THERMAL DILEPTONS AS A POSSIBLE SOURCE OF THE SOFT DILEPTON ENHANCEMENT MEASURED IN A-A COLLISIONS AT SPS ENERGIES

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The production of soft dileptons in a thermal mesonic medium is discussed in the context of recent CERN experimental data reported by the CERES Collaboration. We do not intend to give a general and critical review, but instead concentrate mainly on our approach, however, incorporating many of the recent attempts in the literature. We calculate the contributions to the dilepton yield arising from pion annihilation and \( \pi^- \rho \) scattering. It is shown that thermal dileptons from \( \pi^- \rho \) scattering give a significant contribution to the low-mass yield, however, it can only partly account for the experimentally observed soft dilepton excess seen in S-Au and Pb-Au collisions at SPS energy. The out of-equilibrium effects as well as a dropping vector meson mass are discussed in the context of the thermal dilepton yield. We emphasize, following the results of Li, Ko, and Brown, that, until now, the best way to provide a quantitative explanation of the observed enhancement of low-mass dileptons by the CERN experiments is the assumption of a decreasing vector meson mass in a high density thermal medium.

1 Introduction

Electromagnetic radiation has been widely discussed as one of the most sensitive signals to probe the dynamics of nuclear interactions. Recently, three experiments at CERN with S-beams of 200 GeV/nucleon: CERES, HELIOS/3, and NA38 - report an enhanced production of dileptons with a yield far beyond a mere superposition of p-p or p-nucleus collisions. Also recent measurements by the CERES Collaboration with Pb-beams at SPS energy show a similar behaviour of the dilepton rate. The excess starts at a mass \( > 200\text{MeV}/c^2 \) and persists up to the mass of the \( J/\Psi \). These results have recently implied very intensive theoretical discussions in order to understand the origin of the excess.

The properties of the observed yield, particularly the fact that the enhancement starts at \( M \sim 2m_\pi \) might indicate that the excess is just due to additional thermal dileptons originating from pion annihilation. The possibility of the creation of hot and dense QCD matter in thermal equilibrium in relativistic collisions of heavy nuclei at SPS energy has already got experimental as well as theoretical support. In particular, the measured particle spectra at CERN experiments with heavy ion beams seem to be rather well explained by a thermal model for particle production. The appearance of a thermal hadronic medium in heavy ion collisions naturally implies the additional source of dileptons, absent in p-p or p-nucleus collisions. At SPS energy the thermal medium is mostly of mesonic origin as the measured charged-pion/proton ratio is still of the order of five. Thus, the most relevant process for dilepton production should be due to meson scatterings and decays. The differential thermal rate per unit space-time volume \( d^4x \) at which mesons interacting create \( e^+e^- \) pairs of invariant mass \( M \) can be obtained either in terms of kinetic or thermal field theory.

In heavy ion collisions, the additional complication arises as the rate per unit spacetime volume is not an experimentally measured distribution. Dileptons are produced in an expanding medium, thus to compare the theoretical results with the experiment one still needs to perform the space-time integration. In our following discussion we apply Bjorken’s hydrodynamical model for the expansion dynamics. In a mesonic medium pion annihilation with rhos and virtual photons in the
intermediate state is the basic source of thermal $e^+e^-$ pairs. In fig.1 we compare thermal dielectron yields from pion annihilation with the CERES experimental data. The calculation has been done in the Bjorken model in comparison to the measured yield in central S-Au collisions. The initial thermalization time is taken as $\tau_i \sim 1$ fm and the freeze-out temperature is considered in fig.1 as a free parameter. The results of fig.1 confirm that indeed in the vicinity of $\rho$-meson peak pion annihilation together with the hadronic cocktail from Dalitz and vector meson decay is well compatible with the data. This, however, requires the freezeout temperature in the range between 120-140 MeV, where the mean free path of pions is of the order of the sulphur radius.

Recently the CERES Collaboration has measured dilepton yields in Pb-Au collisions at SPS energy. The preliminary data averaged over all events with different $dN_{ch}/dy$ show a dilepton enhancement by a factor $2.5 \pm 0.5$ in a mass range $0.2 < M < 1.5$ GeV. This is a smaller excess than previously seen for S-Au collisions. Thus, we have additional data to check the validity of a thermal model at least near the $\rho$-meson peak. The comparison of a thermal model with Pb-Au experimental data would require, however, weighted averages over all events with different $dN^{ch}/dy$. For that one would still need to define a model describing the dependence of the effective initial volume on the impact parameter. In order to avoid additional uncertainties we compare here a thermal model with the CERES data corresponding to the highest multiplicity beams with $<dN_{ch}/dy> \sim 410$. For the most central collisions, the transverse size of the initially created fire-cylinder in Pb-Au is assumed to be of the order of the Au-radius.

For the isentropic longitudinal expansion the temperature $T_0$, the initial thermalization time $\tau_0$ and transverse size $R_A$ of the initially created fire-cylinder in central A-A collisions can be related to the final state hadron multiplicity by

$$\frac{dN}{dy} \sim \pi R_A^2 \tau_0 s(T_0)$$

where $R_A \sim 1.2 A^{1/3}$ is the nuclear radius and $s(T_0)$ the initial entropy density in the thermal medium.

From Eq.1 one establishes and compares the initial thermal parameters for S-Au and Pb-Au collisions. CERES has measured $<dN^{ch}/dy> \sim 125$ and $<dN^{ch}/dy> \sim 410$ charged particles in central collisions in S-Au and Pb-Au, respectively. Thus, assuming the same thermalization time for S-Au and Pb-Au one derives from Eq.1,

$$\frac{<dN^{ch}_{S}/dy>^S}{<dN^{ch}_{Pb}/dy>^Pb} \sim \left( \frac{A_S}{A_{Pb}} \right)^{2/3} \frac{s(T_0^S)}{s(T_0^{Pb})}$$

This result indicates that the increase of the charged particle multiplicity in central Pb-Au in comparison to S-Au collisions by factor $\sim 3.3$ is almost entirely described by the increase of the initial transverse size of the system since $(A_{Pb}/A_S)^{2/3} \sim 3.35$. Thus, the temperature of the initially created fire-cylinder in S-Au and Pb-Au central collisions is the same within a few percent. Similar initial temperatures imply similar results for the dilepton yield normalized to the charged particle multiplicity. Thus, in terms of a thermal model the dilepton data measured by CERES in S-Au and Pb-Au for the most central collisions should coincide. In fig.1 we see that the measured yield by CERES follows the above expectations. The results of fig.1 show that indeed thermal production could be the source of the dilepton excess seen in the CERES experiment. However, the Born term alone can not
explain the characteristic structure and the magnitude of the excess seen in the data. Similar conclusions have been obtained in the previous studies even when a more complete model for the expansion dynamics, reproducing not only the total pion multiplicities but also their measured $p_t$ and rapidity distributions has been applied. This result is as well independent on the assumption made about the nature of the initially created thermal fireball, that is, whether it is highly excited hadronic matter or a quark-gluon plasma. In fig.1 we have already seen the importance of the pion annihilation process to partly understand the dilepton data. In a thermal medium, however, this basic reaction is not the only one which should be considered. For example the contribution from the two-body reaction $\pi^+\pi^- \rightarrow \rho^+ \rightarrow \rho^+ e^+ e^-$ does not have a kinematical threshold at $2m_\pi$, and therefore will dominate pion annihilation for $M \sim 2m_\pi$. This example indicates, that a more complete analysis of the low mass dilepton spectrum originating from $\pi - \rho$ interactions is required.

2 Thermal dileptons from $\pi - \rho$ scattering

The thermal emission rate of heavy photons with invariant mass $M$, energy $E$ and momentum $\vec{q}$ can be obtained from the photon self-energy tensor $\Pi_{\mu\nu}$ as follows:

$$\frac{dR}{dM^2 d^2 q/E} = -\frac{\alpha}{24\pi^4 M^2} n(E) \text{Im} \Pi_{\mu
u}^\mu(E, \vec{q})$$

(3)

where $n(E)$ is the Bose distribution function at temperature $T$. The virtual photon self-energy is usually approximated by carrying out a loop expansion to some finite order. On the one-loop level one recovers the expression for the Born term $\pi^+\pi^- \rightarrow \gamma \rightarrow e^+e^-$, which under the Boltzmann approximation and with $E^2 = \vec{q}^2 + M^2$ reads:

$$\frac{dR}{dM^2 d^2 q/E} = \frac{\alpha^2}{96\pi^4} |F_\pi(M)|^2 \exp(-E/T)$$

(4)

where $|F_\pi|$ is the pion form factor

$$|F_\pi(M)|^2 = \frac{m_\rho^4}{(M^2 - m_\rho^2)^2 + \Gamma_\rho^2 m_\rho^2}$$

(5)

The parameters $m_\rho = 0.775$ GeV, $m_\rho^* = 0.761$ GeV and $\Gamma_\rho = 0.118$ GeV are chosen to get a reasonable description of the measured pion electromagnetic form factor. [5]
To go beyond the one-loop approximation and to include the contribution due to $\pi^\pm\rho^0$ scattering we adopt the effective Lagrangian with the rho-meson and electromagnetic fields coupled to the pion current. From this Lagrangian and using the closed-time-path formalism the dilepton production rate has been calculated at the two-loop level. There are two types of diagrams contributing to the thermal dilepton rate from $\pi - \rho$ interactions. These are the diagrams with real and virtual $\rho^0$ vector mesons. The processes involving real $\rho^0$'s are due to $\pi\pi \rightarrow \rho\gamma^*$, $\pi\rho \rightarrow \pi\gamma^*$ and $\rho \rightarrow \pi\pi\gamma^*$ reactions. The estimate of the resulting thermal rate can be found in Ref.[14].

For heavy photon production the virtual contributions lead to $O(g^2_\rho)$ order corrections to the Born term. In the limit where $m_\rho \gg T$ the dilepton yield due to pion annihilation including strong interaction $O(g^2_\rho)$ corrections can be estimated as,

$$\frac{dN_{\text{Born} + \text{virtual}}}{dM^2 dx} \simeq \frac{dN_{\text{Born}}}{dM^2 dx} \left[1 - \frac{7}{2\pi} \frac{g^2_\rho}{4\pi} \left(\frac{T}{m_\rho}\right)^2\right]$$

In fig.2 we summarize the contributions to the thermal dilepton rate originating from $\pi - \rho$ scattering. It is clear that dileptons with invariant masses $M < 0.45$ GeV are mostly produced due to $\pi - \rho$ scattering processes. It is also interesting to note that the $O(g^2_\rho)$ order corrections to the Born term are negative and relatively large. It suggests that resummations could be required here.

The result in fig.2. shows that in a mesonic medium dileptons originating form $\pi - \rho$ interactions have to be necessarily included as they lead to substantial modifications of the Born rate.

Applying Bjorken’s model for the space-time evolution one can compare then the thermal dilepton production with the experimentally measured yield. In fig.3 we show the overall thermal dilepton rate from $\pi - \rho$ interactions including acceptance and kinematical cuts of the CERES experiment. In fig.3 one can see that the thermal source for dielectron pairs can only partly account for the excess measured by the CERES Collaboration. In the model describing dilepton production due to $\pi - \rho$ scattering we have not included the possible coupling to the $A_1$ axial vector meson. However, the role and the contribution of the $A_1$ resonance to thermal dilepton yield is extensively discussed in Ref.[17,26].

2.1 Non-equilibrium effects

In the previous section discussing thermal dileptons we assume the free phase space thermal-distribution function for all particles. In a high density medium, however, the particle properties can be substantially modified. This modification could have a dynamical origin, or it could as well appear due to non-equilibrium effects. In the following we discuss how the chemical off-equilibrium effects may influence the soft dilepton yields.

Thermalization of a hadronic medium created in heavy ion collisions should be rather a fast process. Recent calculations in kinetic theory show that only few elastic particle collisions are already sufficient to maintain thermal particle spectra. The chemical equilibration, in contrast, could be much slower as it requires a detailed balance between different reactions with particle number changing processes. The absence of chemical equilibrium in a pion medium can be effectively taken into account by modifying the pion distribution function

$$n_\pi(E,T) = (\lambda_\pi^{-1} \exp E/T - 1)^{-1}$$

with $\lambda_\pi \equiv \exp(\mu_\pi/T)$ and $\mu_\pi$ being the pion chemical potential. Assuming relative equilibrium between pions and rho-mesons implies that $\mu_\rho = 2\mu_\pi$. If the pion fluid were in chemical equilibrium,
then naturally $\mu_\pi$ would vanish. The modification of the dilepton production rate due to $\mu_\pi \neq 0$ can be qualitatively verified taking as an example the Born term for the pion annihilation process. The dilepton production rate due to pion annihilation in a non-equilibrium mesonic medium may be obtained in the following form:

$$\frac{dN}{d^4x dM^2 \left( \frac{d^3q}{E} \right) |_{\mu_\pi \neq 0}} \approx \frac{dN}{d^4x dM^2 \left( \frac{d^3q}{E} \right) |_{\mu_\pi = 0}} \times F_h$$

where the equilibrium rate is as in Eq.4 and the function $F_h$ reads

$$F_h \sim \frac{T}{q} \frac{1}{1 - \exp[-(E - 2\mu_\pi)/T]} \left( e^{2\mu_\pi/T} \right) \times \ln \left( \frac{e^{-\beta q} - e^{-\beta \mu_\pi}}{e^{\beta q} - e^{\beta \mu_\pi}} \right)$$

where $E_\pm = \frac{1}{2}[E \pm q(1 - 4m_\pi^2)^{1/2}]$.

The $\mu_\pi$ is modifying the dilepton rate in Eq.8 in two different ways: first, due to the factor $\exp(2\mu_\pi/T)$ the overall thermal production rate is enhanced independently on the dilepton kinematics. Second, the appearance of the Bose-like term in the denominator of Eq.9 enhances the dilepton production when $E \to 2\mu_\pi$. This second feature is of particular interest as it leads to an excess of soft dileptons just above the $2m_\pi$ threshold.

It is clear that not only pion annihilation but all processes involving pions and rho mesons in the initial state are modified in an over-saturated compared to an equilibrium medium. In particular the processes listed in the previous section, arising from $\pi - \rho$ scattering are influenced by the off-equilibrium effects. Discussing dilepton production in a thermal medium requires additional care with respect to finite temperature modifications of the rho meson mass and/or decay width. The previous study of the rho self-energy in a mesonic medium up to the one-loop order has shown that in an equilibrium system the medium effects on rho properties are rather modest. The situation can, however, change in supersaturated pion or baryon rich matter. In the first case, for large values of $\mu_\pi$ and $T$ the increase of the rho decay width may be significant leading to the suppression of dilepton production close to the rho resonance peak.

To include non-equilibrium effects in the processes from $\pi - \rho$ scattering, one would just multiply naively the rate by a factor of $\lambda_\pi^i$ or $\lambda_\rho^i$ depending whether there is a $\pi\pi$ or $\pi\rho$ initial state. For sufficiently large $\mu_\pi$ the increase of the soft part of the dilepton yield due to a non-equilibrium chemical potential is then sufficient to explain the experimental data. However, a more careful analysis shows that it is not justified to simply multiply the equilibrium emission rate for dileptons from $\pi - \rho$ scattering by $\lambda_\pi^i$ factors. This is mostly due to the structure of the (one-loop) self-energy correction to the pion propagator which in the non-equilibrium medium leads to an ad-
tional pinch-singular term contributing to the overall dilepton rate. If the deviation from equilibrium distributions is small such that \( \delta \lambda \equiv \lambda - 1 < 1 \), then the pinch-singular term is found as follows:

\[
\frac{dN_{\text{pinch}}}{dM^2 d^4x} \sim -\delta \lambda \frac{\alpha^2 (g_\rho^2/4\pi)}{24\pi^3} \sqrt{\frac{\pi T^3}{\pi T^3}} \frac{m_\rho^3}{2m_\rho} \frac{2m_\rho^2 + M^2}{2m_\rho^2 + M^2}\lambda \lambda \frac{\delta \lambda}{T} \nonumber
\]

Thus, since this term is negative it reduces the naive expected increase of low mass dileptons due to a nonzero pion chemical potential.

In fig.4 we plot the total rate, including the Born term with \( O(g_\rho^2) \) corrections, for the non-equilibrium case characterized by different values of the pion chemical potential \( \mu_\pi \). We observe that the rate is increasing with increasing \( \mu_\pi \). However, naively one would expect an increase by a factor of \( \lambda^2 \), whereas the results in fig.4 show much lower enhancements. Changing \( \mu_\pi \) from \( \mu_\pi = 0 \) to \( \mu_\pi = 100 \text{ MeV} \) only an effective increase by a factor 2 results in fig.4, contrary to a factor 4 expected from \( \lambda^2 \). This is mostly because of the negative contribution of the pinch-singular term in Eq.10. From this we stress the importance of taking into account the non-trivial term (Eq.10), which is traced back to the structure of the pion propagator.

In fig.3 we show the thermal rate (long-dashed line) calculated in the longitudinally expanding fire-cylinder assuming deviations from chemical equilibrium with a value of the chemical potential of \( \mu_\pi = 100 \text{ MeV} \). Indeed, we observe an increase of the rate below the rho peak. This increase, however, is rather modest due to the pinch-singular term. In addition, the off-equilibrium distributions of pions and rho mesons imply lower initial temperature and a shorter lifetime of a thermal system. All these effects are the reason of the small increase of the low mass yield when going from an equilibrium to a non-equilibrium medium.

### 2.2 Dropping vector-meson masses

The modification of the pion and rho meson properties by a finite chemical potential although implies some increase of the low mass dilepton rate but still it is not sufficient to explain the data. In general, all the models discussed in literature, until now, lead to the similar conclusions that the conventional sources for dilepton production can only partly account for the excess measured by the CERES Collaboration. One possible explanation of why the conventional approach fails may be due to the fact that hadronic properties in a high density medium may be modified and these effects have to be taken into account. Particularly relevant here would be the modification of the rho meson mass.

The properties of the rho meson in a high density medium are, however, theoretically not under complete control. The results of the configurations of lattice gauge theory calculations in quenched QCD [18] as well as the calculations based on the effective lattice gauge Lagrangian [19] show that the rho meson mass at finite temperature remains almost unchanged. On the other hand the results of gauged linear sigma models suggest an increase of the rho meson mass with temperature.

Finally, Brown and Rho [27] have shown that the restoration of chiral symmetry implies a decreasing rho mass in dense matter. In the following we assume a decreasing rho meson mass in a medium and discuss how this influences the dilepton yield.

In fig.5 we compare the dilepton rate due to \( \pi - \rho \) scattering for two different values of \( m_\rho = 0.77 \text{ GeV} \) and \( m_\rho = 0.5 \text{ GeV} \) keeping the rho decay width unchanged. As expected decreasing \( m_\rho \) leads to the shift in the position of the resonance peak, increasing in this way the production of low mass dileptons. This is the feature which is required to understand the low mass dilepton excess. It is also interesting to note that the height of the peak at \( M = m_\rho \) is a decreasing function of mass. This result is entirely due to the \( O(g_\rho^2) \) term which as seen in Eq.6 to be strongly dependent on the value of \( m_\rho \). This also means that assuming a decreasing vector meson mass we have to worry about the strong interaction corrections to the purely electromagnetic pion annihilation process, e.g. when using the Lagrangian from Refs.[14,25].

In order to develop a shift in the position of the rho meson peak in the dilepton yield, the rho meson should stay off-shell a substantial amount of time during the evolution of the hadronic medium. This can be the case if \( m_\rho \) is a slowly varying function of temperature and/or baryon density or if the system stays sufficiently long close to the chiral symmetry restoration phase transition point. To illustrate how a dropping rho meson mass mod-
ifies the yield we adopt a very simple parameterization of the T-dependence of \( m_\rho \). We assume that up to half of the lifetime of the thermal medium the rho meson stays with reduced mass \( m_\rho^* \sim 0.5 \) GeV and then very quickly recovers its on-shell value \( m_\rho \sim 0.77 \) GeV. From this simple example, one can already see in fig.6 that a dropping rho meson mass may be the source of the structure of the rate seen in the CERN experiments.

The quantitative explanation of the data with a dropping vector meson mass has been shown first by Li, Ko and Brown. In fig.7 we show the results of Ref.[10] obtained in terms of a hadronic transport model for expansion dynamics and the parameterization of the vector meson masses deduced from Brown-Rho scaling. The same model shows also very good agreement with HELIOS/3 dimuon data. A similarly good agreement with the CERN dilepton data is obtained in different dynamical models for dilepton production in A-A collisions when assuming dropping vector meson masses. Until now including the decrease of vector meson masses seems to be the best way to understand the properties, shape and excess of low mass dilepton yields reported by CERN experiments.

3 Outlook and Conclusions

We have discussed thermal dilepton production in a hot mesonic medium in the context of recent CERN experimental data by the CERES Collaboration for S-Au and the most central Pb-Au collisions at SPS energies. The calculation includes all production processes due to \( \pi - \rho \) scattering originating from two-loop approximations of the virtual photon self-energy. We argue that in an equilibrium model \( \pi - \rho \) scattering is an important source of low mass dileptons. Adding it together with the Born term for pion annihilation one can partly explain the dilepton excess measured in the CERN experiment. Next, the off equilibrium contributions to the dilepton rate due to a non zero pion chemical potential have been found to imply only a modest modification of the dilepton production. This is mostly due to the structure of the non-equilibrium pion propagator. Finally, the modification of dilepton yields due to in medium effects on vector meson properties is discussed. We emphasize that a dropping rho meson mass is the best way, until now, to provide a quantitative explanation of the recently observed low mass dielectron enhancement in S-Au and Pb-Au collisions. The concept of a dropping vector meson mass should be, however, cross checked with the upper limit of direct photon yields measured in S-Au collisions by the WA80 Collaboration. It is not excluded that the thermal photon yields calculated with a dropping rho meson mass may overwhelm the experimental upper limit. Additional attention should be given to the higher \( O(g_\rho^2) \) corrections to the \( \pi^+\pi^- \rightarrow e^+e^- \) annihilation process. We estimate that the \( O(g_\rho^2) \) term is negative and thus reduces the Born term. This reduction of the dilepton yield is particularly important in case of a dropping rho resonance mass.

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