce successfully both the WA80 data of direct photon upper limits and the WA93 data of low transverse momentum inclusive photons. We have also compared the contributions from different hadron decays in inclusive photon production. The effects of the partonic QCD processes and the hadronic final-state interactions on direct photon production are discussed as well.

II. BRIEF DESCRIPTION FOR THE MODEL

A hadron and string cascade model, JPCIAE, was proposed to describe the relativistic nuclear collision [25,26]. In JPCIAE the simulation is performed in the laboratory system. The origin of coordinate space is positioned at the center of the target nucleus and the beam direction is taken as the $z$ axis. As for the origin of time it is set at the moment when the distance between the projectile and target nuclei along $z$ direction is equal to zero (the collision time can be negative).

A colliding nucleus is depicted as a sphere with radius $\sim 1.05 A^{1/3}$ (A refers to the atomic mass number of this nucleus) in its rest frame. The spatial distribution of nucleons in this frame is sampled randomly due to the Woods-Saxon distribution. The projectile nucleons are assumed to have an incident momentum and the target nucleons are at rest. That means the Fermi motion in a nucleus and the mean field of a nuclear system are here neglected due to relativistic energy in question. For the spatial distribution of the projectile nucleons the Lorentz contraction is taken into account. A formation time is given to each particle and a particle starts to scatter with others after it is “born”. The formation time is a sensitive parameter in this model, see Ref. [25] for the details.

![Graph showing transverse momentum distribution of direct photon production](image)

**FIG. 1.** Transverse momentum distribution of direct photon (in rapidity range of $2.1 \leq y \leq 2.9$) produced in S + Au central collisions at 200A GeV/c. The arrows stand for WA80 upper limits at the 90% confidence level [11], the solid circles refer to the results of JPCIAE, and the dashed curve are the results of [17].
are “born”. All the possible collision pairs are then ordered into a collision time sequence, called the collision time list. The initial collision time list is composed of the colliding nucleon pairs, in each pair here one partner is from the projectile nucleus and the other from the target nucleus.

Then the pair with the least collision time in the initial collision time list is selected to start the first collision. If the c.m.s. energy, $\sqrt{s}$, of this colliding pair (a hadron-hadron collision) is larger than or equal to $\sim 4$ GeV, two string states are formed and PYTHIA is called to produce the final state hadrons (scattered state). Otherwise no string state is formed and the conventional two-body scattering process \[25\] \[26\] is executed. After the scattering of this colliding pair, both the particle list and the collision time list are then updated and they are now not only composed of the projectile and target nucleons but also the produced hadrons. Repeat the previous steps to perform the second collision, the third collision, · · · , until the collision time list is empty, i.e. no more collision occurs in the system. Finally, we consider the decay of the unstable particles.

In PYTHIA we consider not only the low-$p_T$ processes but also the high-$p_T$ processes of the particle production \[30\], \[31\]. Many partonic QCD scattering processes including photon production have been considered. A user is allowed to run the program with any desired subset of those processes.

![Graph 2](image2.png)

**FIG. 2.** The solid curve is the theoretical transverse momentum distribution of direct photons (i.e. the inclusive photons after subtraction of $\pi^0$ and $\eta$ decay photons) in full rapidity space produced in $S + Au$ central collisions at 200A GeV/c. The full triangles, the open squares, the full squares, and the open circles are the $\rho$, $\Delta$, $\eta'$, and $\phi$ and $\omega$ decay photons, respectively. The photons from hadronic interactions, cf. Eqs. \[3\] and \[7\] are shown by full circles.

![Graph 3](image3.png)

**FIG. 3.** The transverse momentum distribution of inclusive photons in $S + Au$ central collisions at 200A GeV/c. The solid circles represent WA93 data, the open circles refers to the results of JPCIAE normalized to the experimental data at $p_T = 0.5$ GeV/c, the open triangles are the results of VENUS 4.12 normalized to the experimental data at $p_T = 0.3$ GeV/c and the dotted histogram is WA80 decay photons.

We have inspected this model and the corresponding event generator, JPCIAE, by comparing model predictions with the NA35 data of the charge multiplicity, the rapidity and the transverse momentum distributions of the negative charge particles ($h^-$) and the participant protons in $pp$, $pA$, and $AB$ collisions \[25\]. The agreements between theory and experiment are reasonably good. The model has explained successfully the $J/\psi$ suppression in $pA$ and $AB$ (including PbPb) as well \[23\], \[26\].
III. RESULTS AND DISCUSSIONS

We have studied the photon production in S + Au central collisions at 200A GeV/c using JPCIAE model. Following partonic QCD scattering processes with photon emission were selected

\[ f_i + \bar{f}_i \rightarrow g + \gamma, \quad (1) \]
\[ f_i + \bar{f}_i \rightarrow \gamma + \gamma, \quad (2) \]
\[ f_i + g \rightarrow f_i + \gamma, \quad (3) \]
\[ g + g \rightarrow \gamma + \gamma, \quad (4) \]
\[ g + g \rightarrow g + \gamma, \quad (5) \]

where \( f_i \) refers to the quark with \( i \) flavor and both low-\( p_T \) and high-\( p_T \) contributions are included. The hadronic photon production reactions

\[ \pi + \pi \rightarrow \rho + \gamma, \quad (6) \]
\[ \pi + \rho \rightarrow \pi + \gamma, \quad (7) \]

were taken into account as well. For simplicity, the isospin averaged parameterization formulas [9,17] were used for the relevant cross sections here. Of course, the hadron decays, such as \( \pi^0, \eta, \rho, \omega, \eta', a_1, \Delta, \) etc. were included as well.

The results of the transverse momentum distribution of direct photons (i.e., the inclusive photons after subtraction of \( \pi^0 \) and \( \eta \) decay photons) produced in a rapidity range of \( 2.1 \leq y \leq 2.9 \) in central S + Au collisions at 200A GeV/c are given in Figure 1. In this figure the arrows that at low transverse momentum region the sum of above decay photons and the photons from hadronic interactions is far below the direct photons. That indicates the prompt direct photon is visible at low transverse momentum region in the case of no QGP formation.

![Figure 1](image-url)  
**Figure 1.** The transverse momentum distributions of photons in central collisions S + Au at 200A GeV/c. The solid, the long-dashed, the dotted, the dashed, and the dot-dashed curves represent the inclusive photons, the \( \pi^0 \) decay, the \( \Delta \) decay, the \( \eta \) and \( \eta' \) decays, and the \( \rho \) decay photons, respectively.

After WA80 measured the upper limits of direct photon in S + Au central collisions at 200A GeV/c, WA93 measured further the low transverse momentum distribution of inclusive photons for the same reaction system. WA93 data (solid circles with error bar) are compared with the WA80 results of decay photons (dotted histogram) and with the theoretical calculations of VENUS 4.12 (open triangles, normalized to the experimental data at \( p_T = 0.3 \) GeV/c) in Figure 2. In this figure the open circle are the results of JPCIAE normalized to the experimental data at \( p_T = 0.5 \) GeV/c. From this figure one knows that the WA93 datum point below \( p_T = 0.1 \) GeV/c is distinctly larger than the WA80 decay photons and the VENUS 4.12 results. However, JPCIAE reproduces this WA93 datum point and others successfully due to the contributions from partonic QCD processes (low-\( p_T \) processes) and from emission of photons off quarks and lep-
tons in shower were taken into account in JPCIAE calculations.

We have calculated also the transverse momentum distributions of different decay photons in \( S + Au \) central collisions at 200\( A \) GeV/c using JPCIAE model, as shown in Fig. 4. In this figure the solid, the long-dashed, the dotted, the dashed, and the dot-dashed curves represent inclusive photons, the \( \pi^0 \) decay, the \( \Delta \) decay, the \( \eta \) and \( \eta' \) decay, and the \( \rho \) decay photons, respectively. The results indicate that the \( \pi^0 \) decay photons are absolutely dominant in the production of inclusive photons. The contributions from \( \eta \), \( \eta' \), and \( \rho \) decay and even from \( \Delta \) decay are much less than one from the \( \pi^0 \) decay, which accounts for nearly 98.8\% of total decay photons.

\[ \frac{1}{p_T} dN/dp_T \]

![FIG. 5. The rescattering effects to the \( \pi^0 \) production in central \( S + Au \) collisions at 200\( A \) GeV/c. The solid and the dashed curves are the results with and without rescattering, respectively.](image)

IV. ACKNOWLEDGMENTS

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[1] J. Stachel and G. R. Young, Annu. Rev. Nucl. Part. Sci. 42, 537 (1992).
[2] J. W. Harris and B. Müller, Ann. Rev. Nucl. Part. Phys. 46, 71 (1996).
[3] Proceedings of the Quark Matter ’96 Conference, Heidelberg, 1996, edited by P. Braun-Munzinger, H. J. Specht, R. Stock, and H. Stöcker, published in Nuclear Physics, Vol. A610 (1996).
[4] R. C. Hwa, Quark-Gluon Plasma, Vol. 2, World Scientific Publishing Company, 1995.
[5] E. V. Shuryak, Phys. Rep. 61, 71 (1980); L. McLerran, Rev. Mod. Phys. 58, 1001 (1986).
[6] R. C. Hwa and K. Kajantie, Phys. Rev. D32, 1109 (1985).
[7] L. D. McLerran and T. Toimela, Phys. Rev. D31, 545 (1985).
[8] K. Kajantie, J. Kapusta, L. McLerran, and A. Mekjian, Phys. Rev. D34, 2746 (1986).
[9] J. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D44, 2774 (1991). [Erratum: ibid. D47, 4323 (1993).]
[10] D. K. Srivastava, B. Sinha, M. Gyulassy, and X. N. Wang, Phys. Lett. B276, 285 (1992).
[11] R. Albrecht et al. (WA80 Collaboration), Phys. Rev. Lett. 76, 3506 (1996).
[12] T. Peitzmann et al. (WA98 Collaboration), invited talk presented at Quark Matter '96, Heidelberg, Germany, May 20-24, 1996.
[13] B. Wyslouch et al., WA98 Collaboration, Proceedings of Quark Matter '98, Japan, 1997.
[14] L. Xiong, E. V. Shuryak, and G. E. Brown, Phys. Rev. D46, 3798 (1992).
[15] C. M. Hung and E. V. Shuryak, Phys. Rev. C 56, 453 (1997).
[16] J. V. Steele, H. Yamagishi, and I. Zahed, Phys. Lett. B384, 255 (1996).
[17] G.Q. Li, G.E. Brown, C. Gale, and C.M. Ko, nucl-th/9712048.
[18] D.K. Srivastava and B. Sinha, Phys. Rev. Lett. 59, (1994) 2421.
[19] A. Dumitru, U. Katscher, J. A. Maruhn, H. Stöcker, W. Greinre, and D. H. Rischke, Phys. Rev. C 51, 2166 (1995).
[20] A. Dumitru, M. Bleicher, S.A. Bass, C. Spieles, L. Neise, H. Stöcker, and W. Greiner, Phys. Rev. C 57, 3271 (1998).
[21] C. Song and G. Fai, Phys. Rev. C 58, 1689 (1998).
[22] J. Sollfrank, P. Huovinen, M. Kataja, P. V. Ruuskanen, M. Prakash, and R. Venugopalan, Phys. Rev. C 55, 392 (1997).
[23] M. M. Aggarwal et al. (WA93 Collaboration), Phys. Rev. C 56, 1160 (1997).
[24] Cheuk-Yin Wong and Hui Wang, Phys. Rev. C 58, 376 (1998).
[25] Sa Ben-Hao, Tai An, Wang Hui and Liu Feng-He, nucl-th/9803033 and Phys. Rev. C in press.
[26] Sa Ben-Hao, Amand Faessler, Tai An, T. Waidzoch, C. Fuchs, Z.S. Wang, Wang Hui, nucl-th/9809020 and J. Phys. G in press.
[27] J. Cugnon, T. Mizutani, J. Vandermeulen, Nucl. Phys. A 352, 505 (1981).
[28] G. F. Bertsch, S. Das Gupta, Phys. Reports 160, 189 (1988).
[29] Sa Ben-Hao, Tai An, Comp. Phys. Commu. 90, 121 (1995); ibid. 116, 353 (1999).
[30] T. Sjöstrand, Comp. Phys. Commu. 82, 74 (1994).
[31] B. Andersson, G. Gustafson, I. Holgersson and O. Månsson, Nucl. Phys. B 178, 242 (1981).