ρ meson broadening and dilepton production in heavy ion collisions[*]

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The modification of the width of the rho meson due to in-medium decays and collisions is evaluated. In high temperature and/or high density hadronic matter, the collision width is much larger than the one-loop decay width. The large width of the ρ meson in matter seems to be consistent with some current interpretations of the e^+e^- mass spectra measured at the CERN/SPS.

1. INTRODUCTION

The measurement and calculation of dilepton and photon emission in heavy ion collisions represent great interest from a theoretical point of view. Once the radiation is formed, it can propagate virtually unscathed to the detectors, owing to the smallness of the fine structure constant α. This signal is also sensitive to the hot and dense phase of the nuclear reaction. This can only be probed indirectly by hadronic observable. Lepton pairs have been proposed as valuable tools in studies of reaction dynamics and also as a possible signature of the quark-gluon plasma which is a prediction of QCD [1]. At SPS energies at CERN, the HELIOS [2] collaboration has measured the low mass sector and more recently the CERES collaboration has produced tantalizing experimental results for soft pairs [3]. The intermediate mass sector has been covered by HELIOS, and by the NA38 and NA50 collaborations.

Our goal here is to compute dielectron emission from $\pi\rho \to \pi e^+e^-$ processes, including a_1, π, ρ, ω mesons in the intermediate states. We will highlight interference effects and also show the explicit consequences of rho meson collision broadening in matter.

2. DILEPTON PRODUCTION RATES

At CERN energies, nucleus-nucleus reactions have been seen to create a medium that is meson-dominated. Thus, a large number of lepton production calculation have concentrated exclusively on meson reactions. The two-body cases were studied in Ref. [4]. There, reactions of the type $a + b \to e^+e^-$ were calculated and their strength compared with each other. The rates obtained from that study and from very similar ones were

used to compare with CERES experimental results, using a variety of dynamical simulation models. Strikingly, all results turned out to be in agreement with each other, but in significant disagreement with the data [3]. The situation called for additional physics ingredients. A first school of thought successfully fitted the CERES data by invoking a dropping ρ meson mass reflecting a many-body effect, possibly a chiral phase transition precursor [5]. A second school of thought successful in reproducing the dilepton data invokes a widening of the ρ meson which originates mainly from its strong coupling to baryon resonances [6]. While each of these two possibilities is enticing, they still need to be disentangled and furthermore the physical conditions necessary for each to occur may actually coexist. In the spirit of a systematic study of this physics, it is necessary to explore the two-loop case.

We consider a thermal medium of pions and their main resonance, ρ mesons. It has been shown that the dominating contribution to lepton pair emission from reactions other than two-body is actually $\pi\rho \to \pi e^+ e^-$ [7, 8]. Our goal here is to revisit this contribution and to extend the previous evaluations by **(a)** including a more complete set of mesons mediating the $\pi\rho$ interaction, **(b)** providing a consistent calculation of ρ collisional broadening, and its influence on the lepton pair production rates.

The dilepton production rate for $1 + 2 \to 3 + l^+ l^-$ process can be written as [9]:

$$
\begin{aligned}
\frac{dN}{d^4x} &= \mathcal{N} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \frac{d^3p_2}{(2\pi)^3 2E_2} \frac{d^3p_3}{(2\pi)^3 2E_3} n_1(E_1) n_2(E_2)[1 + n_3(E_3)] \\
&\times \frac{d^3p_+}{(2\pi)^3 2E_+} \frac{d^3p_-}{(2\pi)^3 2E_-} (2\pi)^4 \delta(p_1 + p_2 - p_3 - p_+ - p_-) \cdot \overline{|\mathcal{M}_{12 \to 3l^+l^-}|^2},
\end{aligned} \tag{1}
$$

where $\mathcal{N}$ is an overall degeneracy factor, $n_i(E_i)$ are statistical distribution functions, and $\mathcal{M}$ is the scattering amplitude.

In order to calculate the dilepton production rates from reaction $\pi\rho \to \pi e^+ e^-$, the following four processes should be considered: (1) $\pi^\pm \rho^0 \to (\pi^\pm, a_1^\pm) \to \pi^\pm e^+ e^-$, (2) $\pi^0 \rho^\pm \to (\pi^\pm, a_1^\pm, \rho^\pm) \to \pi^\pm e^+ e^-$, (3) $\pi^\pm \rho^\mp \to (\pi^\pm, \rho^\pm, \omega) \to \pi^0 e^+ e^-$, (4) $\pi^0 \rho^0 \to \omega \to \pi^0 e^+ e^-$. In the processes (1) - (3), the appropriate $\pi\pi\rho\rho$ four point diagram is included. It is well known that the numerical integration for $\pi\rho \to \pi \to \pi e^+ e^-$ (t-channel) is singular, we regulate it following the effective approach of Peierls[10]. We have checked that the results are gauge invariant in the electromagnetic sector.

3. ρ COLLISION RATE IN THERMAL BACKGROUND

The elementary reactions which tend to thermalize ρ's in hot and dense matter are the channels $\rho_1 \pi_2 \to \rho_3 \pi_4$ and/or $\rho_1 N_2 \to \rho_3 N_4$. A ρ with arbitrary momentum p_1 (and energy ω) can be captured by the thermal background. A ρ with momentum p_1 can also be produced from the thermal background by the inverse reaction: $\rho_3 \pi_4 \to \rho_1 \pi_2$. This inverse rate is omitted in many similar treatments. The total collision rate for bosons is the difference $\Gamma^{\mathrm{coll}}(\omega) = \Gamma_d(\omega) - \Gamma_i(\omega)$. We have explicitly verified that, for the physical conditions relevant to this work, the inverse rate can be neglected, thus, the collision rate can be written as:

$$
\Gamma^{\mathrm{coll}}(\omega) \approx \Gamma_d(\omega) = \frac{1}{\omega} \int \frac{d^3p_2}{(2\pi)^3 2E_2} n_2(E_2) \lambda^{1/2}(s, m_1^2, m_2^2) \sigma(s), \tag{2}
$$

where $\sigma(s)$ is the cross section of $\rho\pi$ (or ρN) collision. But bear in mind that this practice can't however be generalized to all cases and that at least the consideration of the inverse rate remains important from the point of view of first principles. Then we can calculate the collision rates of the ρ in medium. For $\rho\pi$ scattering, we use effective Lagrangians for the hadronic interaction [11, 12], the scattering proceeds through s- and t-channels respectively, where the π, ρ, ω, ϕ, a_1 and $\omega'(1420)$ might be intermediate states, to calculated the cross section which needed in the collision rate calculations [13, 14]. For ρN scattering, we use the cross section from the Manley resonances method[15], furthermore, the resonances below the ρ N threshold, like the N*(1520) are also considered. In the rest frame of the fluid, our results are shown in Fig. 1.

In the equilibrated matter, the thermal average of $\Gamma^{\text{coll}}(\omega)$ can be written as,

$$\overline{\Gamma}^{\text{coll}} = \frac{\mathcal{N}_1 \mathcal{N}_2}{\rho_1} \int_{s_0}^{\infty} \mathrm{d}s \frac{T}{2(2\pi)^4 \sqrt{s}} \lambda(s, m_1^2, m_2^2) \tilde{K}(\sqrt{s}, m_1, m_2, T, \mu_i) \sigma(s), \tag{3}$$

where ρ_1 is the ρ meson density, and $s_0 = (m_1 + m_2)^2$, when using Boltzmann statistics, $\tilde{K} = K_1(\sqrt{s}/T)\exp[(\mu_1 + \mu_2)/T]$, with K_1 being the modified Bessel function. Fig. 2 shows the the thermal average of the ρ collision rates from $\rho\pi$ and ρN collisions.
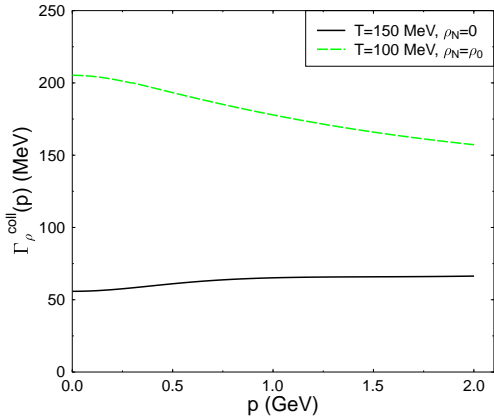

Figure 1. ρ collision rates in hadronic matter. Solid curve indicate pure pion gas, dashed curve is in the medium of pion and nucleon.
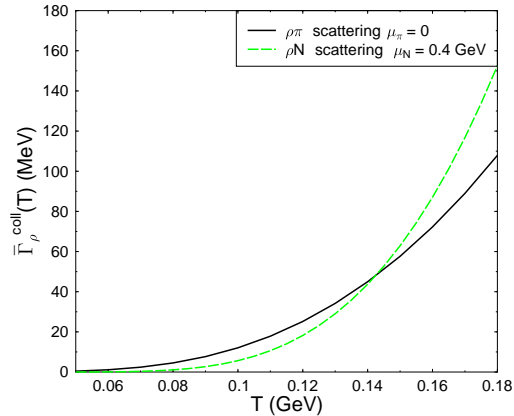

Figure 2. The thermal average of the ρ collision rate $vs.$ the temperature. Solid curve due to $\rho\pi$ interactions, dashed curve is ρN collisions.

4. RESULTS AND CONCLUSION

In this section we will explore the results obtained by putting together the different pieces we have described so far. In Fig. 3, we show the effects of the quantum interference resulting from coherently adding and then squaring the contributions with the same initial and final configuration. It follows from this plot that the quantum effects are not small and that their net effect is to decrease the dilepton signal in the mass region below the ρ. In Fig. 4, we essentially repeat the calculations leading to the previous figure, with one

important exception: the rho width now has a temperature-dependent component, owing to its interaction with other species in the strongly-interacting thermal ensemble.
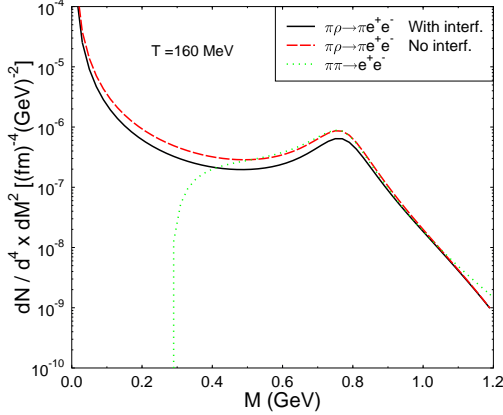

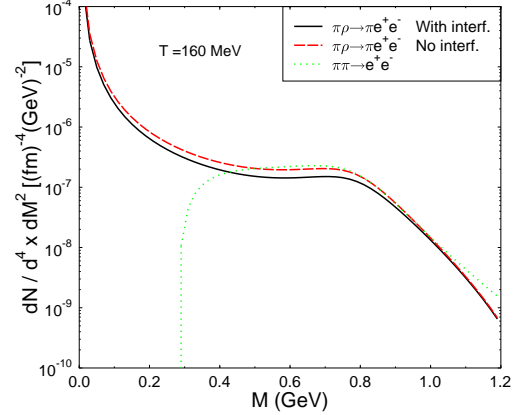Figure 3. Net rates for dielectrons, the ρ has its vacuum width.

Figure 4. Same as Fig. 3, but the ρ has its collision-broadened width.

In summary, our results indicate that, for the collision rates, the contribution from $\rho\,\pi$ collisions is the most important one in the high temperature pion gas, while at low temperatures and high density nuclear matter the ρN contribution is more important. For dilepton production $\rho\pi \to \pi e^+e^-$, the quantum interference effect is to decrease the dilepton signal in the mass region below the ρ, and due to temperature-dependent ρ width, there is a large suppression of the dilepton rates, especially around the ρ peak.

REFERENCES

[1] See, for example, Hildegard Meyer-Ortmanns, Rev. Mod. Phys. **68** (1996) 473.
[2] A. L. S. Angelis *et al.*, Eur. Phys. J. C **5** (1998) 63.
[3] A. Drees, Nucl. Phys. **A 630** (1998) 449c, and references therein.
[4] C. Gale and P. Lichard, Phys. Rev. **D 49** (1994) 338.
[5] G. Q. Li, C. M. Ko, and G. E. Brown, Nucl. Phys. **A 606** (1996) 568.
[6] R. Rapp, G. Chanfray, and J. Wambach, Nucl. Phys. **A 617** (1997) 472.
[7] R. Baier, M. Dirks, K. Redlich, Phys. Rev. **D 55** (1997) 4344.
[8] J. Murray, W. Bauer, K. Haglin, Phys. Rev. **C 57** (1998) 882.
[9] P. Lichard, Phys. Rev. **D 49** (1994) 5812.
[10] R. F. Peierls, Phys. Rev. Lett. **6** (1961) 641.
[11] H. Gomm, Ö. Kaymakcalan and J. Schechter, Phys. Rev. **D 30** (1984) 2345.
[12] S. Gao and C. Gale, Phys. Rev. **C 57** (1998) 254.
[13] K. Haglin, Nucl. Phys. **A 584** (1995) 719.
[14] S. Gao, C. Gale, C. Ernst, H. Stöcker and W. Greiner, nucl-th/9812059.
[15] L. A. Kondratyuk *et al.*, Phys. Rev. **C 58** (1998) 1078.