Energy distribution of muon pairs: A signal for the creation of a baryon-rich quark-gluon plasma in relativistic heavy-ion collisions

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A study of the energy distribution of muon pairs and photon pairs produced in ultrarelativistic heavy-ion collisions shows that muon pairs may be better signatures than photon pairs for the detection of a baryon-rich quark-gluon plasma (QGP). The value of the transverse mass of the muon pairs at which the ρ-meson peak disappears from their invariant-mass spectrum is sensitive to the equation of state of the QGP. Hence dimuons are useful not only for the detection of a QGP but also for a study of its equation of state.

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I. INTRODUCTION

Among the various signatures proposed for the detection of a quark-gluon plasma (QGP) formed in ultrarelativistic heavy-ion collisions [1–10], the dileptons (dimuons) and diphotons may serve as better signals since they do not interact strongly with the constituents of the QGP. Yoshida *et al.* [6] claim that the photon pairs are better signals than the dileptons because the diphotons have a *larger* production rate. On the other hand, Redlich [7], after taking into account the dynamics of the hadronization phase transition, has shown that dimuons can be better than diphotons, as a study of the muon pairs at *lower* invariant masses is enough for the detection of a QGP. In our earlier work [9], we have shown that the muon pairs are better than the photon pairs for the detection of a QGP, while the photon pairs seem to be sensitive to the equation of state of the QGP. Hirasawa *et al.* [11] have studied the angular distribution of muon pairs and photon pairs and pointed out the superiority of the photon pair data. Recently, Yoshida [12] has calculated the energy distribution of muon pairs and photon pairs and found that an analysis of the muon pair data is easier than that of photon pairs for distinguishing between the QGP phase and the hadronic phase.

The purpose of this article is to study (i) the thermal production rates of dimuons and diphotons produced in the QCD phase transition at *finite* baryon densities with different energy distributions of the constituents of the pair and (ii) the invariant-mass distribution of thermal dimuons and diphotons at various transverse masses of the pair for two different equations of state (EOS). Our analysis is applicable to the experiments at the Brookhaven Alternating Gradient Synchrotron (Au+Au collisions at 14.5 GeV/N) and the CERN Super Proton Synchrotron.

Our article is organized as follows. Expressions for thermal production rates of dimuons and diphotons as a function of their energies are presented in Sec. II. The ratio of the production rates for different energy distributions of the pairs is also studied. In Sec. III the invariant-mass distribution of dimuons and diphotons at various transverse masses of the pairs and the transverse mass distribution of the production rates of the pairs are given. Also the invariant-mass spectrum of thermal dileptons is compared with the background due to the Drell-Yan process. Section IV contains our results and discussions.

II. ENERGY DISTRIBUTION OF MUON PAIRS AND PHOTON PAIRS

We consider a baryon-rich QGP undergoing a first-order phase transition into a hadron resonance gas (HRG). Conservation of entropy and baryon number is assumed [13]. In the QGP phase we consider only u and d quarks, their antiparticles, and gluons. Our HRG phase consists of all the well established nonstrange hadrons and their resonances with a mass less than 2 GeV [4,9]. The particles in both the phases are treated relativistically and the appropriate quantum statistical distributions are used. Hagedorn's pressure ensemble correction [4] is also included to account for the finite size of the hadrons in the HRG phase. The calculations also include the interactions between quarks and gluons in the QGP phase via the running coupling constant α_s [4,9,13]. Chemical, thermal, and mechanical equilibria are assumed between the two phases. We follow Ref. [13] for the dynamics of the hadronization phase transition. (We take into account only the longitudinal expansion of the system.) The QGP created in high-energy heavy-ion collisions expands in the QGP phase, enters into the mixed phase, and finally hadronizes [9,13]. Hence the dileptons and diphotons produced thermally during the collisions are emitted from the QGP, HRG, and mixed phases.

We consider the four reactions

$$\text{(i)}\quad q\bar{q}\rightarrow\mu^{+}\mu^{-}+X\ , \tag{2.1a}$$

$$\text{(ii)}\quad q\bar{q}\rightarrow\gamma\gamma+X\quad (q=u,d\ \text{only})\ , \tag{2.1b}$$

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(iii) $\pi^+\pi^- \rightarrow \mu^+\mu^- + X$, (2.1c)

(iv) $\pi^+\pi^- \rightarrow \gamma\gamma + X$ (2.1d)

to be the most dominant channels for dimuon and diphoton production in the QGP and HRG phases. If

$$\mathcal{D}N^i_{\rm pair}(E_1,E_2)=E_1E_2dN^i_{\rm pair}/d^3k_1d^3k_2 \tag{2.2}$$

is the invariant production rate of the pair produced in the phase i with energies E_1 and E_2 and momenta $\mathbf{k}_1$ and $\mathbf{k}_2$, then we have the following expressions for the thermal production rates of dimuons and diphotons both in the QGP and HRG phases ($\hbar=c=1$) [3,12]:

$$\mathcal{D}N^i_{\rm pair}(E_1,E_2)=C\int_{t_i}^{t_f}\lambda_i(t)t\,dt\int dy\, I^i_{\rm pair}(t,y)\ , \tag{2.3}$$

where

$$C=[\alpha^2/(2\pi)^6]\pi R_A^2 \tag{2.4}$$

and

$$I^i_{\rm pair}(t,y)=4\int d^4p\;\delta^4(p^2-m^2)\theta(p_0)d^4q\delta^4(q^2-m^2)\theta(q_0)\times f^i(p,y)f^i(q,y)W^i_{\rm pair}\delta^4(p+q-k_1-k_2)\ . \tag{2.5}$$

Here R_A is the radius of the colliding nuclei (Au+Au in our case), $\lambda_i(t)$ the probability that the system is in phase i, and α is the fine structure constant. ($i=Q$ or H depending upon whether the system is in the QGP or the HRG phase.) From Ref. [12] we get the following relations (Q=QGP, H=HRG, MP=muon pairs, and PP=photon pairs):

$$W^Q_{\rm MP}=20[2(p\cdot k_1)^2+2(p\cdot k_2)^2+(m_\mu^2+m_q^2)M^2]/(3M^4)\ , \tag{2.6}$$

$$W^H_{\rm MP}=2|F_\pi(M^2)|^2[4(p\cdot k_1)(p\cdot k_2)-m_\pi^2M^2]/M^4\ , \tag{2.7}$$

$$W^Q_{\rm PP}=\tfrac{34}{27}[(2m_q^2+p\cdot k_2)/(p\cdot k_1)+(2m_q^2+p\cdot k_1)/(p\cdot k_2)]\ , \tag{2.8}$$

and

$$W^H_{\rm PP}=\{2m_\pi^2[1/(2p\cdot k_1)+1/(2p\cdot k_2)]-1\}^2+1\ . \tag{2.9}$$

Here p and q are the four-momenta of the initial particles [q and $\bar{q}$ in reactions (2.1a) and (2.1b) and π^+ and π^- in reactions (2.1c) and (2.1d)] and k_1 and k_2 are those of the lepton or photon pairs produced. In the above equations $m_\mu=0.106$ GeV is the mass of the muon, $m_\pi=0.14$ GeV, the mass of the pion, and $m_q=0.005$ GeV, the mass of the quark. The functions

$$f^Q(p,y)=\{\exp[\beta(p_0\cosh y-|\mathbf{p}|\sinh y-\mu_q)]+1\}^{-1} \tag{2.10a}$$

and

$$f^H(p,y)=\{\exp[\beta(p_0\cosh y-|\mathbf{p}|\sinh y)]-1\}^{-1} \tag{2.10b}$$

are the statistical distribution for quarks and pions, respectively. $\beta=1/T$; μ_q is the quark chemical potential ($\mu_{\bar{q}}=-\mu_q$). For pions, the chemical potential is zero. The pion form factor is given by ($m_\rho=0.775$ GeV; $\Gamma_\rho=0.155$ GeV) [1,9]

$$|F_\pi(M^2)|^2=m_\rho^4/[(M^2-m_\rho^2)^2+m_\rho^2\Gamma_\rho^2]\ . \tag{2.11}$$

For two EOS, the above production rates are calculated in the pure QGP phase, pure HRG phase, and mixed phase. The limits for the time integration for a softer EOS ($B=250$ MeV/fm^3, with an entropy per baryon $S/A=11$ and energy density $\epsilon=2.6$ GeV/fm^3) and a stiffer EOS ($B=400$ MeV/fm^3, with $S/A=20$ and $\epsilon=4.2$ GeV/fm^3) are taken from our earlier papers [9,13]. The total contribution to the pair production rate is given by

$$\mathcal{D}N^{\rm total}_{\rm pair}(E_1,E_2)=\mathcal{D}N^Q_{\rm pair}(E_1,E_2)+\mathcal{D}N^{Q,\rm mixed}_{\rm pair}(E_1,E_2)+\mathcal{D}N^H_{\rm pair}(E_1,E_2)+\mathcal{D}N^{H,\rm mixed}_{\rm pair}(E_1,E_2)\ . \tag{2.12}$$

Following Yoshida [12], we also consider the pairs of particles which are *collinearly* produced in the *transverse* direction. In other words, the detectors are assumed to be opposite to each other in the plane perpendicular to the ion-beam axis in the center of the ion-momentum frame. The pairs of this arrangement are advantageous to test the azimuthal independence of the energy distribution experimentally without the disturbance of the fragments of nuclei [12]. The assumption of collinear pairs (i.e., the angle between the particles constituting the pair is π) gives the relation

$$M^2=(k_1+k_2)^2=2m_i^2+2(E_1E_2+|\mathbf{k}_1||\mathbf{k}_2|)\ , \tag{2.13}$$

where m_i is the rest mass of the particle produced (lepton or photon) and M the invariant mass of the pair. The

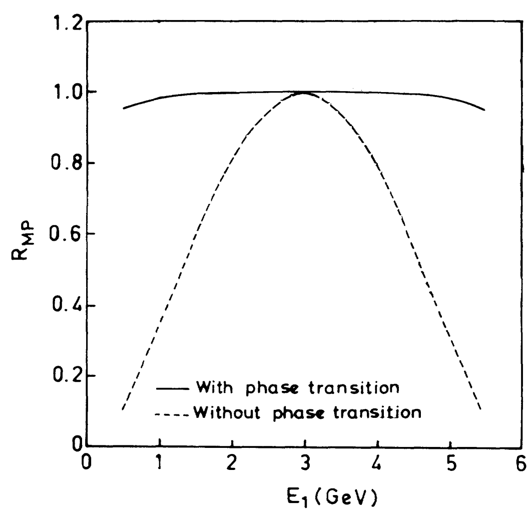

FIG. 1. The ratio of energy distributions for muon pairs, $R_{\rm pair}(E_1,E_2)\equiv R_{\rm MP}$, as a function of the energy E_1 of one of the muons [see Eq. (2.14)]. The solid line corresponds to the case when a QGP is formed and the dashed line represents the case without the formation of a QGP. Here $B=250$ MeV/fm^3 and $S/A=11$. The behavior of $R_{\rm MP}$ is nearly the same for $B=400$ MeV/fm^3 and $S/A=20$ also.

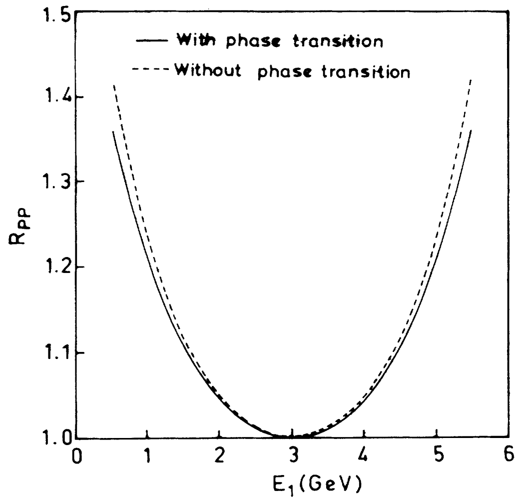

FIG. 2. As in Fig. 1, but for photon pairs. Here $R_{PP} \equiv R_{pair}(E_1,E_2)$ for photon pairs.

pairs with total energy $E=E_1+E_2=6$ GeV with $E_1,E_2 \geq 0.5$ GeV are chosen; the ratio

$$R_{pair}(E_1,E_2)=\frac{\mathcal{D}N^{total}_{pair}(3\text{ GeV},\ 3\text{ GeV})}{\mathcal{D}N^{total}_{pair}(E_1,E_2)} \tag{2.14}$$

is calculated, varying E_1 from 0.5 to 5.5 GeV. We define the contrast between the energy distribution ratios defined in Eq. (2.14) with the phase transition (WPT) and without phase transition (WOPT) for the pairs as

$$R^{pair}_{cont}(E_1,E_2)=R^{WPT}_{pair}(E_1,E_2)/R^{WOPT}_{pair}(E_1,E_2)\ . \tag{2.15}$$

In Fig. 1, $R_{MP}(E_1,E_2)$ is plotted as a function of E_1 for muon pairs. The solid line corresponds to the case when the QGP is formed and the dashed line represents the case without phase transition. While calculating the production rate in the case of no phase transition, only hadronic processes contribute and we have incorporated the excluded volume effect [14] for the treatment of hadrons in the pure HRG phase corresponding to no phase transition. The ratio $R_{PP}(E_1,E_2)$ for the cases with and without phase transition is shown in Fig. 2 for photon

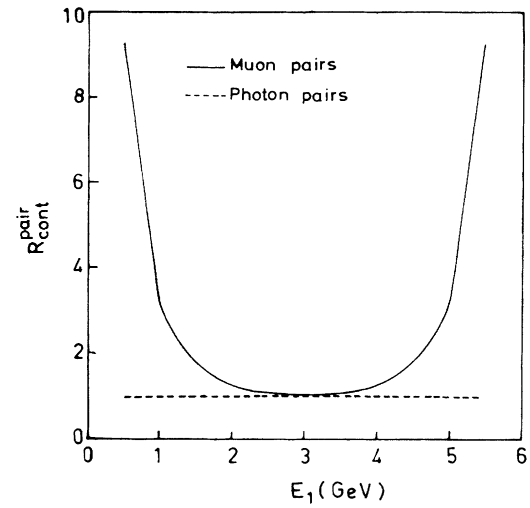

FIG. 3. The ratio R^{pair}_{cont} [see Eq. (2.15)] as a function E_1, the energy of one of the particles constituting the pair. The solid line represents the case of muon pairs and the dashed line denotes the same for photon pairs.

pairs. Figure 3 shows R^{pair}_{cont} as a function of E_1 for muon pairs (solid line) and photon pairs (dashed line). The behavior of the above quantities is almost the same for the stiffer EOS ($B=400$ MeV/fm^3) also.

III. TRANSVERSE MASS SPECTRUM OF DIMUONS AND THE EOS OF QGP

For a baryonless plasma, Siemens *et al.*, Kajantie *et al.*, and Ruuskanen [3] have shown that the dependence of the invariant-mass spectrum of lepton pairs on their transverse mass permits the separation of the plasma dileptons from the hadronic dileptons. We have extended their calculations to a baryon-rich QGP.

Let N^Q_{MP} be the number of dimuons produced through reaction (2.1a), N^H_{MP}, those produced via (2.1c), N^Q_{PP}, the number of photon pairs produced through (2.1b), and N^H_{PP} those produced via (2.1d). Following Refs. [3] and [9], the thermal production rate for the lepton/photon pair as a function of their invariant mass M and transverse mass M_T is found to be

$$dN^i_{pair}/dM^2dM_T=C^i_{pair}\int_{t_i}^{t_f}\lambda_i(t)t\,dt\int_{-\infty}^{\infty}g^i[M_T,T(t),\mu_i(t),y]dy\ , \tag{3.1}$$

where i again stands for QGP or HRG. The factors C^i_{pair} in the four reactions (2.1a)–(2.1d) are given below:

$$C^Q_{MP}=\tfrac{5}{36}(\alpha R_A/\pi)^2\{1+2m_\mu^2/M^2\}\{1-4m_\mu^2/M^2\}^{1/2}M_T\ , \tag{3.2}$$

$$C^H_{MP}=\tfrac{3}{20}C^Q_{MP}(1-4m_\pi^2/M^2)^{3/2}|F_\pi(M^2)|^2\ , \tag{3.3}$$

$$C^Q_{PP}=\tfrac{17}{27}M_T(\alpha R_A/\pi)^2\left\{[1+4m_q^2/M^2-8m_q^4/M^4]\ln\left[\frac{M^2}{2m_q^2}\{1+(1-4m_q^2/M^2)^{1/2}\}-1\right]\right.$$
$$\left.-[1+4m_q^2/M^2][1-4m_q^2/M^2]^{1/2}\right\}\ . \tag{3.4}$$

$$C_{\mathrm{PP}}^{H}=\tfrac{1}{16}M_T(\alpha R_A/\pi)^2\left\{[1+4m_\pi^2/M^2][1-4m_\pi^2/M^2]^{1/2}\right.$$
$$\left.-(4m_\pi^2/M^2)(1-2m_\pi^2/M^2)\ln\left[\frac{M^2}{2m_\pi^2}\{1+(1-4m_\pi^2/M^2)^{1/2}\}-1\right]\right\}. \quad (3.5)$$

The distribution function g^i is given by

$$1/g^i=(\exp[\beta\{(M_T/2)(\cosh y-\sinh y)-\mu_i\}]+\theta_i)\times(\exp[\beta\{(M_T/2)(\cosh y+\sinh y)+\mu_i\}]+\theta_i)\ . \quad (3.6)$$

When $i=$QGP, $\mu_i=\mu_q$, the quark chemical potential and $\theta_i=1$; if $i=$HRG, $\mu_i=\mu_\pi$, the pion chemical potential (=zero) and $\theta_i=-1$. The rapidity of the pair is y. The total rate for a given process is the sum of the rates from the pure phase and the mixed phase [see Eq. (3.1)]. While the contribution from the QGP shows a smooth behavior, that from the HRG has a prominent peak at the ρ-meson mass (0.775 GeV). In Figs. 4 and 5 we have plotted the total contribution from both the phases as a function of M for various values of M_T. Since the HRG contribution is far below that of the QGP beyond a certain M_T, we find that the vector-meson peak vanishes from the total contribution for large M_T's.

Next we integrate Eq. (3.1) over M^2 to find an expression for dN_{pair}/dM_T. To fix the limits of M^2, the well-known relation $M_T^2=P_T^2+M^2$, where P_T is the transverse momentum of the pair, is used. Since M^2 cannot exceed M_T^2, the maximum value of M^2 is M_T^2. In the case of dimuons, the minimum value of M^2 is $4m_\mu^2$ in the case of the QGP and $4m_\pi^2$ in the HRG phase. [See Eqs. (3.2) and (3.3).] In Fig. 6 the quantity $\ln\{(dN/dM_T)$ in $\mathrm{GeV}^{-1}\}$ for muon pairs is plotted against M_T for the two EOS. It is clear that the two curves are distinct with different slopes and the deviation between them increases with M_T. Hence the M_T distribution is useful to study the EOS of the QGP. The behavior of the same quantity for photon pairs is shown in Fig. 7 for two EOS. Here also the slopes are found to be different.

In the above, we considered only the rates for thermal emission of the dileptons and photon pairs. But the actual measured spectra contain the background from various other sources [15–18]. In the case of dileptons, the back-

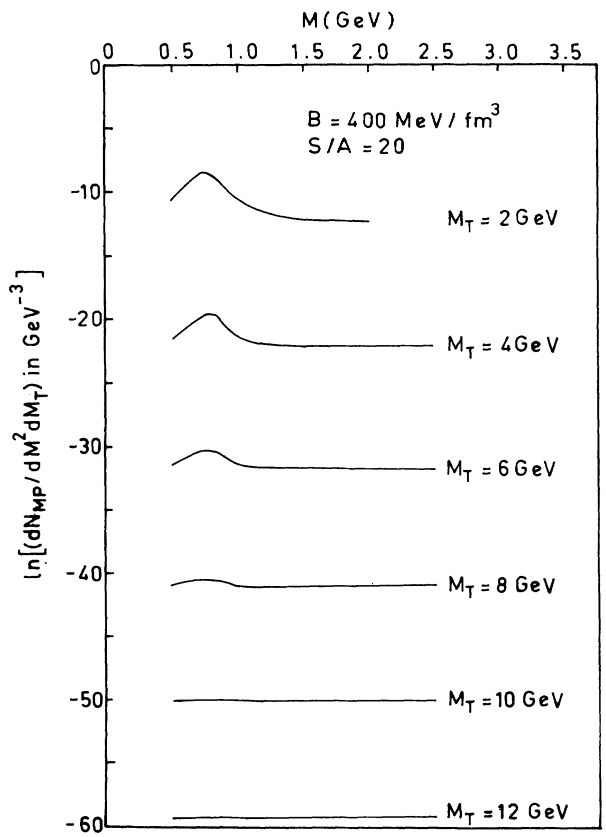

FIG. 4. The production rate for dimuons as a function of their invariant mass, for different values of their transverse mass, for the EOS of the QGP corresponding to $B=400$ MeV/fm^3 and $S/A=20$.

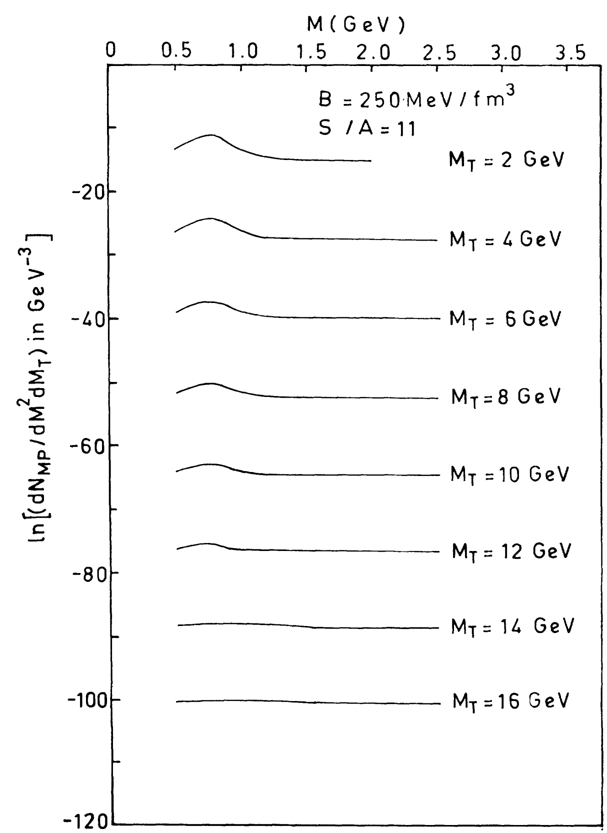

FIG. 5. As in Fig. 4, but for $B=250$ MeV/fm^3 and $S/A=11$.

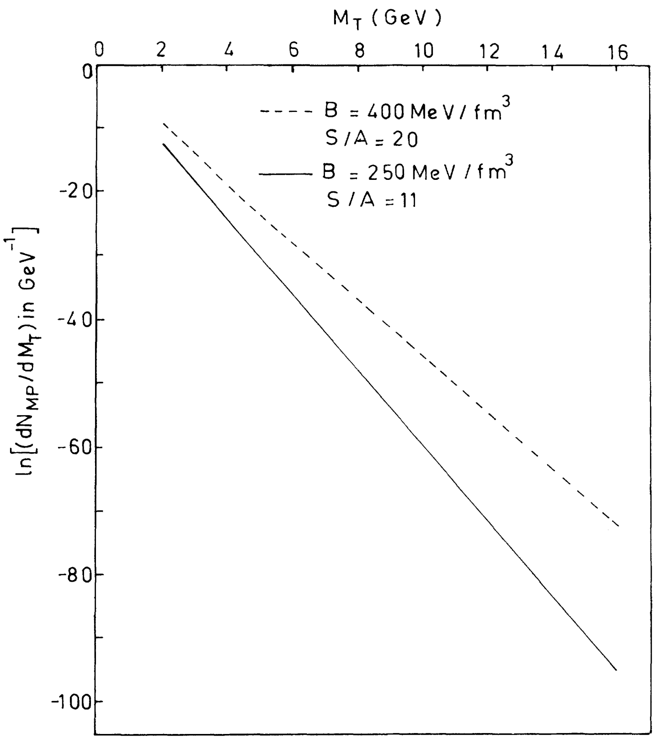

FIG. 6. The transverse mass spectrum of dimuons for two EOS. The dashed line corresponds to $B=400$ MeV/fm^3 and $S/A=20$ (stiffer EOS) and the solid line denotes the case when $B=250$ MeV/fm^3 and $S/A=11$ (softer EOS).

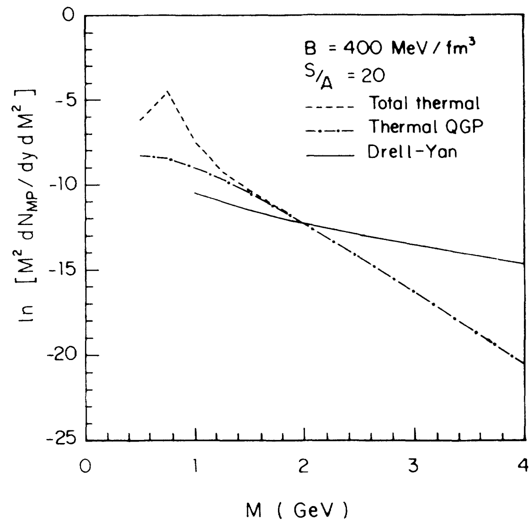

FIG. 8. Comparison of the thermal rate with the Drell-Yan background for $B=400$ MeV/fm^3 and $S/A=20$ (stiffer EOS). The dashed-dotted line corresponds to the contribution from the pure QGP phase through process (2.1a). The dashed line is the total thermal rate which is the sum of the contributions from the pure QGP, pure HRG, and mixed phases through the processes (2.1a) and (2.1b). The solid line is the Drell-Yan contribution for $\sqrt{s}=20$ GeV.

ground to the small M region comes from the decays of D mesons, hadronic bremsstrahlung, and Dalitz decays of π^0, η, η', and ω mesons; at large enough mass values, the Drell-Yan process will be the dominant source [15].

The transverse mass dependence of the Drell-Yan rate in the nucleus + nucleus level is very involved [16]. To have a feeling for the significance of the background sources, we present the production rates $dN/dy\, dM^2$ at $y=0$ in Figs. 8 and 9 for $B=400$ MeV/fm^3 and $B=250$ MeV/fm^3, respectively, for thermal dileptons and Drell-Yan pairs, say for $\sqrt{s}=20$ GeV. (The rate increases with $\sqrt{s}$.) The Drell-Yan rate was calculated following Refs. [15] and [16], using the set 1 parameters of Duke and Owens [19] for evaluating the structure functions. The background due to the sources other than the Drell-Yan source are not considered here because we are interested in the invariant-mass region $M>2.25$ GeV where the contribution from the pure QGP phase dominates the hadronic contribution in the thermal spectrum of dileptons (see Ref. [9]). It is seen from Figs. 8 and 9 that the

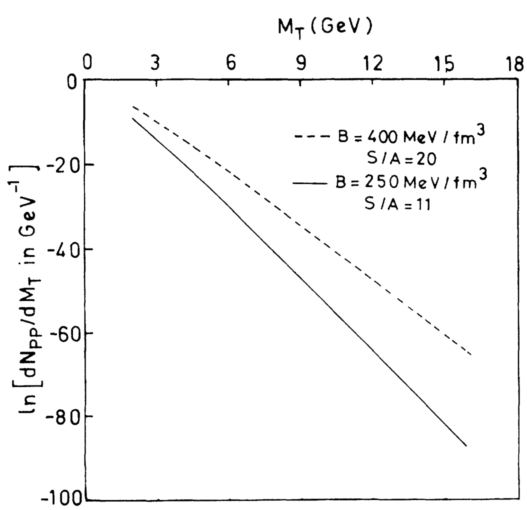

FIG. 7. Same as Fig. 6, but for photon pairs.

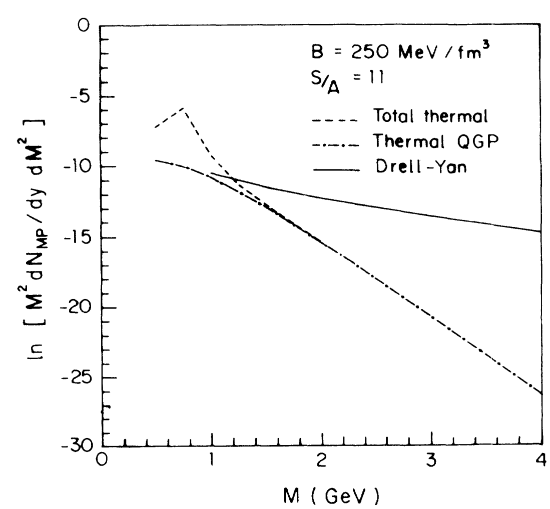

FIG. 9. As in Fig. 8, but for $B=250$ MeV/fm^3 and $S/A=11$.

Drell-Yan rate dominates over the thermal emission rate beyond $M=2$ GeV for a stiffer EOS and beyond 1.2 GeV for a softer EOS.

Similarly, for photon pairs, the dominant sources of background come from the neutral pion decay [15,17] at lower transverse momenta and the direct photon pairs from initial interactions of the incoming partons at higher transverse momenta through the subprocess $q\bar{q}\rightarrow\gamma\gamma$ and $gg\rightarrow\gamma\gamma$ [15,18]. But in the case of photons, throughout the spectrum, one or the other background source dominates the thermal spectrum. Therefore, while studying the diphoton spectrum one has to take into account the effect of background sources and choose the appropriate window for the transverse momentum such that the thermal pairs are not drowned in the background. Work is in progress to estimate the contribution from the background sources to the diphoton spectrum.

IV. DISCUSSIONS AND CONCLUSIONS

From Fig. 1 it is clear that the ratio R_{MP} remains almost a constant for all values of E_1 if there is a phase transition producing a QGP. If a QGP is not formed the same ratio increases, reaches the maximum value of unity, and then decreases with the variation in the energy of the muon E_1. From Fig. 2 we observe that the ratio R_{PP} decreases with E_1 and then increases for both cases of with and without a phase transition. There is not much of a difference between the two cases. From Fig. 3 it is clear that while $R_{\mathrm{cont}}^{\mathrm{pair}}$ remains almost a constant in the case of photon pairs, that for muon pairs shows a nice variation. $R_{\mathrm{cont}}^{\mathrm{pair}}$ for muon pairs is an order of magnitude more than that for photon pairs at $E_1=0.5$ GeV. Therefore the study of muon pairs is better than that of photon pairs to test whether or not a QGP is formed in relativistic heavy-ion collisions. Also the energy distribution ratios are not very sensitive to the EOS of the QGP.

From Figs. 4 and 5, we see that the dependence of the mass spectrum on M_T allows the separation of the hadronic dileptons from the plasma dileptons. Had there been only hadronic processes, the ρ peak would have persisted at all transverse masses of the dileptons. The extinction of the ρ-meson peak at higher values of the transverse mass of the dileptons can serve as a powerful signature for the formation of a QGP in heavy-ion collisions. The mass spectrum of the thermal dileptons can give information on the EOS of the QGP also. Whereas the vector-meson peak disappears at a lower value of M_T (~ 4 GeV) in the case of a baryonless plasma [3], it does so only at larger values of M_T for a baryon-rich plasma. It is found that for a stiffer EOS ($B=400$ MeV/fm^3) the peak vanishes for $M_T \gtrsim 10$ GeV, while for a softer EOS ($B=250$ MeV/fm^3) it disappears for $M_T \gtrsim 14$ GeV. Hence the dileptons can be used not only to detect the formation of a QGP but also to study its EOS. A study of the dimuon spectrum itself is therefore sufficient to detect the creation of a QGP as well as to study the EOS of the QGP. In this respect dimuons can be better than diphotons. It should be remembered that in the study of the spectra an appropriate window for M (or M_T) has to be chosen so that the background sources are not too dominant.

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