RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 51, NUMBER 6 JUNE 1995

Thermal photons from S+Au collisions at 200*A* GeV: A hadron gas picture

A. K. Chaudhuri*
Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Calcutta–700 064, India

(Received 12 January 1995)

We have analyzed the preliminary results for the single photon spectrum, obtained by the WA80 Collaboration for 200*A* GeV S+Au collisions in a conventional hot hadronic gas model. It was seen that photon spectra depend sensitively on the value of the thermalization time. It is also affected greatly by the dissipative effects like viscosity. Experimental data are well described by the viscous hadron gas model with initial time of 5 fm. If one takes into account that experimental pion multiplicity may be uncertain by 15%, then hadron gas with viscosity gives excellent description of the data for initial time of 3 fm.

PACS number(s): 25.75.+r, 12.38.Mh, 24.85.+p

Possibility of creation of quark-gluon plasma (QGP) phase of matter, in relativistic heavy ion collisions, has been under investigation for several years now [1]. Suppression of J/ψ [2], enhancement of strangeness [3], thermal photons and dileptons [4–9], etc., have been suggested as plausible signature of QGP. Photons and dileptons have added significance as signals as they are not affected by rescattering and can provide for the *pristine* information of the early stage of QGP matter. Hadrons, on the other hand, are affected by rescattering and reflect the properties of the last stage of hadronic gas *irrespective* of the early nature of the produced matter. Much interest has been aroused after the WA80 Collaboration published the single photon emission (preliminary) data for the 200*A* GeV S+Au collisions [10]. Shuryak *et al.* [11] had analyzed the data and found that conventional expansion scenario of QGP underpredicts the data. He argued that the expansion in the mixed phase will be much slower than the convention. Srivastava *et al.* [12] have also analyzed the same data. They came to the conclusion that the data can be explained *only if* QGP formation is assumed. Pure hadron gas overpredicts the data by a factor more than 100. In their calculation, the QGP and also the hadronic matter was assumed to be ideal. It was also assumed that the thermalization time (which is the initial time for hydrodynamic evolution) of the QGP matter or of the hadron matter are same. However, QGP and also the hot hadronic matter are not ideal fluids. Dissipative effects like viscosity do affect them [13,14]. Also, the assumption that the thermalization time of QGP and of hadron matter are the same is not a valid one. In the present work we would like to explore the effect of dissipative effects and thermalization time in hadron gases and its consequent effects on single photon emission spectra.

Let us first examine the thermalization time of hadron gases vis-à-vis QGP. The thermalization time (τ) should be proportional to mean free path (λ),

$$\tau \propto \lambda \propto \frac{1}{n\sigma}, \tag{1}$$

where n and σ are the number density and scattering cross section, respectively. Then taking into account that the degrees of freedom in QGP gas (~ 40) is ten times larger than the degrees of freedom in hadron gas (~ 3) and scattering cross sections in hadron gases are four times larger than cross sections in QGP (in the additive quark model), we obtain

$$\tau^{\mathrm{had}}/\tau^{\mathrm{QGP}} \approx 3. \tag{2}$$

The simple-minded calculation then gives thermalization times of hadron gases three times larger than QGP. Thus the assumption, that the thermalization time of QGP and of hadron gases are the same, will make the hadron gases equilibrated at much larger initial temperature than they indeed do. There are uncertainties about the thermalization time of QGP. It is customary to take the thermalization time as 1 fm (canonical) or $1/3T_i$ (obtained from uncertainty principle) [12]. Detailed calculations indicate that the thermalization time for quarks and gluons vary; gluons thermalize faster ($\tau \sim 1$ fm) than quarks ($\tau \sim 3$ fm) [15,16]. Also, thermalization time of quarks is flavor dependent; lighter quarks thermalize faster than heavy quarks [17]. It is then reasonable to expect that thermalization times of QGP are larger than 1 fm and that of hadron gases will be larger than 3 fm.

We will consider the following scenario. After the collision, hadron gas comprising π, ρ, η, and ω mesons is formed, at initial temperature T_i and (proper) time τ_i. It expands *longitudinally* and cools, until the freeze-out temperature T_f ($=100$ MeV). We further assume that the fluid flow is a similarity flow. We are neglecting the transverse expansion completely. At SPS energies, transverse expansions are not much [18]. Photon spectra with transverse expansion *on* or *off* differ marginally [12]. The energy-momentum conservation equation for the viscous hadronic fluid can be written as

$$\frac{d\varepsilon}{d\tau} = -\left(\varepsilon + p - \frac{4\eta}{3\tau} - \frac{\zeta}{\tau}\right) \Big/ \tau, \tag{3}$$

where η and ζ are the shear viscosity and the bulk viscosity coefficients. The other variables have the usual meaning.

From kinetic theory consideration, a simple estimate of η for hadron gas was obtained by Danielewicz and Gyulassy [13],

---

*Electronic address: akc@veccal.ernet.in

0556-2813/95/51(6)/2889(4)/$06.00

$$\eta \simeq T/\sigma_\eta, \tag{4}$$

where σ_η is the transport cross section $\simeq$ 10–20 mb. Hosoya and Kajantie [14] also obtained transport coefficients for QCD matter in the framework of relativistic kinetic theory. For $T<T_c$, η and ζ were obtained in the glueball limit,

$$\frac{3}{2}\zeta = \eta = \tau_G n T, \tag{5}$$

where n is the glueball density and τ_G is the glueball-glueball collision time. Presently we chose to use Eq. (4) as the shear viscosity coefficient with $\sigma_\eta = 10$ mb. The bulk viscosity coefficient was computed as two-thirds of shear viscosity coefficient [Eq. (5)]. The viscosity coefficients we use are then very much conservative.

The equation of state of the hadron gas consisting of π, ρ, ω, and η mesons is parametrized as [12]

$$p_h = g_h \frac{\Pi^2}{90} T^4, \tag{6a}$$

$$\varepsilon_h = g_h \frac{\Pi^2}{30} T^4 \tag{6b}$$

with $g_h = 4.6$.

To solve Eq. (3), the boundary conditions have to be specified. For isentropic expansion, for a given initial proper time (τ_i), the initial temperature T_i can be obtained by equating the initial entropy density with observed pion multiplicity (assuming the pion decoupling to be adiabatic) [19],

$$T_i^3 \tau_i = \frac{1}{\pi R_A^2} \frac{c}{4a_h} \frac{dN}{dy}(b=0), \tag{7}$$

where $c = 2\pi^4/45\zeta(3)$, $a_h = g_h \pi^2/90$, and R_A is the transverse radius of the system. $b=0$ corresponds to central collisions. However, for viscous flow entropy generated, the flow is no longer isentropic, and the equation cannot be used to obtain initial conditions. However, we can still assume that pion decoupling is adiabatic. Then, since, as stated earlier, the pions reflect the condition of the system at the freeze-out time, we argue that one should equate the final entropy density with the pion multiplicity. Thus Eq. (7) can be rewritten as

$$T_f^3 \tau_f = \frac{1}{\pi R_A^2} \frac{c}{4a_h} \frac{dN}{dy}(b=0). \tag{8}$$

For S+Au collision at CERN SPS, the observed charged pion multiplicity $dN^{AB \to \pi^{ch}}/dy \sim 150$ [20]. Assuming that for every charged pion pair, there is a neutral pion, the total pion multiplicity is 225. From Eq. (8), for this multiplicity, we obtain the boundary condition for solving Eq. (3) as, at $\tau_f = 67.32$ fm, $T_f = 100$ MeV, for a freeze-out temperature of 100 MeV. The evolution equation (3) was then solved, backward in time, to obtain the initial temperature of the hot hadron gas, for a given initial time. For a different pion multiplicity, τ_f will be different, freeze-out temperature being fixed.

TABLE I. The initial temperatures (T_i) of the hadron fluid obtained from evolution equation, solving backward in time, for different initial (thermalization) times (τ_i).

τ_i (fm)	T_i (MeV)[a]	T_i (MeV)[b]
1	407	328
2	323	272
3	282	244
4	256	225
5	237	212

[a] Ideal gas.

[b] Viscous gas.

Photon emission spectra were obtained by convoluting the photon emission rate from the hot hadron gas, using methods well established [18,21,22]:

$$E\frac{dR}{d^3p} = \pi R_A^2 \int \tau d\tau d\eta E \frac{dR^\gamma}{d^3p}, \tag{9}$$

where EdR^γ/d^3p is the rate of thermal photon production from hot hadron gas. The differential cross section is then obtained by multiplying the above result by $\sigma_{\text{in}} = 900$ mb, the inclusive cross section appropriate for the data.

For the thermal photon production rate from an equilibrated hadron gas, consisting of π, ρ, ω, and η, we use the parametric form given by Kapusta *et al.* [23]:

$$E\frac{dR^\gamma}{d^3p} = \frac{5\alpha\alpha_s}{18\pi^2} T^2 e^{E/T} \ln\left[1 + \frac{2.912E}{g^2 T}\right], \tag{10}$$

where E is the photon energy in the local rest frame. In the following we fix $\alpha_s = g^2/4\pi = 0.4$. Incidentally, Eq. (10) also describes the photon emission rate from equilibrated quark-gluon plasma. Equation (10) does not contain the contribution of A_1 resonances. However, in the temperature regime ($T > 100$ MeV) considered here, a $\pi\rho$ pair can easily form an $A_1(1260)$ resonance and as shown by Xiong *et al.* [24], this can be the leading mechanism of photon production. We include the A_1 contribution in the photon production rate via the parametric form given by Xiong *et al.* [24],

$$E\frac{dR}{d^3p} = 2.4 \times T^{2.15} \times \exp[-1/(1.35E)^{0.77} - E/T](\text{fm}^{-4}\ \text{GeV}^{-2}). \tag{11}$$

We have calculated photon production cross sections for five different initial times ($\tau_i = 1$–5 fm). In Table I, the corresponding initial temperatures of the hot hadron gas obtained by solving Eq. (3) are shown. We find that, if the hadron gas is assumed to be ideal, it leads to initial temperature higher by 10–20%, compared to the initial temperature obtained when the gas is assumed to be viscous. Viscosity generates entropy, and as a consequence, the same entropy or pion multiplicity is obtained at a reduced temperature. In Fig. 1, we have compared the photon spectra, presently obtained for different initial times with experiment [10]. It can be seen that for ideal fluid flow, even if the initial (thermalization) time is 5 fm, it still overpredicts data. However, the difference between data and theory gets diminished with increas-

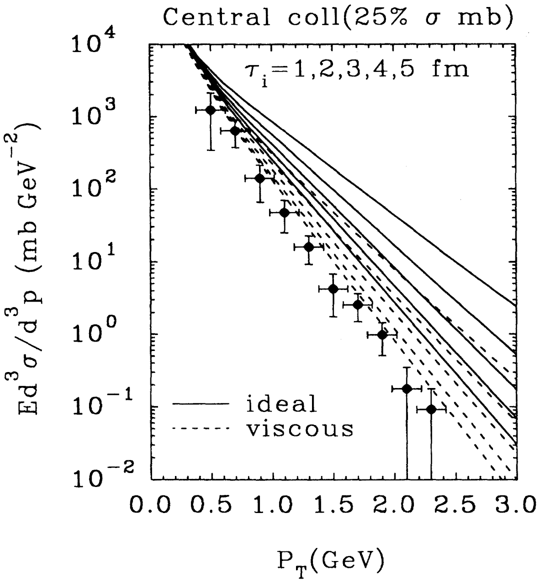

FIG. 1. Single photon spectrum for central collisions of S+Au system obtained by the WA80 Collaboration. The solid lines are obtained for hot ideal hadron gas flow for different initial times (τ_i). The upper one is for τ_i=1 fm and so on. The dashed lines are for viscous hadron gas. The pion multiplicity dN/dy is assumed to be 225.

ing τ_i. With higher τ_i, the hadron gas is formed at lesser temperature, and as large p_T photons are predominantly from the high-temperature part, their production decreases. In Fig. 1, the dotted lines correspond to viscous fluid flow. We observe a pronounced effect of viscosity on the photon spectrum, for all the initial times. It is interesting to note that the large P_T part of the spectra is reduced (compared to ideal gas flow), making the theoretical prediction closer to the experiment. Large P_T photons are predominantly from initial high-temperature gas and as viscosity is directly proportional to the temperature, they are most affected. For an initial time of 5 fm, we find that the viscous hadron gas can explain the data reasonably well.

Evolution of the hot hadron gas depends crucially on the boundary condition. We have obtained the boundary condition from Eq. (8), assuming a total pion multiplicity of 225. However, the experimental charged pion multiplicity has a statistical uncertainty of 10%, while the systematic errors are between 5–10 % [20]. The total uncertainty in the charged pion multiplicity can very well be ~15%. We now assume that the pion multiplicity is 190 rather than the previously used 225. For this multiplicity, the boundary condition obtained is at τ_f=57.2 fm, T_f=100 MeV. With this boundary condition the evolution equation gives T_i=298 MeV for τ_i=1 fm and T_i=227 MeV for τ_i=3 fm. In Fig. 2, the photon spectra obtained thus are shown. The solid line corresponds to initial time of 1 fm. It still overpredicts data. The dashed line, obtained with initial time of 3 fm, is seen to give excellent description of data. The viscous hadron gas with τ_i=3 fm explains the data, if we take into account the experimental uncertainties in pion multiplicity measurement.

At this point, I would like to take note of one problem, which is generally overlooked in the literature. What about the photons produced before thermalization? They are not accounted for in the calculation. This is a problem with all the hydrodynamic calculations with nonzero τ_i. We can assume that the preequilibrium photons are small in number and their contribution to the photon spectra can be neglected. While this assumption may hold for small τ_i, will it hold for τ_i as large as 3–5 fm? The other possibility is that preequilibrium photons are hard photons and dominantly produced at P_T>4 GeV, and do not interfere with the present result. At present, we are unable to do better, and hope that this point will be clarified later with more insight into the nonequilibrium thermodynamics.

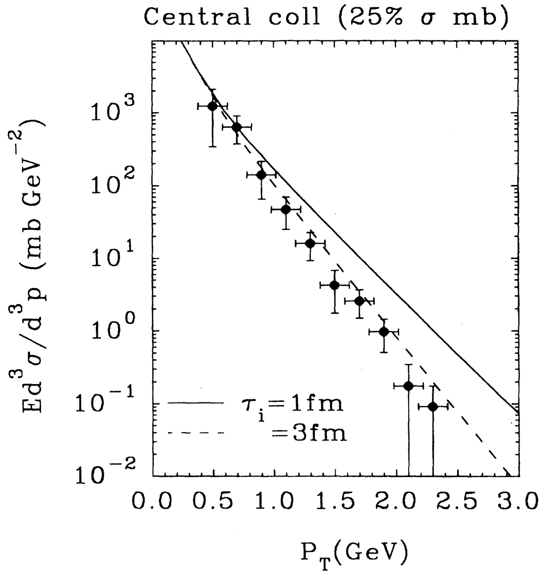

FIG. 2. Single photon spectrum for central collisions of S+Au system obtained by the WA80 Collaboration. The solid line is obtained for hot (viscous) hadron gas flow for initial times (τ_i) of 1 fm. The dashed line is for the viscous hadron gas flow with τ_i=3 fm. The pion multiplicity dN/dy is assumed to be 190.

To summarize, we have calculated the thermal photon spectra from CERN SPS for S+Au collisions at 200 MeV in a pure hot hadron gas picture, for different initial times. It was seen that photon spectra depend sensitively on the value of the initial time, i.e., the thermalization time of the hadron gas. We have also studied the effect of viscosity on the photon spectra. A very conservative estimate of shear and bulk viscosity was used and found to have a pronounced effect on the photon spectrum. It was seen that viscous hadron gas formed at τ_i=5 fm can explain the data. Lastly, it was also shown that if the uncertainty in the pion multiplicity measurement is taken into account, the viscous hadron gas can give excellent description of the experiment for an initial time of 3 fm.

To conclude, at the present stage, it is not possible to state conclusively that the photon spectra from CERN SPS need QGP formation. Pure hadron gas with viscosity, thermalized at 3–5 fm, can be an alternative explanation.

The author wishes to thank Prof. Bikash Sinha for his continued interest in the present work. He also thanks Dr. D. K. Srivastava, Dr. J. N. De, and Dr. S. Pal for offering suggestions and discussions.

[1] For a general survey, see Nucl. Phys. **A498** (1989); **A525** (1991); **A544** (1992); **A566** (1994).

[2] T. Matsui and H. Satz, Phys. Lett. B **175**, 416 (1986).

[3] J. Rafelski, Nucl. Phys. **A418**, 215 (1984); J. Kapusta and A. Mekjian, Phys. Rev. D **33**, 1304 (1986).

[4] L. D. Maclerran and T. Toimela, Phys. Rev. D **31**, 545 (1985).

[5] B. Sinha, Phys. Lett. **128B**, 91 (1983); Phys. Lett. B **197**, 263 (1985); Z. Phys. C **38**, 259 (1988).

[6] S. Raha and B. Sinha, Phys. Lett. **58**, 101 (1987).

[7] G. Domokos and J. Goldman, Phys. Rev. D **23**, 203 (1981); **28**, 123 (1983).

[8] J. Clemans, J. Fingberg, and K. Redlich, Phys. Rev. D **35**, 2153 (1987).

[9] B. Sinha, Nucl. Phys. **A459**, 717 (1986).

[10] R. Santo *et al.*, in Proceedings of the Tenth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Borlange, Sweden, 1993, edited by E. Stenlund, H. A. Gustafsson, A. Oskarsson, and I. Otterlund [Nucl. Phys. **A566**, 61c (1994)]; R. Santo *et al.*, Report No. IKP-MS-93/0701, Muenster, 1993.

[11] E. V. Shuryak and L. Xiong, Phys. Lett. **333**, 316 (1994).

[12] D. K. Srivastava and B. Sinha, Phys. Rev. Lett. **73**, 2421 (1994).

[13] P. Danielewwicz and M. Gyulassy, Phys. Rev. D **31**, 53 (1985).

[14] A. Hosoya and K. Kajantie, Nucl. Phys. **B250**, 666 (1985); University of Helsinki Reports No. HU-TFT-83-62, 1983.

[15] E. Shuryak, Phys. Rev. Lett. **68**, 68 (1992).

[16] B. Muller, in Proceedings of the Workshop on Preequilibrium Parton Dynamics, Berkeley, California, 1993, edited by Xin-Nian Wang (unpublished).

[17] Jan-e Alam, S. Raha, and B. Sinha, Phys. Rev. Lett. (in press).

[18] Jan-e Alam, D. K. Srivastava, B. Sinha, and D. N. Basu, Phys. Rev. D **48**, 1117 (1993).

[19] R. C. Hwa and K. Kajantie, Phys. Rev. D **32**, 1109 (1985).

[20] WA80 Collaboration, R. Albrecht *et al.*, Report No. GSI-92-27, 1992.

[21] D. K. Srivastava, B. Sinha, M. Gyulassy, and X.-N. Wang, Phys. Lett. B **276**, 285 (1992).

[22] D. K. Srivastava and B. Sinha, J. Phys. G **18**, 1467 (1992).

[23] J. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D **44**, 2774 (1991); H. Nadeau, J. Kapusta, and P. Lichard, Phys. Rev. C **45**, 3034 (1992).

[24] L. Xiong, E. Shuryak, and G. E. Brown, Report No. SUNY-NTG-92-15.