Enhancement of low-mass dileptons in heavy ion collisions

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Abstract

Using a relativistic transport model for the expansion stage of S+Au collisions at 200 GeV/nucleon, we show that the recently observed enhancement of low-mass dileptons by the CERES collaboration can be explained by the decrease of vector meson masses in hot and dense hadronic matter.

Typeset using REVTEX

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Based on the broken scale invariance of QCD, Brown and Rho have shown that the masses of non-strange vector mesons should be reduced in dense matter [1,2]. This is supported by studies using the QCD sum rules [3]. Experimentally, this can be verified by measuring the dileptons produced from heavy ion collisions. Since dileptons are not subject to the strong final-state interactions associated with hadronic observables, they are the most promising probe of the properties of hot dense matter formed in the initial stage of high energy heavy ion collisions [4–11]. Indeed, our recent study using the relativistic transport model has shown that in heavy ion collisions at SIS/GSI energies significant differences exist between the dilepton spectra with and without medium modifications of the masses and widths of vector mesons [12]. In particular, we have found that the rho peak from pion-pion annihilation shifts to around 550 MeV, and its height increases by about a factor of four.

Dileptons have already been measured at Bevalac/LBL by the DLS collaboration [13] in heavy-ion collisions at incident energy around 1 GeV/nucleon. Theoretical studies have shown that the observed dileptons with invariant masses above about 450 MeV are mainly from pion-pion annihilation [14,15]. Unfortunately, statistics are not good enough in the Bevalac experiments to give definite information on the in-medium vector meson properties. However, similar experiments with vastly improved statistics has been planned at SIS/GSI by the HADES collaboration [16].

A calculation similar to that of Ref. [12] has been carried out in the RQMD [17]. Using the in-medium rho meson mass from the QCD sum rules, a shift in the rho meson peak in the dilepton invariant mass spectrum is also seen in heavy ion collisions at AGS/BNL energies. Because of higher incident energies than at SIS/GSI, about 75% of the rho mesons in this study are produced from reactions other than pion-pion annihilation. Unfortunately, no experiments at the AGS/BNL have been designed to measure dileptons to verify the theoretical predictions.

For heavy ion collisions at the SPS/CERN energies, hot and dense matter is also formed in the initial stage of the collisions. We expect that medium effects will also lead to a shift in the vector meson peaks in the dilepton invariant mass spectra. Experiments from both

the HELIOS-3 [18] and the CERES [19] collaboration have shown that there is an excess of dileptons over those known and expected sources which can not be explained by uncertainties and errors of the normalization procedures. In particular, in the CERES experiment on central S+Au collisions at 200 GeV/nucleon, a significant enhancement of dileptons with invariant masses between 250 MeV to 1 GeV over that from the proton-nucleus collision has been found. In this Letter, we shall show that the modification of vector mass properties in medium can explain the enhancement of dileptons in this mass region.

To study this quantitatively, we generalize the relativistic transport model [20,21], which is based on the nonlinear σ-ω model for the nuclear matter [22], to describe the expansion of a hot dense fire-cylinder that is expected to be formed in the S+Au collisions at 200 GeV/nucleon. The initial conditions of this fire-cylinder are determined by fitting the observed pion and proton rapidity distributions and transverse mass spectra after the full dynamical evolution of the system. Specifically, they are fixed by the data from the NA44 collaboration [23] on central S+Pb collisions at 200 GeV/nucleon, which is very similar to the S+Au collisions in the CERES collaboration.

To describe reasonably the proton rapidity distribution, we find that the baryon number in the initial fire-cylinder is about 72. We include all baryon resonances with masses below 1720 MeV. We also include the lowest-lying hyperons, i.e., lambda (Λ) and sigma (Σ). Assuming that there are 32 baryons from the projectile and 40 from the target, the center-of-mass rapidity of the fire-cylinder with respect to the laboratory frame is then 2.63, which is close to the prediction from the RQMD simulation [17]. Initially, these baryons are distributed in a fire-cylinder whose cross section is taken to be about 40 fm^2, similar to the geometrical cross section of the projectile nucleus. If we further assume that the initial baryon density is about $3.5\rho_0$ ($\rho_0 = 0.16$ fm^{-3}), then the longitudinal length $2z_L$ of the fire-cylinder is found to be 3.2 fm. For mesons, we include pions, rhos, and omegas, as well as kaons and antikaons. Their intial abundance is determined by requiring that the final pion number agrees with the measured value and will be specified later. Furthermore, both baryons and mesons are distributed uniformly within the fire-cylinder.

The initial transverse momentum distributions of these particles are assumed to be given by a thermal distribution. We find that an initial temperature of about 185 MeV is needed to reproduce the observed slopes of the transverse momentum spectra for both protons and pions. Their longitudinal momentum distributions are determined by imposing a rapidity field as in the hydrodynamical model [24,25]. Specifically, we assume that the rapidity of a particle in the fire-cylinder frame is correlated to its longitudinal position via $y = 1.2 \sinh(z/z_L)$. Thus, particles at the surface of the cylinder move faster than those in the interior.

The fire-cylinder is then evolved as in the usual transport model for heavy-ion collisions [20,21]. For baryon-baryon interactions, we include both elastic and inelastic scattering for nucleons and deltas (1232), while for higher resonances we consider only elastic scattering with cross sections taken to be the same as that for NN scattering at the same center-of-mass energy. The meson-baryon interactions are formulated through resonance formations and decays. For meson-meson interactions, we include both pion-pion annihilation to a rho meson and the rho meson decay. This process is mainly responsible for the production of dileptons with invariant masses from $2m_\pi$ to m_ρ. The decay of an omega into three pions is also explicitly included, but the reverse process of omega formation from three pions is neglected. As the omega has a very small decay width (≈ 8 MeV), this is expected to have negligible effects on dilepton production.

In the calculation, dileptons are all produced from the decay of rho and omega mesons, i.e., $\rho^0 \to e^+e^-$, and $\omega \to e^+e^-$. The contribution of pion-pion annihilation is treated as a two-step process with explicit rho meson formation, propagation and decay, i.e., $\pi^+\pi^- \to \rho^0 \to e^+e^-$. As shown in Ref. [12], to study properly medium effects, it is essential to treat the intermediate vector meson explicitly in meson-meson annihilation.

For a pair of pions with a total invariant mass M, a rho meson of this mass is formed with a cross section given by the Breit-Wigner form [12]

$$\sigma_{\pi^+\pi^-\to\rho^0} = \frac{12\pi}{k^2} \frac{(m_\rho\Gamma_\rho)^2}{(M^2 - m_\rho^2)^2 + (m_\rho\Gamma_\rho)^2},$$

(1)

where k is the pion momentum in the center-of-mass frame of the rho meson. In the above, m_ρ and Γ_ρ are the centroid and width of the rho meson. When the medium modification of the rho-meson mass is included, m_ρ and Γ_ρ are replaced by m_ρ^* and Γ_ρ^*, respectively [12].

The decay width of the rho meson into a dilepton is proportional to its mass [26], i.e., $\Gamma_{\rho^0 \to e^+e^-}(M) = \lambda_\rho M$, where $\lambda_\rho = 8.814 \times 10^{-6}$ is determined from the observed width at $m_\rho \approx 768$ MeV. Similarly, for the omega decay width, we have $\Gamma_{\omega \to e^+e^-}(M) = \lambda_\omega M$, with $\lambda_\omega = 0.767 \times 10^{-6}$.

To make a quantitative comparison with the experimental data, we need to include the experimental acceptance and resolution. The former is taken into account by first transforming the dilepton momentum and energy from the fire-cylinder frame to the laboratory frame, using the rapidity determined previously, and then including only those dileptons with transverse momentum $p_t > 0.2$ GeV and pseudo-rapidity $2.1 < \eta < 2.65$. The effect from the cut-off in the opening angle $\theta_{ee} > 35$ mrad is estimated to be very small (on the level of 10%) and has been neglected. Following Ref. [11], the experimental resolution is included by folding the original dilepton mass spectrum with a normalized smearing function of the Gaussian form with a variance $\sigma \approx 15$ MeV, similar to the mass resolution in the CERES experiment.

We first consider the case in which both rho and omega mesons are treated as free particles. We assume that pions, rhos, and omegas are in chemical equilibrium, i.e, $\mu_\rho = 2\mu_\pi$ and $\mu_\omega = 3\mu_\pi$. In order to reproduce the observed pion rapidity distribution and spectrum, we find that the pion chemical potential is about 135 MeV at an initial temperature of 185 MeV. The initial pion, rho and omega numbers are then determined to be 95, 57, and 39, respectively. At this temperature, we find that nucleons and deltas (1232) account for about 60% of all baryons, while for higher resonances each contributes about 1-3%.

The final proton and pion transverse momentum spectra and rapidity distributions are shown in Fig. 1 by the dotted histograms. They are seen to agree reasonably with the preliminary data from the NA44 collaboration for central S+Pb collisions at 200 GeV/nucleon shown in Fig. 1 by solid circles. We note that initially both protons and pions are assumed

to have the same temperature. The final pion spectrum is, however, steeper than the proton spectrum, and this is mainly due to the transverse expansion of the system.

There are three sources for dilepton production in our model, i.e., the decay of primary rho mesons (those already exist in the initial fire-cylinder), the decay of omega mesons, and the decay of rho mesons formed from pion-pion annihilation during the evolution of the system. The latter one is usually identified as the contribution from pion-pion annihilation. As expected, a strong omega peak is seen around 780 MeV, which becomes flatter after folding with the experimental resolution. Also, we see a broad rho peak around 770 MeV due to decays of primary rho mesons. If there were no pion-pion annihilation, then the dilepton yield would decrease substantially once its mass is below $m_{\rho,\omega}$. Pion-pion annihilation, on the other hand, builds up the dilepton strength between $2m_\pi$ and m_ρ, as already shown in heavy ion collisions at Bevalac energies [14,15]. Therefore, the CERES data clearly indicate the importance of pion-pion annihilation, as noted in Ref. [19]. As shown in Fig. 2 by the dotted histogram, even with the inclusion of pion-pion annihilation, the theoretical dilepton yield disagrees with the experimental data. The former is about a factor of 3-5 too low between $2m_\pi$ and 550 MeV, and about a factor of 3 too high around $m_{\rho,\omega}$.

The effects of the medium modification of vector mesons can be consistently included in our model by extending the non-linear σ-ω model used in our previous studies [12] and in the above calculation to include the explicit coupling of vector mesons to the scalar field using the idea of the quark-meson coupling model of Ref. [27]. The generalized scalar field then satisfies the following self-consistent conditions

$$m_q^* = m_q - \frac{1}{3}g_\sigma\langle\sigma\rangle,$$
$$m_\sigma^2\langle\sigma\rangle + b\langle\sigma\rangle^2 + c\langle\sigma\rangle^3 = g_\sigma\rho_{sN} + \frac{2}{3}g_\sigma\rho_{s\rho} + \frac{2}{3}g_\sigma\rho_{s\omega}, \tag{2}$$

where the constituent quark mass is denoted by m_q, and ρ_{sN}, $\rho_{s\rho}$, and $\rho_{s\omega}$ are the 'scalar' densities of the nucleon, the rho meson, and the omega meson, respectively. The parameters g_σ, b and c are taken from Ref. [21] that correspond to a soft nuclear equation of state with a nucleon Dirac mass $m_N^* \approx 0.83\, m_N$ and a compressibility $K \approx 200$ MeV at normal nuclear

density. The nucleon, rho-meson and omega-meson masses are then given by $m_N^* \approx 3m_q^*$ and $m_\rho^* \approx m_\omega^* \approx 2m_q^*$ according to the constituent quark model. In this model, the scalar field energy is large in hot dense matter when hadron masses are reduced. As the system expands and cools, the field energy decreases and is converted back to hadron masses so they return to free masses at freeze out.

By including the direct coupling of vector mesons to the scalar field, we have implicitly taken into account, although partially, the temperature dependence of hadron masses, in addition to the density dependence. The effective nucleon and rho-meson masses are shown in Fig. 3 as functions of temperature, for different densities. At $3.5\rho_0$ and a temperature of 185 MeV, the rho meson mass reduces to about 380 MeV. Because of the reduction of their masses, the abundance of the rho and omega mesons in the initial fire-cylinder increases, and we need thus only a small pion chemical potential of about 50 MeV in order to reproduce the experimental pion rapidity distribution and transverse momentum spectrum. The initial pion, rho and omega numbers are then determined to be 44, 88, and 39, respectively. The initial low mass rho and omega mesons thus act as a reservoir for the observed large pion yield. We expect that including also reduced in-medium masses of mesons other than vector mesons such as the a_1 will further decrease the initial pion chemical potential as well as the initial temperature.

The comparison with the experimental data for the proton and pion spectra and rapidity distributions in this case is shown in Fig. 1 by the solid histograms, and the agreement is again reasonable. The final dilepton mass spectrum is shown in Fig. 2 by the solid histogram. It is seen that with reduced rho and omega meson masses in hot and dense hadronic matter, the agreement with the experimental data from $2m_\pi$ to m_ρ is greatly improved. In particular, we have about a factor of 5 enhancement in the yield of dileptons with masses from 250 MeV to about 500 MeV. This magnitude is similar to that found in Ref. [12] for heavy ion collisions at the SIS/GSI energies. Also, the shape of the mass spectrum is now in better agreement with the experimental data. The enhancement at low invariant masses is mainly due to pion-pion annihilation occurring in the hot and dense matter. Since pions have a

thermal distribution, most pion pairs are of low invariant mass. When the rho-meson mass is reduced in hot and dense matter, its formation probability from the pion-pion annihilation is enhanced, and thus increasing the production of low-mass dileptons. Furthermore, we also have a good agreement with the data around $m_{\rho,\omega}$, while in the previous calculation (the dotted histogram in Fig. 2) the data are overestimated by about a factor of three. This is due to the shift of the rho-meson yield to lower masses. The remaining peak around $m_{\rho,\omega}$ then comes from the decay of omega mesons which have a very small decay width, and therefore mostly decay in the final stage when their masses have returned to their free values.

We note that the first three points in the data are mainly from the Dalitz decays of π_0 and η as pointed out in Ref. [19], which are thus not essential for present discussions. For the fourth experimental point at 250 MeV, the Dalitz decays also contribute about half the strength [19], while according to our model another half comes from the decay of very low mass rho mesons.

For dileptons at larger pseudo-rapidities $(3.7 < \eta < 5.5)$ as measured in the HELIOS-3 collaboration [18], the enhancement of low mass dileptons due to dropping vector meson masses is found to be only about a factor of two and is consistent with the experimental observation. This can be understood as follows. The dileptons measured in the CERES experiment is in the central rapidity corresponding to the peak of the initial distribution. These dileptons are therefore produced early in the expansion when the baryon density is high and the rho meson mass is small. In the HELIOS-3 experiment, the dileptons are measured in the forward rapidity for which there are initially very few particles. They are thus produced later in the expansion when interactions lead to a broader rapidity distribution. The baryon density at which large rapidity dileptons are produced is thus lower and the reduction of the rho meson mass is smaller.

In conclusion, using the relativistic transport model to describe the expansion stage of a fire-cylinder formed in heavy-ion collisions at SPS energies, we have calculated the dilepton spectra including the medium modification of vector meson properties in hot dense matter. It

has been found that the model can explain quantitatively the observed enhancement of low-mass dileptons in central S+Au collisions at 200 GeV/nucleon by the CERES collaboration. The medium effects are expected to be more prominent in future experiments for Pb+Pb collisions at the SPS/CERN due to the larger initial baryon density in the collisions.

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Figure Captions

Fig. 1: Proton and pion transverse mass spectra and rapidity distributions. Dotted and solid histograms are obtained from simulations based on the relativistic transport model with free and in-medium vector meson masses, respectively, and solid circles are experimental data from the NA44 collaboration [23].

Fig. 2: Dilepton invariant mass spectra from calculations with free (dotted histogram) and in-medium vector meson (solid histogram) masses, respectively. Solid circles are the experimental data from the CERES collaboration [19].

Fig. 3: Effective masses of the nucleon and rho-meson as functions of temperature for different baryon densities.