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Dilepton emission from heavy ion collision

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We extend to study the dilepton emission from heavy-ion collision of quark gluon plasma incorporating the temperature and chemical potential dependent on quark mass. The dilepton emission rate is found to be enhanced in comparison to the earlier calculation of dilepton emission from temperature dependent quark mass and to other theoretical calculations. The study finds that the emission rate of dilepton through the chemical potential is increasing function depending on the increasing value of chemical potential ranging from $\mu = 0.10 - 0.40$ GeV. This indicates that the overall result of dilepton emission through both chemical potential and temperature provide better information about the signature of forming quark-gluon plasma.

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1. Introduction

The study of phase transition in QCD (quantum chromodynamics) is investigated in the phase structure of high energy physics. The transition is happened from a confined to a deconfined state is predicted by the theory of strong interactions [1]. This deconfined state of matter after transformation is known as Quark-Gluon Plasma (QGP) and its relevant degree of freedom is controlled by free quarks and gluons. The study of strongly interacting matter at very high energy density and temperature has specific feature in the present day of heavy-ion experiments. The ongoing experiments like ultra-relativistic heavy-ion collision at BNL and CERN have come out as a platform in the study of QGP since adoption of heavy-ion research. The study has attracted great interest in cosmology and in the study of compact stars. The existence of matter about a few microseconds after the big-bang, has become a great task in the detection of matter in these experiments. So there are probable signals like strangeness enhancement [2], J/ψ suppression [3], dilepton and photon emissions [4, 5, 6] etc. Among these indirect probes, dilepton and photon emissions are assumed to be the best signal for the formation of QGP. As they are produced at the early stage of collision and coming out from the deep core of QGP, they escape with little or no interaction bringing relatively direct information about the initial stage of QGP formation. On the basis of these promising information, they are actively investigated by many authors. So dilepton emissions have been studied in a QGP in a finite temperature. Assuming the formation of QGP at the experiments at AGS and SPS energies [7], the presence of sizable amount of baryon chemical potential has been considered at the central collision zone and even at RHIC, the presence of these baryon chemical potential is accounted for consideration. The baryon chemical potential μ is to be at energies around $\sqrt{s} \leq 200$ AGeV. Moreover, in boost invariant space time approach, it was explained that the increase chemical potential was found in the central rapidity region and found the formation of plateau region of these dense matter [8]. It is again reported by the microscopic models [9, 10] limit that the colliding heavy ions may not be fully transparent. The work of Hammon and coworkers [11] have proved these idea of chemical potential produced at RHIC energy and reported the initial QGP have finite chemical potential. With these information, dilepton emission rate in (local) thermodynamic equilibrium is defined as function of temperature and quark chemical potential μ of the QGP. So Dumitru *et al*. [12] studied dilepton production with finite chemical potential long time ago. He showed the production rate as increasing function of the various chemical potentials. Similarly, this type of work are followed by Strickland modifying the distribution function as a quark and gluon fugacities in jüttner distribution function [13, 14]. Recently, Majumder *et al*. [15] have discussed dileptons from QGP produced at the RHIC energies at finite baryon density and Bass *et al*. [16] have pointed out that parton re-scattering and fragmentation lead to a substantial increase in the net-baryon density at mid-rapidity region. Thus, these works encourage us in the calculation of dilepton production rate with influence of quark chemical potential and temperature in the quark mass.

In this work we study dilepton emission in heavy-ion collision of QGP with the effect of temperature and chemical potential We did the calculation of dilepton emissions mainly in the intermediate mass region (IMR) even though the reports of low mass dileptons [17] are found in the emission rate. This is because that we expect thermal quark-antiquark annihilation as a measurable signal in the intermediate mass region [18]. So we explicitly exclude emission rate produced in the low mass regime. Moreover it is due to the fact that the Drell-Yan mechanism produces large amount of dilepton in the intermediate mass region [19, 20].

The main objective of the present article is to investigate dilepton emission in a QGP with temperature and finite baryonic chemical potential μ dependent on quark mass [21, 22]. Due to this temperature and chemical potential, quark mass has a finite value. The value removes the infrared divergence produced in the process of dilepton emission. The chemical potential is considered as $\mu = 1.574, 2.515$ and 3.583 GeV, which is good approximation as assumed in the scale of lattice data of having chemical potential in the centrality zone. Besides this, He and Dutta [23, 24] have used this chemical potential in their distribution function. Now, the finite quark mass is defined as: [25]

$$m_q^2(T,\mu) = \frac{N_c^2 - 1}{8N_c}[T^2 + \frac{\mu^2}{\pi^2}]g^2 \tag{1.1}$$

which is called as quasi model thermal and chemical potential dependent quark mass. Its value gives the minimum finite value on the basis of critical temperature. $g^2 = 4\pi\alpha_s$ known as the QCD coupling factor where,

$$\alpha_s = \frac{4}{(33 - 2N_f)ln(1 + \frac{p^2}{\Lambda^2})} \tag{1.2}$$

In the coupling constant, $\Lambda = 0.15$ GeV is QCD parameter for the appropriate number of quark flavors, N_f and p is low momentum cut-off value.

Now the article is organized as follows: In Sec. 2 we give a brief highlight of different mechanism to look at dilepton emission at finite temperature, T and quark chemical potential, μ from the QGP. In the last Sec. 3 we present our results, compared them with those of other authors and we finally give the main conclusion.

2. Dilepton emission from QGP

Computing dilepton emissions at finite temperature and baryon chemical potential have come out an interesting problem in the present day of heavy-ion collision. There are attractions of theoretical and experimental experts towards the works of dilepton emission. The theoretical experts did the calculation as they expect a similar output from the results of the experimental observations. Similarly we do our calculation of dilepton emission from a thermalized QGP as it treats a simple phenomena. In the calculation we consider the Drell-Yan mechanism [26] $q\bar{q} \to l^+l^-$ or $q(\bar{q})g \to q(\bar{q}) + l^+l^-$ as the most prominent reaction. Yet in recent times, Compton like processes such as $q(\bar{q})g \to q(\bar{q})l^+l^-$, $gg \to q\bar{q}l^+l^-$ are investigated by other authors [17, 23]. Here we exclusively use $q\bar{q} \to l^+l^-$ reaction as our choice because of its higher production of intermediate mass of dilepton pair in these reactions. In the calculation we use approximated Fermi-Dirac distribution function for quarks and antiquarks with their corresponding parton fugacities $\lambda_{q(\bar{q})} = e^{\mu/T}$ [27]. They are defined as:

$$f_q(p_1,T,\mu) = \frac{\lambda_q}{\exp^{\frac{(p_1-\mu)}{T}} + \lambda_q} \ , \ f_{\bar{q}}(p_2,T,\mu) = \frac{\lambda_{\bar{q}}}{\exp^{\frac{(p_2+\mu)}{T}} + \lambda_{\bar{q}}} \tag{2.1}$$

The function is slightly modified due to the approximation from Jüttner distributions of a chemically non-equilibrated system with its parton fugacity λ. At the chemical equilibrium the two

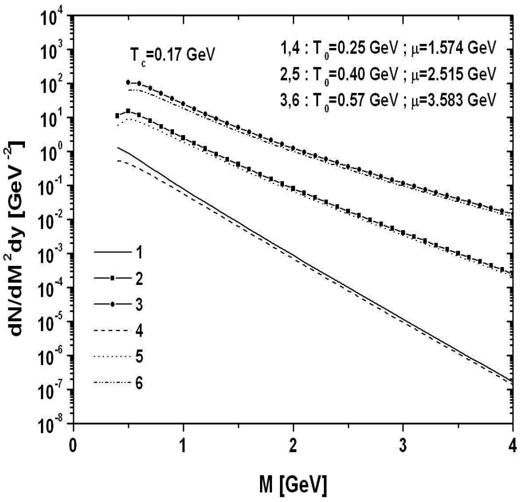

Figure 1: The dilepton emission rate, $\frac{dN}{dM^2dy}$ (GeV^{-2}), at initial temperatures $T_0 = 0.25$, 0.40 , 0.57 GeV and at critical temperature $T_c = 0.17$ GeV for different values of $\mu = 1.574, 2.515$ and 3.583 GeV

functions of quark and antiquark behave as Fermi-Dirac distribution function. For gluon distribution, it is also approximated Bose-Einstein and it is defined as:

$$f_g(p_g, T, \mu) = \frac{\lambda_g}{\exp^{\frac{p_g}{T}} - \lambda_g} \tag{2.2}$$

with parton fugacity λ_g which is approximately equal to unity. The gluon distribution function is specially used in the Compton process $q(\overline{q})g \to l^+l^-$ or gg fusion reaction. p_μ is lepton pair four momentum. Due to the approximated function in the Fermi-Dirac and Bose-Einstein, the emission rate is enhanced from the emission rate of using simple Fermi-Dirac distribution function. Now we define the parameters used in the calculation like as $M^2 = p^\mu p_\mu$ invariant lepton pair mass, p_μ is lepton pair four momentum. and m_l is lepton mass which is zero (ie $m_l = 0$). The dilepton emission rate $\frac{dN}{dM^2d^4x}$(i.e the number of dilepton emitted per space time volume per invariant lepton pair mass) is given by

$$\frac{dN}{dM^2d^4x} = \frac{5\alpha^2}{18\pi^3} TM\lambda_q^2(1 + \frac{2m_q^2}{M^2})K_1(M/T) \tag{2.3}$$

In this above solution, $K_1(M/T)$ is the modified Bessel's function which is taken as $K_1(M/T) = G(z)$ and volume element is $d^4x = d^2x_T dy\tau d\tau$. By expanding longitudinally, we finally obtain

$$\frac{dN}{dM^2dy} = \frac{5\alpha^2R^2}{18\pi^2} M(1 + \frac{2m_q^2}{M^2}) \int \lambda_q^2(\tau)G(z,\tau)T(\tau)\tau d\tau \tag{2.4}$$

where, $T(\tau) = T_0(\frac{\tau_0}{\tau})^{1/3}$ and λ_q is quark fugacity dependent on the baryonic potential.

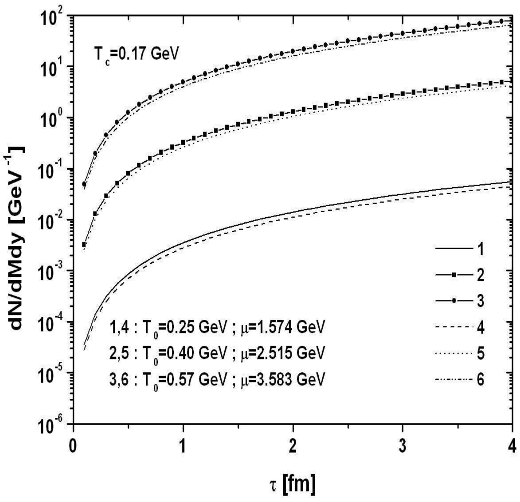

Figure 2: The dilepton integrated yield,$\frac{dN}{dMdy}$ (GeV^{-1}), at initial temperatures $T_0 = 0.25$,0.40 ,0.57 GeV and at critical temperature $T_c = 0.17$ GeV for different values of $\mu = 1.574, 2.515$ and 3.583 GeV

3. Results

The dilepton emission rates through quasi model of temperature and chemical potential in the quark mass are shown in the figures $(1-2)$ with the corresponding finite temperatures for the various chemical potentials. The results are obtained for the range of the low mass and intermediate mass region. Even though the contribution from hadronic decay is not considered in the calculation, there is significant production from the annihilation process. In Fig.(1) we show the dilepton emission rate for various values of quark chemical potential at different initial temperatures ranging from $T_0 = 0.25$ GeV to $T_0 = 0.57$ GeV and at critical temperature $T_c = 0.17$ GeV. The emission rate for these various values of quark chemical potential increases with increased in the chemical potential. The result is found to be very much effective in low mass region through the annihilation process and significant is still obtained up to the range of intermediate mass region. Beyond this range of invariant lepton pair mass the emission rate is insignificant. The result is compared with the earlier results of Ref. [23, 24, 27]. So the model with the temperature and chemical potential dependent on quark mass gives better outputs and agrees well with the recent theoretical results in dilepton emission. Moreover, further looking into the production rate of dilepton with the increase in lepton pair mass M for all the different chemical potentials, there is uniform decrease in the yield rate.

In the case of the dilepton integrated yield, result is increased in the form of exponential process. The increasing with the evolution time and after a certain time, it shows a consistent result for these different values of chemical potential. With further increase in the lifetime of QGP evolution, the effect of the increase in the quark chemical potential is observed more significantly and suppression produced at the initial stage can be overcome by increasing quark chemical potential with the evolution time. This is shown in the figure 2 with the corresponding initial temperatures at the transition temperature, $T = 0.17$ GeV. It implies that at larger chemical potential, the fields produced by the interaction of $q\bar{q}$ quickly stop the relativistic moving particles and take shorter time. However at slightly lower chemical potential the process take longer time due to weak fields of $q\bar{q}$ interaction. Here, we show the integrated yield by adopting the parameters of Z. He, Dutta [23, 24] and compared the results with the results produced by others. At the transition temperature $T = 0.17$ GeV the result starts increasing from our earlier results and the yield rate has very much effect with the chemical potential. There is clear-cut improvement with the increase in the chemical potential. It indicates that integrated yield at the lower initial temperature is much lower compared to the initial temperature $T = 0.57$ GeV. So, there is much effect on the integrated yield due to these two initial temperatures. An increment observed at the higher initial temperature $T = 0.57$ GeV indicates that the integrated yield increases near the formation of the early universe. This is due to the fact that the large chemical potential as well as the higher initial temperature enhance in the interaction of the constituent particles in the system and dominates over the effect of low initial temperature $T = 0.25$ GeV. It implies that temperature and chemical potential dependent on quark mass enhance our emission rate in comparison to other results of dilepton emissions [23, 24, 27]

4. Conclusion

We conclude that the quasi model of temperature and chemical potential dependent quark mass give improved results over those of massless quark in the production of dileptons and integrated yields. This improved output is specially contributed by the chemical potential and large tempertaure. So, we finally conclude that the results on dilepton production is found to be good and it is almost in the spectrum of the most recent theoretical calculations.

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