Intermediate-Mass Dilepton Production in Heavy-Ion Collisions at 200*A* GeV

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Through the analysis of HELIOS-3 data obtained at the CERN Super Proton Synchrotron (SPS), we demonstrate the importance of secondary processes for dilepton production in heavy-ion collisions in the intermediate invariant mass region. We find that while the dilepton spectra between 1 and 2.5 GeV from proton-induced reactions can be attributed to the decay of primary vector mesons, charmed hadrons, and initial Drell-Yan processes, the strong enhancement seen in the heavy-ion data comes mainly from secondary processes. Furthermore, we find $\pi a_1 \to l\bar{l}$ to be the most important process in this mass region, as was found by thermal rate calculations. [S0031-9007(98)06932-4]

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The experimental measurement and theoretical investigation of dilepton production in nuclear collisions constitutes one of the most active and exciting fields in heavy-ion physics [1]. Because of their relatively weak final-state interactions with the hadronic environment, dileptons are considered ideal probes of the early stage of heavy-ion collisions, where quark-gluon-plasma (QGP) formation and chiral symmetry restoration are expected [2,3].

Dilepton mass spectra in heavy-ion collisions can be divided into three regions. The region below m_ϕ ($\sim$1 GeV) is dominated by hadronic interactions and hadronic decays at freeze-out. In the intermediate-mass region, $m_\phi < M < m_{J/\Psi}$, the contribution from the thermalized QGP might be seen [4]. In the high-mass region at and above $m_{J/\Psi}$ the major effort has been the detection and understanding of J/Ψ suppression. So far, the experimental measurement of dilepton spectra at the CERN SPS has mainly been carried out by three collaborations: the CERES Collaboration has specialized in dielectron spectra in the low-mass region [5,6], the HELIOS-3 [7] Collaboration has measured dimuon spectra from threshold up to the J/Ψ region, and the NA38/NA50 [8] Collaboration measures dimuon spectra in the intermediate and high-mass regions.

Recent observation of the enhancement of low-mass dileptons in central heavy-ion collisions over the proton-induced reactions by the CERES [5,6] and the HELIOS-3 [7] Collaborations has generated a great deal of theoretical activity. The results from many groups with standard scenarios (i.e., using vacuum meson properties) are in remarkable agreement with each other, but in significant disagreement with the data: The experimental spectra in the mass region from 0.3–0.6 GeV are substantially underestimated [6]. This has led to the suggestion of various medium effects that might be responsible for the observed enhancement [9,10].

In the high-mass region around $m_{J/\Psi}$, the J/Ψ suppression has been a subject of great interest, since it was first proposed as a signal of the deconfinement phase transition [11]. Various investigations show that up to central S + U collisions, the normal preresonance absorption in nuclear matter is sufficient to account for the observed J/Ψ suppression. However, recent data from the NA50 Collaboration for central Pb + Pb collisions show an additional strong "anomalous" suppression which might indicate the onset of the color deconfinement [12].

Another piece of interesting experimental data that has not received much theoretical attention is the dilepton spectrum in the intermediate-mass region between 1 and 2.5 GeV. Both the HELIOS-3 and NA38/NA50 Collaborations have observed a significant enhancement of the dilepton yield in this mass region in central S-induced collisions, as compared to that in the proton-induced reactions [7,8]. Preliminary data from the NA50 Collaboration also show significant enhancement in central Pb + Pb collisions [8] (see also Ref. [6]).

The intermediate-mass dilepton spectra in heavy-ion collisions are particularly useful for the search of the QGP [4]. However, to extract from the measured dilepton spectra any information about the phase transition and the properties of the QGP, it is essential that the contributions from the hadronic phase be precisely understood and carefully subtracted. It is the purpose of this work to calculate the dimuon spectra in central S + W collisions based on the relativistic transport model used in Refs. [9,13] for low-mass dilepton and photon production. The chief motivation for such a study is to understand the origin of the observed enhancement in the intermediate-mass region, and to see whether the enhancement can be explained by hadronic processes, or whether the formation of the QGP needs to be invoked.

Previous thermal rate calculations based on kinetic theory show that in the mass and temperature region relevant for this study, the following thermal processes (from the hadronic phase) are important: $\pi\pi \to l\bar{l}$, $\pi\rho \to l\bar{l}$, $\pi\omega \to l\bar{l}$, $\pi a_1 \to l\bar{l}$, $K\bar{K} \to l\bar{l}$, and $K\bar{K}^* + \text{c.c} \to l\bar{l}$ [14–16]. Among them, the $\pi a_1 \to l\bar{l}$ has been found to be the most important, mainly because of its large cross section [14,16] (a similar conclusion has been drawn for

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thermal photon production [17,18]). In this work we shall verify quantitatively the previous estimates.

To compare with experimental data, one needs a transport model that describes the dynamical evolution of the colliding system and integrates the dilepton production over the entire reaction volume and time. In heavy-ion collisions at CERN SPS energies, many hadrons are produced in the initial nucleon-nucleon interactions. This is usually modeled by the fragmentation of strings. One successful model for taking into account this non-equilibrium dynamics is the Relativistic Quantum Molecular Dynamics (RQMD) model [19]. As in Refs. [9,13], we use 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 in a relativistic transport model. This model is found to provide a good description of hadronic observables in heavy-ion collisions at CERN SPS energies and does not rely on assumptions of thermal equilibrium [9,13].

To calculate the dilepton spectra in heavy-ion collisions, we need to know the elementary cross sections for the secondary processes mentioned above. These processes can be classified into pseudoscalar-pseudoscalar (PP), vector-pseudoscalar (VP), vector-vector (VV), and axial-vector-pseudoscalar (AP) types. Relying on vector meson dominance (VMD), the first three types can be evaluated using effective hadronic Lagrangians [14,20]. Concerning the last case, there exist a number of models for $\pi\rho a_1$ dynamics. In Ref. [21], a comparative study was carried out for both on-shell properties and dilepton production rates in those models. By using the experimentally constrained spectral function [22] it was found that the effective chiral Lagrangian of Ref. [23] in which the vector mesons are introduced as massive Yang-Mills fields provides satisfactory off-shell, as well as on-shell, properties for $\pi\rho a_1$ dynamics. The Lagrangian of Ref. [23] will be used in this work in close conjunction with experimental data, as described below.

The cross sections for these processes have a similar global structure. Here we take that for PP $\to l\bar{l}$ as an example,

$$\sigma_{\mathrm{PP}\to l\bar{l}}(M) = \frac{8\pi\alpha^2 k}{3M^3}\,|F_P(M)|^2\left(1 - \frac{4m_l^2}{M^2}\right) \times \left(1 + \frac{2m_l^2}{M^2}\right), \qquad (1)$$

where k is the magnitude of the three-momentum of the pseudoscalar meson in the center-of-mass frame, M is the mass of the dilepton pair, m_l is the lepton mass, and $|F_P(M)|^2$ is the electromagnetic form factor of the process. The cross sections for $\pi\rho \to l\bar{l}$ and $\bar{K}K^* + c.c. \to l\bar{l}$, which are of the VP type, have been studied in Ref. [15]. The cross section for $\pi\omega \to l\bar{l}$ has the same form as that for $\pi\rho \to l\bar{l}$, but with a different form factor. Finally, the cross section for $\pi a_1 \to l\bar{l}$ is discussed below.

We emphasize that these cross sections can be constrained by a wealth of experimental data [24] for the reverse process, $e^+e^- \to$ hadrons, via detailed balance. One way this is achieved is by introducing vector meson dominance form factors which are fitted to the $e^+e^- \to$ hadrons data and then used in the meson-meson $\to l\bar{l}$ processes, as we will do in this work. The pion electromagnetic form factor is dominated by the $\rho(770)$ meson, while that of the kaon is dominated by the $\phi(1020)$ meson. At large invariant masses, higher ρ-like resonances such as $\rho(1450)$ were found to be important. High isoscalar vector mesons such as $\omega(1420)$ and $\phi(1680)$ play important roles in the electromagnetic form factors of $\pi\rho \to l\bar{l}$ and $\bar{K}K^*$ + c.c. $\to l\bar{l}$ [15]. Similarly, the electromagnetic form factor for $\pi\omega \to l\bar{l}$ can be measured in $e^+e^- \to \pi^0\pi^0\gamma$. The extraction of the form factor for $\pi a_1 \to l\bar{l}$ from $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ does involve some uncertainties concerning the $\rho(1700)$ resonance. As this issue is not totally free of theoretical prejudice we will consider three scenarios for the $\pi a_1 \to l\bar{l}$ form factor: one with and one without the $\rho(1700)$ contribution, and one which uses a form factor determined from the DM2 Collaboration's partial wave analysis data. The sensitivity of the final dimuon spectra to those cases will be assessed. A clear advantage of the e^+e^- data is that its measurements cover the invariant mass region we are interested in here. Thus, no off-shell extrapolations are needed. Note that, however, the treatment of quantum interference remains a possible issue in our framework; see, e.g., Ref. [25].

For dilepton spectra with mass above 1 GeV, the contributions from charm meson decay and initial Drell-Yan processes begin to play a role. These hard processes, however, scale almost linearly with the participant nucleon number, and can thus be extrapolated from the proton-proton and proton-nucleus collisions. Such a study has recently been carried out by Braun-Munzinger *et al.* [26]. The results for the central $S + W$ collisions corresponding to the HELIOS-3 acceptance are shown in the left panel of Fig. 1 and are taken from Ref. [6]. These, together with the dileptons from the decays of primary vector mesons, are collectively termed "background". It is seen that these background sources describe well the dimuon spectra in the $p + W$ reactions, shown in the figure by solid circles.

However, as can be seen from the figure, the sum of these background sources grossly underestimates the dimuon yield in central $S + W$ collisions, shown in the figure by open circles. Since the dimuon spectra are normalized by the measured charged particle multiplicity, this underestimation indicates additional sources of dilepton production in heavy-ion collisions. Some candidates are QGP and/or hadronic reactions. So the immediate next step is to check whether the contribution from the secondary hadronic processes can explain this enhancement. For dilepton spectra at low invariant masses, it is well known that the $\pi\pi$ annihilation plays an extremely

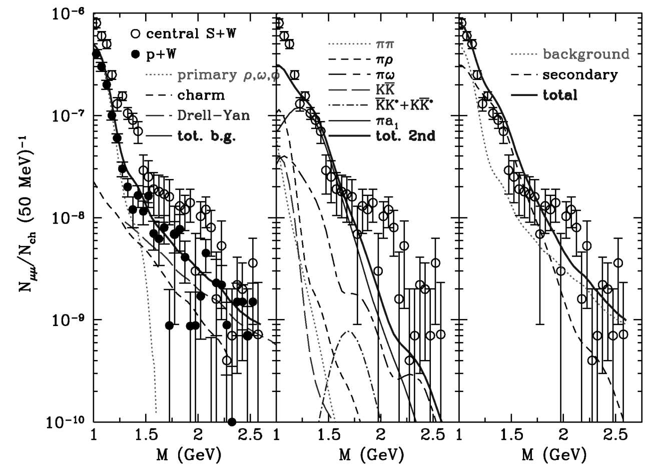

FIG. 1. Left panel: Comparison of background and preliminary data in $p + W$ and $S + W$ collisions. Middle panel: contributions of various secondary processes of dimuon production in central $S + W$ collisions. Right panel: Comparison of the sum of the background and secondary contributions with the preliminary data in central $S + W$ collisions.

important role in heavy-ion collisions. It is also expected that the other secondary processes will play a role in the dilepton spectra in the intermediate mass region.

The contributions from the thermal processes outlined above are shown in the middle panel of Fig. 1. These are obtained in the relativistic transport model of Refs. [9,13], including the HELIOS-3 acceptances, mass resolution, and normalization [7]. It is seen that the πa_1 process is by far the most important source for dimuon yields in this mass region, as was found in thermal rate estimates. The $\pi\omega$ process also plays some roles in the entire intermediate mass region, while the contributions from $\pi\pi$, $\pi\rho$, and $K\bar{K}$ are important around 1 GeV. We have also verified that the AV (where $A = a_1$) contributions are suppressed [27].

In the right panel of Fig. 1, we add the secondary contributions to the background, and compare again with the HELIOS-3 data for central $S + W$ collisions. It is seen that the data can be adequately reproduced. This highlights for the first time the importance of the secondary processes for the intermediate-mass dilepton spectra in heavy-ion collisions, even though the evaluation of the background itself is not entirely free of complications. This is an important step forward in the use of intermediate-mass dilepton spectra as a probe of the phase transition and QGP formation. Although the current data do not show any necessity to invoke the QGP formation in S-induced reactions, consistent with some conclusions from J/Ψ physics, we believe that the observation that the secondary processes do play a significant role in the intermediate-mass dilepton spectra is interesting and important. We note in passing that the slight change of the slope observed in the experimental data corresponds in our interpretation to a crossover between the secondary processes and the (Drell-Yan) background. This signals a passage from hard to soft physics and could lead to interesting developments.

In the previous calculation we assumed that all the observed 4π final state in the e^+e^- cross section proceeds through the πa_1 intermediate state. We also did a calculation in which the πa_1 form factor contains only the normal $\rho(770)$. The results are shown in the left panel of Fig. 2 by the dotted curve. Finally, to complete our survey of possible constraints and uncertainties in $\pi a_1 \rightarrow e^+e^-$ cross sections, we did a calculation in which this cross section is obtained from the $e^+e^- \rightarrow \pi a_1$ cross section determined by the DM2 Collaboration in partial wave analysis (PWA) [28]. The results are shown by dashed curve in Fig. 2. The region between the solid and dashed curves thus reflects the uncertainty for heavy-ion collisions due to our limited knowledge of the πa_1 cross section. This area is not unreasonably large. From a formal point of view, it is fair to say that no strong evidence currently exists coupling the $\rho(1700)$ to a πa_1 state [29], even though better 4π data could help resolve this issue along with others of interference and πh_1 contribution [24].

Another topic to be addressed here is the effect of dropping vector meson masses on the entire dimuon spectra from threshold to about 2.5 GeV. In Ref. [9] it was shown that the enhancement of low-mass dileptons could be interpreted as a signature of vector meson masses decreasing with increasing density and temperature. This should affect the dilepton spectra in the intermediate-mass region, mainly through two effects. One is the change of the invariant energy spectra of these secondary meson pairs. The second effect enters through the modification of the electromagnetic form factor. Since we can only conjecture how the masses of the higher vector resonances change with density and temperature, we shall assume for simplicity that they experience the same amount of scalar field as the "common" rho meson,

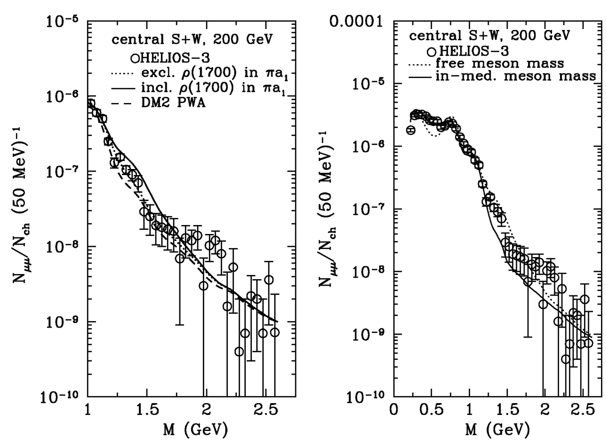

FIG. 2. Left panel: Comparison of dimuon spectra obtained with and without the $\rho(1700)$ in the πa_1 form factor, with those obtained with the DM2 data. Right panel: Comparison of dimuon spectra with in-medium and vacuum meson masses.

namely, $m^*_{V,V'} = m_{V,V'} - 2/3 g_\sigma \langle\sigma\rangle$ [9]. The results of this calculation are shown in the right panel of Fig. 2. Below 1.1 GeV and especially from 0.4 to 0.6 GeV, the agreement with the experimental data is much better when the dropping vector meson mass scenario is introduced, as was already shown in Ref. [9]. At higher invariant masses the dropping mass scenarios somewhat underestimate the experimental data, admittedly not by a large amount. For completeness, however, we have to state that there might be additional contributions from, e.g., secondary Drell-Yan processes [30] that were not included in this study. Furthermore, as we progress higher in invariant mass, the role of baryons has to be carefully assessed. So far, the baryons seem to play a small role in the overall dilepton yield [31]. This statement was made [32] for masses below 1 GeV, and is being extended to the intermediate-mass region in [33]. See, however, Ref. [10] for a contrasting viewpoint on the role of baryons. Finally, the dropping mass curve was obtained using the topmost curve of the left panel as a starting point.

So far, collision broadening is not explicitly included in our calculation. However, since the "common" rho meson is treated as a dynamical particle in our transport model, its collisions with mesons and baryons are included. This shall partially reflect its collision broadening in hot and dense matter [34]. The higher resonances, such as $\rho(1450)$ and $\rho(1700)$, are not treated dynamically. Their effects on dilepton production are included through electromagnetic form factors. Therefore, collision broadening is not considered explicitly for these higher resonances. However, Since they typically have a natural width of 200–300 MeV, a moderate broadening width shall not affect our results dramatically. This will be dealt with quantitatively in a more elaborate way in the future.

In summary, we have analyzed the recent HELIOS-3 data on intermediate-mass dilepton production in heavy-ion collisions at CERN SPS energies using a relativistic transport model, with the elementary dilepton production cross sections constrained by the e^+e^- annihilation data. We have shown the importance of secondary processes for the dilepton production in heavy-ion collisions in this mass region.

The current investigation can be extended to higher incident energies, such as those of the RHIC collider, by combining the cross sections (or thermal rates) obtained in this study with, e.g., hydrodynamical models for the evolution of heavy-ion collisions at the RHIC energies. This kind of study is useful for the determination of hadronic sources in the dilepton spectra, and for the clear identification of the dilepton yield from the QGP.

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