Enhancement of low-mass dileptons in SPS heavy-ion collisions: possible evidence for dropping rho meson mass in medium

C. M. Ko\textsuperscript{a}, G. Q. Li\textsuperscript{a}, G. E. Brown\textsuperscript{b}, and H. Sorge\textsuperscript{b}

\textsuperscript{a}Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843, USA

\textsuperscript{b}Department of Physics, State University of New York, Stony Brook, NY 11794, USA

Dilepton production in proton- and nucleus-induced reactions at SPS energies is studied in the relativistic transport model using initial conditions determined by the string dynamics from RQMD. It is found that both the CERES and HELIOS-3 data for dilepton spectra in proton-nucleus reactions can be well described by the conventional mechanism of Dalitz decay and direct vector meson decay. However, to provide a quantitative explanation of the observed dilepton spectra in central S+Au and S+W collisions requires contributions other than these direct decays. Introducing a decrease of vector meson masses in hot dense medium, we find that these heavy-ion data can also be satisfactorily explained. We also give predictions for Pb+Au collisions at 160 GeV/nucleon using current CERES mass resolution and acceptance.

1. INTRODUCTION

Recent observation of the enhancement of low-mass dileptons in central S+Au and S+W collisions at SPS/CERN energies by the CERES \cite{1} and the HELIOS-3 \cite{2} collaboration, respectively, has generated a great deal of interest in the heavy-ion community. Different dynamical models, such as hydrodynamical and transport models, have been used to investigate this phenomenon \cite{3-5}. Although several different mechanisms \cite{3-9} have been put forward to explain the observed enhancement, the most successful explanation seems to be the decrease of vector meson masses in hot dense matter \cite{3,4}. This has been worked out by us using the relativistic transport model based on the extended Walecka model \cite{3}; and was supported by the calculation of Cassing \textit{et al.} \cite{4} using a dropping in-medium rho meson mass predicted from the QCD sum rules.

In this contribution, we shall review the results from our studies for proton- and S-induced collisions and present the predictions for Pb+Au collisions.

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2. THE RELATIVISTIC TRANSPORT MODEL AND IN-MEDIUM MASSES

In studying medium effects in heavy-ion collisions, the relativistic transport model \[10\] based on the Walecka model \[11\] has been quite useful. In this model, the nucleon mass is reduced by a scalar field while its energy is shifted by a vector field. At high densities, the nucleon mass is small and the energy is stored in the fields. As the system expands, the nucleon mass returns to its free value by getting the energy back from the scalar field energy. The model thus provides a thermodynamically consistent description of the medium effects. Applications of the model to heavy-ion collisions at SIS/GSI energies have allowed us to extract from the experimental data useful information on hadron properties in dense matter \[12\].

In heavy-ion collisions at SPS/CERN energies, many hadrons are produced in the initial nucleon-nucleon interactions. This is usually modeled by the fragmentation of strings, which are the chromoelectric flux-tubes excited from the interacting quarks \[13\]. One successful model for taking into account this nonequilibrium dynamics is the RQMD model \[14\]. To extend the relativistic transport model to heavy-ion collisions at these energies, we have used as initial conditions the hadron abundance and distributions obtained from the string fragmentation in RQMD. Further interactions and decays of these hadrons are then taken into account as in usual relativistic transport model.

Figure 1. Rho meson mass at finite density and temperature. The normal nuclear matter density is denoted by $\rho_0 = 0.16 \text{ fm}^{-3}$.

To study the effects of dropping vector meson masses \[15-17\] on the dilepton spectrum
in heavy-ion collisions, we have extended the Walecka model from the coupling of nucleons to scalar and vector fields to the coupling of light quarks to these fields, using the ideas of the meson-quark coupling model [18] and the constituent quark model. For a system of baryons (we take the nucleon as an example), pseudoscalar mesons (π and η mesons), vector mesons (ρ and omega mesons), and the axial-vector meson (a1) at temperature T and baryon density ρ_B, the scalar field ⟨σ⟩ is determined self-consistently from

\[ m_σ^2⟨σ⟩ = \frac{4g_σ}{(2\pi)^3} \int \frac{dk}{E_π^*} \left[ \frac{1}{\exp((E_π^* - μ_B)/T) + 1} + \frac{1}{\exp((E_π^* + μ_B)/T) + 1} \right] \]

\[ + \frac{0.45g_σ}{(2\pi)^3} \int \frac{dk}{E_ρ^*} \frac{1}{\exp(E_ρ^*/T) - 1} + \frac{6g_σ}{(2\pi)^3} \int \frac{dk}{E_ω^*} \frac{1}{\exp(E_ω^*/T) - 1} \]

\[ + \frac{2g_σ}{(2\pi)^3} \int \frac{dk}{E_ω^*} \frac{1}{\exp(E_ω^*/T) - 1} + \frac{6\sqrt{2}g_σ}{(2\pi)^3} \int \frac{dk}{E_α^*} \frac{1}{\exp(E_α^*/T) - 1}, \]  

(1)

where we have used the constituent quark model relations for the nucleon and vector meson masses [18], i.e., \( m_N^* = m_N - g_σ ⟨σ⟩ \), \( m_ρ^* ≈ m_ρ - (2/3)g_σ ⟨σ⟩ \), \( m_ω^* ≈ m_ω - (2/3)g_σ ⟨σ⟩ \), the quark structure of the η meson in free space which leads to \( m_η^* ≈ m_η - 0.45g_σ ⟨σ⟩ \), and the Weinberg sum rule relation between the rho-meson and a1 meson masses [19,20], i.e., \( m_{α1}^* ≈ m_{α1} - (2\sqrt{2}/3)g_σ ⟨σ⟩ \). In Fig. 1, we show the density and temperature dependence of the rho meson mass using \( g_σ = 9.58 \) and \( m_σ = 550 \) MeV from the Walecka model.

3. DILEPTON PRODUCTION

The main contributions to dileptons with mass below 1.2 GeV are the Dalitz decay of π^0, η, and ω, the direct leptonic decay of ρ^0, ω, and φ, the pion-pion annihilation which proceeds through the ρ^0 meson, and the kaon-antikaon annihilation that proceeds through the φ meson. The differential widths for the Dalitz decay of π^0, η, and ω are related to their radiative decay widths via the vector dominance model, which are taken from Ref. [21]. We do not introduce the vector dominance model form factor for the Dalitz decay of a1 meson as the processes \( a1 \leftrightarrow πρ \) and \( ρ \rightarrow l^+l^- \) are treated explicitly as a two-step process in our model.

The decay of a vector meson into dilepton is given by the width,

\[ \Gamma_{V→l^+l^-} (M) = C_{l^+l^-} \frac{m_Y^4}{3M^3} (1 - \frac{4m_π^2}{M^2})^{1/2} (1 + \frac{2m_π^2}{M^2}). \]  

(2)

The coefficient \( C_{l^+l^-} \) in the dielectron channel is \( 8.814 \times 10^{-6}, \ 0.767 \times 10^{-6}, \) and \( 1.344 \times 10^{-6} \) for ρ, ω, and φ, respectively, and is determined from the measured width. For the dimuon channel, these values are slightly larger.

When medium effects on vector meson masses are included, \( m_Y \) is replaced by \( m_Y^* \). Also, the in-medium strong decay width is calculated with the in-medium mass. We have neglected the collisional broadening of vector meson widths in medium [22], based on the argument that their magnitudes are comparable to the mass resolution in CERES experiments, so they do not affect appreciably the final results.

In our model, dileptons are emitted continuously during the time evolution of the colliding system. The way the dilepton yield is calculated can be illustrated by rho
meson decay. Denoting, at time $t$, the differential multiplicity of neutral rho mesons by $dN_{\rho}(t)/dM$, then the differential dilepton production probability is given by

$$\frac{dN_{l^+l^-}}{dM} = \int_{0}^{t_f} \frac{dN_{\rho}(t)}{dM} \Gamma_{\rho \to l^+l^-}(M) dt + \frac{dN_{\rho}(t_f)}{dM} \left( \frac{\Gamma_{\rho \to l^+l^-}(M)}{\Gamma_{\rho}(M)} \right),$$

where $t_f$ is the freeze-out time, which is found to be about 20 fm/c. The first term corresponds to dilepton emission before freeze out while the second term is from decay of rho mesons still present at freeze out.

3.1. Proton-nucleus collisions

Figure 2. Dilepton invariant mass spectra from (a) p+Be collisions at 450 GeV, (b) p+Au collisions at 200 GeV, and (c) p+W collisions at 200 GeV after including the experimental acceptance cuts and mass resolution. Dashed curves give dilepton spectra from different sources. Experimental data in (a) and (b) from the CERES collaboration [1] and in (c) from the HELIOS-3 collaboration [2] are shown by solid circles, with statistical errors given by bars. Brackets represent the square root of the quadratic sum of systematic and statistical errors.

The results for dilepton spectra from p+Be collisions at 450 GeV, p+Au collisions at 450 GeV, and p+W collisions at 200 GeV are shown in Figs. 2(a), 2(b), and 2(c), respectively, together with data from the CERES [1] and the HELIOS-3 collaboration [2]. It is seen that the data can be well reproduced by Dalitz decay of $\pi^0$, $\eta$ and $\omega$ mesons, and direct leptonic decay of $\rho^0$, $\omega$ and $\phi$ mesons. These results are thus similar to that found in
Ref. [4] using the Hadron-String Dynamics and constructed by the CERES collaboration from known and expected sources of dileptons [4].

3.2. Nucleus-nucleus collisions

Figure 3. Dilepton invariant mass spectra in (a) S+Au and (b) S+W collisions at 200 GeV using free (dashed curves) and in-medium (solid curve) meson masses. Experimental data in (a) from the CERES collaboration [1] and in (b) from the HELIOS-3 collaboration [2] are shown by solid circles.

With free meson masses, the calculated dilepton spectra, normalized by the average charged-particle multiplicity, are shown in Fig. 3(a) by the dashed curve together with the CERES data. Although pion-pion annihilation is important for dileptons with invariant mass from 0.3 to 0.65 GeV, it still does not give enough number of dileptons in this mass region. Furthermore, for masses around $m_{\rho,\omega}$ there are more dileptons predicted by the theoretical calculations than shown in the experimental data. These are very similar to our earlier results based on a thermally equilibrated fire cylinder model [3] as well as that of Cassing et al. [4] based on the Hadron-String Dynamics model and Srivastava et al. [5] based on the hydrodynamical model.

The results obtained with in-medium meson masses are shown in Fig. 3(a) by the solid curve. Compared with the results obtained with free meson masses, there is about a factor of 2-3 enhancement of the dilepton yield in the mass region from 0.2 to 0.6 GeV, which thus leads to a good agreement between the theoretical results with the CERES data. This is again very similar to that found in Ref. [3] using the fire-cylinder model.
The same model has been used to calculate the dimuon spectra from central S+W collisions by the HELIOS-3 collaboration. The results obtained with free meson masses are shown in Fig. 3(b) by the dashed curve, and are below the HELIOS-3 data in the mass region from 0.35 to 0.6 GeV, and slightly above the data around \( m_{\rho,\omega} \) as in the CERES case. However, the discrepancy between the theory and the data is somewhat smaller in this case due to the smaller charged-particle multiplicity at a larger rapidity than in the CERES experiment.

Our results obtained with in-medium meson masses are shown in Fig. 3(b) by the solid curve, and are in good agreement with the data. The importance of in-medium meson masses in explaining the HELIOS-3 data has also been found by Cassing et al. [4].

3.3. Predictions for Pb+Au collisions

Figure 4. Dilepton spectra from central Pb+Au collisions with free (dashed curve) and in-medium (solid curve) meson masses. The CERES mass resolution and acceptance cuts for S+Au collisions are included.

Dilepton production in Pb+Au collisions at 160 GeV/nucleon is currently being measured by the CERES collaboration. We have calculated the dilepton spectrum for this reaction using present CERES mass resolution and acceptance cuts. The theoretical predictions for the central collisions are shown in Fig. 4 for the two scenarios of free (dashed curve) and in-medium meson masses (solid curve). The normalization factor \( dN_{ch}/d\eta \) here is the average charge particle pseudo-rapidity density in the pseudo-rapidity range of 2 to 3, and is about 440 in this collision. With free meson masses, there is a strong peak
around $m_{\rho,\omega}$, which is dominated by $\rho^0$ meson decay as a result of an enhanced contribution from pion-pion annihilation in Pb+Au collisions than in S+Au and proton-nucleus collisions. With in-medium meson masses, the $\rho$ meson peak shifts to a lower mass, and the peak around $m_{\rho,\omega}$ becomes a shoulder arising mainly from $\omega$ meson decay. At the same time we see an enhancement of low-mass dileptons in the region of 0.25-0.6 GeV as in S+Au collisions.

Since the dilepton yield from both Dalitz decay and $\omega$ leptonic decay increases roughly linearly with the charged-particle multiplicity, whereas the contribution from pion-pion annihilation increases more than linearly, the dilepton spectra per charged particle in the invariant mass region of $0.3 < M < 0.6$ GeV, where pion-pion annihilation dominates, are somewhat larger in Pb+Au collisions than in S+Au collisions. However, the medium effects are similar in the two collisions. Both dilepton spectra show a low mass peak at about 400 MeV, and this is due to the similar initial rho meson mass in the two cases. The initial nuclear density in Pb+Au collision is about $4\rho_0$ and is higher than that (about $2.5\rho_0$) in S+Au collisions, but the difference in the rho meson mass in the two cases is small as shown in Fig. 1. Furthermore, the yield of low mass dileptons is about the same as the dilepton yield at the rho peak in the spectra obtained with the free rho meson mass. Although there are more rhos when the mass is reduced, their contribution to low mass dileptons is suppressed due to both a smaller leptonic decay width (see Eq. (2)) and a short duration of high density matter in the collision (see Eq. (3)).

4. SUMMARY AND OUTLOOK

In summary, we have studied dilepton production from both proton-nucleus and nucleus-nucleus collisions using the relativistic transport model with initial conditions determined by string fragmentation from the initial stage of the RQMD model. It is found that the dilepton spectra in proton-nucleus reactions measured by the CERES and the HELIOS-3 collaboration can be well understood in terms of conventional mechanisms of Dalitz decay and direct vector meson decay. For dilepton spectra in central S+Au and S+W collisions, these conventional mechanisms, however, fail to explain the data, especially in the low-mass region from about 0.25 to about 0.6 GeV in CERES experiments, and from 0.35 to 0.65 GeV in HELIOS-3 experiments. Including the contribution from pion-pion annihilation, which is important in the mass region from $2m_\pi$ to $m_{\rho,\omega}$, removes some of the discrepancy. But the theoretical prediction is still substantially below the data in the low mass region and somewhat above the data around $m_{\rho,\omega}$. The theoretical results are brought into good agreement with the data when reduced in-medium vector meson masses are taken into account. The results of the present study based on initial conditions from the RQMD model are thus very similar to our earlier results assuming that initially there is a thermally equilibrated fire-cylinder.

We have also presented predictions for the dilepton spectrum from central Pb+Au collisions. Since the medium effects in our model already saturate at a few times of normal nuclear density, the results from this reaction turn out to be very similar to that from S+Au collisions. However, medium effects are expected to become stronger in heavy-ion collisions at lower incident energies when the system is initially in a soft mixed phase and
thus expands slowly, allowing thus a longer time for the emission of low mass dileptons [24].

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