Production of $\gamma\gamma$ pairs in quark-gluon plasma and hadron plasma

Ritsu Yoshida, Tadashi Miyazaki, and Morihiro Kadoya
Department of Physics, Science University of Tokyo, Kagurazaka 1-3, Shinjuku-ku, Tokyo 162, Japan
(Received 26 June 1986)

The ratio of the production rate of $\gamma\gamma$ pairs in the quark-gluon plasma to that in the hadron plasma is shown to be much larger than the ratio of the production rate of $\mu^+\mu^-$ pairs for the two plasma states. Hence the $\gamma\gamma$-pair production is more adeqnate to discriminate the plasma states.

There has been considerable interest recently in the collision processes of heavy ions at high energies. In the high-energy and high-density processes, one would be faced with, it may be guessed, quark-gluon-plasma (QGP) states.[1] Heavy nuclei consist of many hadrons and hadrons consist of quarks, antiquarks, and gluons. When the nuclei meet together in collision, forming a fireball, there exist many hadrons and, to take a more fundamental viewpoint, a lot of quarks, antiquarks, and gluons. In the many-body system of constituents, namely, in the fireball, one would think there would be a plasma state. But the question arises: what are the constituents of the plasma? Are they better regarded as hadrons (especially pions), or quarks and gluons?

To discriminate the plasma states of hadrons from those of quarks and gluons is the first problem to solve. For this purpose Chin, Domokos, Goldman, and Sinha[2,3] (CDGS) took up the distribution of lepton-antilepton pairs. This is because leptons (antileptons) are easily emitted,[4] with no strong interactions, outside the plasma state once they are created inside. CDGS calculated the production rate of $\mu^+\mu^-$ pairs as a function of temperature. The elementary reaction for this production is either $q\bar{q}\rightarrow\mu^+\mu^-$ or $\pi^+\pi^-\rightarrow\mu^+\mu^-$, and the quark or the pion is considered to belong to the plasma states. Sinha[3] numerically calculated the production rate of $\mu^+\mu^-$ pairs via quarks in the QGP and via pions in the hadron plasma (HP). He concluded that seeing the distribution is seeing the signals from the plasma, and the difference between the two states shows itself in the distribution.

In this paper we follow Sinha's reasoning, but now it is the production rate of two photons that concerns us, because the ratio of the production rate of two photons from the QGP to that from HP is much larger (by order 10) than the ratio of the same kind for the $\mu^+\mu^-$ pair production. We think our two-photon process is more adequate than the dilepton process in order to discriminate the QGP states from the HP states.

The two photons are emitted mainly via an elementary reaction $q+\bar{q}\rightarrow 2\gamma$ with q and $\bar{q}$ inside the QGP, or via $\pi^+ + \pi^- \rightarrow 2\gamma$ and $\pi^0\rightarrow 2\gamma$ with pions inside the HP. The cross sections are obtained straightforwardly by the lowest-order perturbation method:

$$\sigma^{(2)}_{q\bar{q}\rightarrow 2\gamma}(s)=\frac{2\pi\alpha^2 e_q{}^4}{s-4m_q{}^2}\left[\left[1+\frac{4m_q{}^2}{s}-\frac{8m_q{}^4}{s^2}\right]\ln\left\{\frac{s}{2m_q{}^2}\left[1+\left[1-\frac{4m_q{}^2}{s}\right]^{1/2}\right]-1\right\}-\left[1+\frac{4m_q{}^2}{s}\right]\left[1-\frac{4m_q{}^2}{s}\right]^{1/2}\right], \tag{1}$$

$$\sigma^{(2)}_{\pi^+\pi^-\rightarrow 2\gamma}(s)=\frac{4\pi\alpha^2}{s-4m_\pi{}^2}\left\{\left[1+\frac{4m_\pi{}^2}{s}\right]\left[1-\frac{4m_\pi{}^2}{s}\right]^{1/2}-\frac{4m_\pi{}^2}{s}\left[1-\frac{2m_\pi{}^2}{s}\right]\ln\left\{\frac{s}{2m_\pi{}^2}\left[1+\left[1-\frac{4m_\pi{}^2}{s}\right]^{1/2}\right]-1\right\}\right\}, \tag{2}$$

and

$$\Gamma^{(2)}_{\pi^0\rightarrow 2\gamma}=\frac{f^2}{16\pi}m_{\pi^0}\ , \tag{3}$$

where $e_q e$ is the quark charge ($-e$ the electron charge) and other notations are adopted in the conventional use. [In deriving Eq. (1), we have set the quark mass $m_q=5.0$ MeV since we have only taken up u and d quarks with $\sqrt{s}$, rather small, and $f=1.7\times10^{-3}$.] Let us denote by $dN_{2\gamma}$ ($dN_{\mu^+\mu^-}$) the number of the two-photon pairs ($\mu^+\mu^-$ pairs) per $d^4x\,d\sqrt{s}$ with $d^4x=dt\,d^3r$ (space-time volume element) and $\sqrt{s}$ =c.m.-system (c.m.s.) energy for $\gamma\gamma$ ($\mu^+\mu^-$). In the QGP state the quarks with energy E are distributed with the Fermi distribution function

$$f(E,\mu)=1/\{\exp[\beta(E-\mu)]+1\}\ ,$$

and in the HP state the pions with energy E are distributed with the Bose distribution function

$$b(E,\mu)=1/\{\exp[\beta(E-\mu)]-1\}$$

(μ is the chemical potential). With these distribution functions we immediately obtain the distribution of $\gamma\gamma$ pairs from the QGP:

$$\frac{dN_{2\gamma}^{\mathrm{QGP}}}{d^4x\,d\sqrt{s}}=\frac{68}{27}\sigma^{(2)}_{q\bar{q}\to 2\gamma}(s)\frac{s}{(2\pi)^4}(s-4m_q{}^2)^{1/2}\int_{m_q}^{\infty}dq_0\int_{m_q}^{\infty}d\bar{q}_0 f(q_0,\mu)\bar{f}(\bar{q}_0,-\mu)\times\theta\left[q_0\bar{q}_0-\frac{m_q{}^2}{s}(q_0+\bar{q}_0)^2-\tfrac{1}{4}(s-4m_q{}^2)\right], \quad (4)$$

where use has been made of the relation

$$\sum_{\text{flavor }(u,d)}\ \sum_{\text{color}}\ \sum_{\text{helicities}} e_q{}^4=\tfrac{68}{27}.$$

In the same way we also get, for the HP,

$$\frac{dN_{2\gamma}^{\mathrm{HP}}}{d^4x\,d\sqrt{s}}=\sigma^{(2)}_{\pi^+\pi^-\to 2\gamma}(s)\frac{s}{(2\pi)^4}(s-4m_\pi{}^2)^{1/2}\int_{m_\pi}^{\infty}dk_0\int_{m_\pi}^{\infty}d\bar{k}_0 b(k_0,\mu)\bar{b}(\bar{k}_0,\mu)\theta\left[k_0\bar{k}_0-\frac{m_\pi{}^2}{s}(k_0+\bar{k}_0)^2-\tfrac{1}{4}(s-4m_\pi{}^2)\right]$$
$$+\Gamma^{(2)}_{\pi^0\to 2\gamma}(s)\frac{\sqrt{s}}{\pi^2}\delta(s-m_{\pi^0}{}^2)\int_{m_{\pi^0}}^{\infty}dE\,b(E,\mu)E(E^2-\mu^2)^{1/2}. \quad (5)$$

As to $dN^{\mathrm{QGP}}_{\mu^+\mu^-}/d^4x\,d\sqrt{s}$ and $dN^{\mathrm{HP}}_{\mu^+\mu^-}/d^4x\,d\sqrt{s}$, see Refs. 2 and 3.

Now we numerically calculate the two-photon spectrum from the QGP [Eq. (4)] and that from the HP [Eq. (5)]. These are plotted in Figs. 1 and 2. As an example the chemical potentials are taken as $\mu=0$ and 200 MeV for the QGP and $\mu=0$ and -200 MeV for the HP. We have also plotted the integrated production rate in Fig. 3(a) and the ratio $(dN^{\mathrm{HP}}/d^4x)/(dN^{\mathrm{QGP}}/d^4x)$ in Fig. 3(b). We note here that Eqs. (4) and (5) reduce to simpler forms by use of the modified Bessel function of order 1 when $|\mu|/T$ is small, which is also the case for the $\mu^+\mu^-$pair production.[2] As compared with the case for vanishing chemical potential the strength of spectra is smaller for nonvanishing chemical potentials. This aspect of $dN/d^4x\,d\sqrt{s}$ is seen more conspicuously when one looks at the integrated distribution Fig. 3(a). For comparison we have plotted the distributions of the $\mu^+\mu^-$ pairs for $\mu=0$ MeV from Ref. 3.

A glance at Fig. 3(b) shows that the difference of the production rates between the QGP and the HP is greater for the $\gamma\gamma$-pair production than for the $\mu^+\mu^-$-pair production. Moreover, from Fig. 3(a), one immediately finds that the particle distribution for the $\mu^+\mu^-$ pair from the QGP is by far smaller (by order 10) than that for the $\gamma\gamma$ pair, and that the particle distribution for the $\mu^+\mu^-$ pair from the HP is a little larger than that for the $\gamma\gamma$ pair. This leads us to a clear-cut conclusion that if one wants to discriminate the QGP state from the HP state with the help of particle distributions, one should take up and detect the two-photon production processes rather than the dilepton processes. As the temperature grows, $(1/4\pi\alpha^2T^4)dN_{2\gamma}/d^4x$ approaches a constant for the HP and still increases quite gradually for the QGP. Hence, in

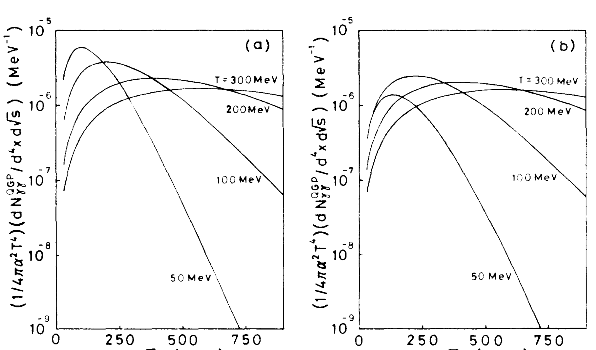

FIG. 1. The two-photon pair production rate for the QGP per unit space-time volume and per unit c.m.s. energy as a function of the c.m.s. energy $\sqrt{s}$ of the pair: (a) for $\mu=0$ MeV and (b) for $\mu=200$ MeV. The distribution form changes as the temperature varies.

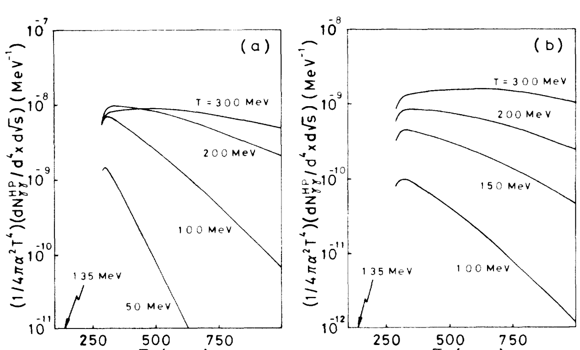

FIG. 2. The two-photon pair production rate for the HP per unit space-time volume and per unit c.m.s. energy as a function of the c.m.s. energy $\sqrt{s}$ of the pair: (a) for $\mu=0$ MeV and (b) for $\mu=-200$ MeV. Here also, the distribution form changes as the temperature varies. At $\sqrt{s}=135$ MeV the process $\pi^0\to 2\gamma$ takes part and the sharp large peak exists there.

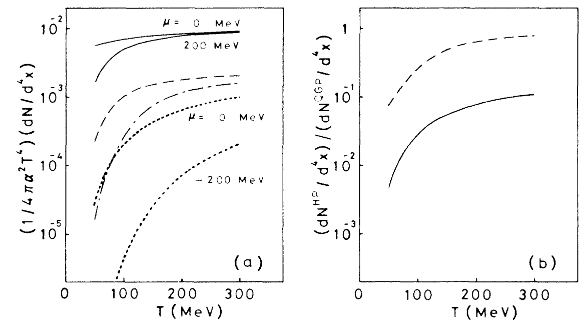

FIG. 3. (a) The integrated (over $\sqrt{s}$) distributions of $\gamma\gamma$ pairs vs T. The solid curve represents those for QGP and the dotted curve represents those for the HP. For comparison, we have also plotted the integrated distribution of $\mu^+\mu^-$ pairs from the QGP (dashed curve) and from the HP (dashed-dotted curve) for $\mu=0$ MeV. (b) The ratio of the integrated distribution from the HP to that from the QGP. The solid curve represents the $\gamma\gamma$ pairs and the dashed curve represents the $\mu^+\mu^-$ pairs.

practice, we may say that the Stefan-Boltzmann law holds approximately for both cases.

In summary we insist that one should measure the dilepton distribution or the two-photon distribution in order to distinguish the QGP state from the HP state. Our proposal is that the latter is much preferable to the former in that the difference of the two distributions is more conspicuous. The shape of the spectrum informs us of the plasma state such as its temperature. In the case of the actual measurement of the two-photon distribution, the contamination comes mainly from (i) one-photon processes of $qG \to \gamma X$ and $q\bar{q} \to \gamma X$ (G represents gluons in plasma) and (ii) two-photon decay products of neutral pions.

The ratio of the number of *two photons* per unit space-time from (i) to that from $q\bar{q} \to \gamma\gamma$ amounts to 14, so that one must necessarily take coincidence of the two photons to pick the latter up. When heavy ions collide with each other neutral pions are quite easy to produce, which is the origin of the contamination (ii). One must measure the momentum of both photons, by which one can discriminate the two photons of our processes from those of (ii). In the latter case the invariant-mass distribution clearly shows the π^0 peak. Now the two photons from $\pi^+\pi^- \to \gamma\gamma$ in the background are not so serious because of the phase-space suppression. The two photons from $qG \to \gamma\gamma X$ (leading bremsstrahlung) and $q\bar{q} \to \gamma\gamma X$ reduces to about 10% of those of our processes.

In any case, the measurement of correlations of two photons are most desirable. In this context our model will be enlarged to a nonisotropic one. Either one may use the collective velocity distribution of quarks (or pions) in the c.m.s. of fireball[5] or one may adopt a nonconstant form of temperature T (space-time dependence of T) (Refs. 2 and 6). With such modifications one may discuss the P_T distribution of photons or lepton pairs in the manner of Halzen and Scott[7] in the case of the parton model.

[1]B. Müller, *The Physics of the Quark-Gluon Plasma* (Lecture Notes in Physics, Vol. 225) (Springer, Berlin, 1985).

[2]S. A. Chin, Phys. Lett. **119B**, 51 (1982); G. Domokos and J. I. Goldman, Phys. Rev. D **23**, 203 (1980); G. Domokos, *ibid.* **28**, 123 (1983).

[3]B. Sinha, Phys. Lett. **128B**, 91 (1983); **160B**, 287 (1985).

[4]E. L. Feinberg, Nuovo Cimento **34A**, 391 (1976).

[5]R. Hagedorn, *Thermodynamics of Strong Interactions* (CERN Yellow Report No. CERN 71-12).

[6]E. V. Shuryak, Phys. Lett. **78B**, 150 (1978).

[7]F. Halzen and D. M. Scott, Phys. Rev. Lett. **40**, 1117 (1978); Phys. Rev. D **18**, 3378 (1978).