Role of the a_1 meson in dilepton production from hot hadronic matter

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Abstract

Dilepton production from hot hadronic matter is studied in an effective chiral Lagrangian with pions, ρ-mesons, and a_1 mesons, We find that the production rates from reactions that involve axial-vector mesons dominate over contributions from all other reactions when the dilepton invariant mass is above 1.5 GeV.

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In nucleus-nucleus collisions at ultrarelativistic energies, a hot and dense matter consisting of quarks and gluons is expected to be formed in the initial stages of the collision. This quark-gluon plasma will, however, transform into hadronic matter as it expands and cools below the critical temperature. Since dileptons and photons produced from the quark-gluon plasma do not suffer final-state interactions, they carry information about their production and have been considered as possible signatures for the formation of the quark-gluon plasma [1–4].

However, hadrons in the hadronic matter still interact violently until freeze out. Dileptons and photons can thus be produced also from the hot and dense hadronic matter. To use dileptons and photons as signatures for the quark-gluon plasma, we need therefore to distinguish them from those produced from the hadronic matter.

For dileptons with invariant masses larger than the J/ψ mass (3 GeV), the dominant contributions are from the Drell-Yan process and direct charm decay [4], while for invariant masses lower than the phi meson mass (1 GeV), radiative and direct decays, together with $\pi\pi$ annihilations, form the brightest source. To distinguish the quark-gluon plasma with these low invariant mass lepton pairs is thus expected to be extremely difficult [5]. However, for dileptons of invariant masses that are between the phi and J/Ψ masses, $m_\phi < M < m_{J/\Psi}$, the original suggestion was that the contribution from the quark-gluon plasma may dominate that from the hadronic matter [2]. One may then be able to study the quark-gluon plasma by concentrating on those lepton pairs.

The dilepton production rates from hadronic matter have usually been calculated by assuming that the hadronic matter consists of only pions. Recently, one of us and P. Lichard [6] have shown that for temperatures $T > 100$ MeV dilepton production from reactions involving higher-mass hadron resonances becomes important. Including both strange and non-strange pseudoscalar and vector mesons, it was found that in the invariant mass region where one could expect dominant dilepton contributions from the quark-gluon plasma, the reactions involving pseudoscalar and vector mesons lead to significant lepton pair signals. It is thus essential to carefully study dilepton production from hot hadronic matter with the inclusion of higher mass mesons.

In connection with photon production from a hot hadronic gas, it has recently been shown that the contributions from processes with a_1 mesons in the intermediate states dominate [7,8]. It is thus reasonable to expect that the a_1 meson would also play an important role in dilepton production. It is the purpose of this paper to investigate this assertion. We shall study dilepton production from processes involving the a_1 meson in thermalized hadronic matter using an effective chiral Lagrangian that includes not only pseudoscalar and vector mesons but also axial-vector mesons [8–10].

In our effective Lagrangian, the pseudoscalar mesons (ϕ) are described by the non-linear σ model while the vector (V_μ) and axial-vector (A_μ) mesons are included as massive Yang-Mills fields of the $SU(2)\times SU(2)$ chiral symmetry. The lowest order interaction terms are given by

$$\begin{aligned}
\mathcal{L}^{(3)}_{V\phi\phi} &= \frac{ig}{2}\mathrm{Tr}\partial_\mu\phi[V^\mu,\phi] \\
&+\frac{ig\delta}{2m_V^2}\mathrm{Tr}(\partial_\mu V_\nu-\partial_\nu V_\mu)\partial^\mu\phi\partial^\nu\phi, \\
\mathcal{L}^{(3)}_{VVV} &= \frac{ig}{2}\mathrm{Tr}(\partial_\mu V_\nu-\partial_\nu V_\mu)V^\mu V^\nu, \\
\mathcal{L}^{(3)}_{VA\phi} &= i\left[\left(\frac{1-\sigma}{1+\sigma}\right)^{1/2}\frac{g^2F_\pi}{4m_V^2}+\frac{2\xi g Z^2}{F_\pi\sqrt{1+\sigma}}\right]\mathrm{Tr}(\partial_\mu V_\nu-\partial_\nu V_\mu)[A^\mu,\partial^\nu\phi] \\
&+i\left[\left(\frac{1+\sigma}{1-\sigma}\right)^{1/2}\frac{g^2F_\pi}{4m_V^2}-\frac{2\sigma}{F_\pi\sqrt{1-\sigma^2}}\right]\mathrm{Tr}(\partial_\mu A_\nu-\partial_\nu A_\mu)[\partial^\mu V^\nu,\phi], \\
\mathcal{L}^{(3)}_{VAA} &= \frac{ig}{2}\mathrm{Tr}(\partial_\mu A_\nu-\partial_\nu A_\mu)[V^\mu,A^\nu] \\
&+\frac{ig}{2}\left(\frac{1-\sigma}{1+\sigma}\right)\left(1-\frac{2\xi g}{\sqrt{1-\sigma}}\right)\mathrm{Tr}(\partial_\mu V_\nu-\partial_\nu V_\mu)A^\mu A^\nu,
\end{aligned} \tag{1}$$

where $F_\pi \approx 135$ MeV is the pion decay constant,

$$\delta = \frac{g^2F_\pi^2}{4m_V^2}-\frac{2\xi g}{\sqrt{1-\sigma}}\frac{4m_V^2}{g^2F_\pi^2}Z^4, \tag{2}$$

and

$$Z^2 = 1-\left(\frac{g^2F_\pi^2}{4m_V^2}\right). \tag{3}$$

The parameters of the effective Lagrangian (g,ξ,σ,m_V) have been determined from the experimental data on the decay widths and masses of ρ and a_1 mesons.

The electromagnetic interaction is introduced through imposing the $U(1)_{EM}$ gauge symmetry on the effective chiral Lagrangian, i.e., we let

$$\mathcal{L} \to \mathcal{L} - \frac{1}{4}(\partial_\mu a_\nu - \partial_\nu a_\mu)^2 + \mathcal{L}_{EM}, \tag{4}$$

where a_μ is the electromagnetic field and

$$\begin{aligned}\mathcal{L}_{EM} &= -\frac{2em_V^2}{g} a_\mu \mathrm{Tr}[QV_\mu] + \frac{2e^2 m_V^2}{g^2} a_\mu^2 \mathrm{Tr} Q^2 \\ &= -\frac{\sqrt{2}e}{g} a^\mu \left[m_\rho^2 \rho_\mu^0 + \frac{1}{3} m_\omega^2 \omega_\mu - \frac{\sqrt{2}}{3} m_\phi^2 \phi_\mu \right] + \mathcal{O}(a_\mu^2),\end{aligned} \tag{5}$$

with Q=dial($\frac{2}{3}$,$-\frac{1}{3}$,$-\frac{1}{3}$) is the quark charge matrix. $\mathcal{L}_{EM}$ ensures that the Lagrangian is invariant under the gauge transformation. The above equation shows that the electromagnetic couplings of the vector mesons are given by the same form as in the vector meson dominance model [11].

The a_1 meson will contribute to dilepton production mainly through the two processes, $\pi^+ + a_1^-(\pi^- + a_1^+) \to e^+ + e^-$ and $a_1^+ + a_1^- \to e^+ + e^-$, as shown by the two diagrams in Fig. 1. While the annihilation of two a_1 mesons yields a lepton pair with a large invariant mass, the annihilation of the a_1 meson with a pion will be of interest in the invariant mass region considered here.

In general, the dilepton production rate from the annihilation of two hadrons h_1 and h_2 can be written as

$$\frac{dN}{d^4x} = \mathcal{N} \int \frac{d^3p_1}{(2\pi)^3} \frac{d^3p_2}{(2\pi)^3} f(p_1) f(p_2) \sigma(1+2 \to l^+ l^-) v_{\mathrm{rel}}, \tag{6}$$

where $\mathcal{N}$ is an overall degeneracy factor, $f(p)$ is the distribution function of the incoming particles at temperature T, v_{rel} is the relative velocity of the two particles, and σ is the dilepton production cross section for the reaction $h_1 + h_2 \to l^+ + l^-$ [3]. As the cross section depends only on the square of the invariant mass $s = (p_1 + p_2)^2 = M^2$, this expression can be simplified to

$$\frac{dN}{d^4x} = \mathcal{N} \frac{T^2}{2(2\pi)^4} \int_{s_0} ds \sigma(s) \sqrt{s^2 - 2s(m_1^2 + m_2^2) + (m_1^2 - m_2^2)^2}\, G(T,s), \tag{7}$$

where

$$G(T,s) = \int_{m_1/T} dx \frac{1}{e^x - 1} \ln\left(\frac{1-\exp(-y_+)}{1-\exp(-y_-)}\right), \tag{8}$$

with

$$y_\pm = \frac{1}{2m_1^2}\left[(s-m_1^2-m_2^2)x \pm \sqrt{s^2-2s(m_1^2+m_2^2)+(m_1^2-m_2^2)^2}\sqrt{x^2-\frac{m_1^2}{T^2}}\right]. \tag{9}$$

In this calculation, we focus on dielectrons and have neglected the small lepton masses but it is straightforward to include them. The differential production rate then becomes

$$\frac{dN}{d^4x dM^2} = \mathcal{N}\frac{T^2}{2(2\pi)^4}\sigma(M^2)\sqrt{M^4-2M^2(m_1^2+m_2^2)+(m_1^2-m_2^2)^2}\, G(T,M^2), \tag{10}$$

where M is the invariant mass of the dilepton.

The dilepton production cross section is given by the product of a form factor and the square of a scattering amplitude, which can be written as

$$|\bar{\mathcal{M}}|^2 = 4\left(\frac{4\pi\alpha}{q^2}\right)^2 L_{\mu\nu}H^{\mu\nu}, \tag{11}$$

with $q = p_1 + p_2 = p_3 + p_4$ and α the fine structure constant. In the above, $L_{\mu\nu}$ is the leptonic tensor given by

$$L^{\mu\nu} = p_3^\mu p_4^\nu + p_4^\mu p_3^\nu - g^{\mu\nu} p_3 \cdot p_4, \tag{12}$$

and $H^{\mu\nu}$ is a hadronic tensor for the reaction.

The hadronic tensor $H^{\mu\nu}$ for the reaction $\pi^+ + \pi^- \to e^+ + e^-$ is given by

$$H^{\mu\nu} = (p_2^\mu - p_1^\mu)(p_2^\nu - p_1^\nu), \tag{13}$$

which leads to the well-known result for the $\pi\pi$ annihilation cross section

$$\sigma_\pi(s) = \frac{4\pi}{3}\frac{\alpha^2}{s}|F_\pi|^2\left(1-\frac{4m_\pi^2}{s}\right)^{1/2}, \tag{14}$$

where F_π is the pion form factor.

For the reaction $\rho^+\rho^- \to e^+e^-$, the hadronic tensor $H^{\mu\nu}$ is

$$H^{\mu\nu} = h_\rho^{\mu\alpha\beta} h_{\rho\,\alpha\beta}^{\nu} - h_\rho^{\mu\alpha\beta} p_{1\,\beta} h_{\rho\,\alpha}^{\nu\beta} p_{1\,\beta}/m_\rho^2$$
$$-h_\rho^{\mu\alpha\beta} p_{2\,\alpha} h_{\rho\,\beta}^{\nu\alpha} p_{2\,\alpha}/m_\rho^2 + h_\rho^{\mu\alpha\beta} p_{1\,\beta} p_{2\,\alpha} h_\rho^{\mu\alpha\beta} p_{2\,\alpha} p_{1\,\beta}/(m_\rho^2)^2, \qquad (15)$$

with

$$h_\rho^{\mu\alpha\beta} = (p_2^\mu - p_1^\mu) g^{\alpha\beta} + (q^\alpha - p_2^\alpha) g^{\beta\mu} + (p_1^\beta - q^\beta) g^{\mu\alpha}. \qquad (16)$$

For πa_1 annihilation into a lepton pair, the hadronic tensor has the form

$$H^{\mu\nu} = h_{a_1}^{\mu\alpha} h_{a_1\,\alpha}^{\nu} - h_{a_1}^{\mu\alpha} p_{2\,\alpha} h_{a_1}^{\nu\alpha} p_{2\,\alpha}/m_{a_1}^2, \qquad (17)$$

with

$$h_{a_1}^{\mu\alpha} = \eta_1[(p_1\cdot q) g^{\mu\alpha} - p_1^\mu q^\alpha] + \eta_2[(p_2\cdot q) g^{\mu\alpha} - p_2^\mu q^\alpha], \qquad (18)$$

where

$$\eta_1 = \left(\frac{1-\sigma}{1+\sigma}\right)^{1/2} \left(\frac{gF_\pi}{2m_\rho^2}\right) + \frac{4\xi Z^2}{F_\pi\sqrt{1+\sigma}},$$
$$\eta_2 = \left(\frac{1+\sigma}{1-\sigma}\right)^{1/2} \left(\frac{gF_\pi}{2m_\rho^2}\right) - \frac{4\sigma}{gF_\pi\sqrt{1-\sigma^2}}. \qquad (19)$$

The hadronic tensor for the reaction $a_1^+ + a_1^- \to e^+ + e^-$ can be obtained from the reaction $\rho^+\rho^- \to e^+e^-$ by replacing h_ρ and m_ρ with h_{a_1} and m_{a_1}, respectively. The $h_{a_1}^{\mu\alpha\beta}$ is then given by

$$h_{a_1}^{\mu\alpha\beta} = (p_2^\mu - p_1^\mu) g^{\alpha\beta} + (\zeta q^\alpha - p_2^\alpha) g^{\beta\mu} + (p_1^\beta - \zeta q^\beta) g^{\mu\alpha}, \qquad (20)$$

with

$$\zeta = \left(\frac{1-\sigma}{1+\sigma}\right)\left(1 - \frac{2\xi g}{\sqrt{1-\sigma}}\right). \qquad (21)$$

We have calculated the dilepton production rate from hadronic matter at two temperatures, T=150 and 200 MeV, and the results are shown in Fig. 2 and Fig. 3, respectively. The dotted curve is the "usual" result from the reaction $\pi^+\pi^- \to e^+e^-$ which dominates at low invariant masses. The contribution from the reaction $\rho^+\rho^- \to e^+e^-$ is shown by the dashed curve. This process was found in ref. [6] to be the dominant one for dileptons of invariant masses in the region 1.5 GeV $< M <$ 3.0 GeV. The solid curves are from the reactions $\pi^+ a_1^- (\pi^- a_1^+) \to e^+e^-$ and $a_1^+ a_1^- \to e^+e^-$, both involving the a_1 meson. We note that in our calculations we have used the same form factors for $\pi^+\pi^- \to e^+e^-$ and $\rho^+\rho^- \to e^+e^-$, as in ref. [6]. For the reactions $\pi^+ a_1^- (\pi^- a_1^+) \to e^+e^-$ and $a_1^+ a_1^- \to e^+e^-$, we assume that the form factors are the same as for $\pi^+\pi^-$ annihilation. This is again consistent with the prescription followed in ref. [6].

Our results at $T = 150$ MeV show that the a_1 meson plays an important role in dilepton production from hadronic matter. Dilepton production from $\pi^+ a_1^- (\pi^- a_1^+) \to e^+e^-$ is seen to dominate over the reaction $\rho^+\rho^- \to e^+e^-$ and is most important in the invariant mass region 1.5 GeV $< M <$ 3.0 GeV: the possible window for observing the quark-gluon plasma in ultrarelativistic nucleus-nucleus collisions. As expected, the reaction $a_1^+ a_1^- \to e^+e^-$ becomes important only at higher invariant masses. Similar conclusions are reached at $T = 200$ MeV, with an overall enhancement in the dilepton yield.

In summary, we have considered dilepton production from reactions that involve the a_1 meson. We have found that dilepton production from the reaction $\pi^+ a_1^- (\pi^- a_1^+) \to e^+e^-$ is more important than that from $\rho^+\rho^-$ annihilation. This observation is independent of the temperature of the hadronic matter. As in photon production from the hadronic matter, the a_1 meson is important in dilepton production from the hot hadronic matter as well. This fact raises an interesting question about the role of heavy mesons in hadronic matter. Will we get an enhanced production of dileptons and photons as we include other heavier mesons? Are heavier mesons more important than the light ones in determining the photon and dilepton production rates? This probably is not the case as the dilepton production rates from reactions that involve the ϕ meson have been shown in ref. [6] to be negligible compared with the production rate from the reaction $\rho^+\rho^- \to e^+e^-$. This might indicate that the enhancement observed in the present study is just due to the a_1 meson. In this respect, it will be of interest to study photon production from strange particles. Also, it would be useful to extend the present study to the case of $SU(3) \times SU(3)$ symmetry.

There are higher order contributions to dilepton production from hot hadronic matter [12], which are related to processes similar to those considered in photon production [8]. We expect that a consistent inclusion of the a_1 should also add significantly to the contribution from higher order reactions. Such studies need to be pursued.

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FIGURES

FIG. 1. Lowest order diagrams for dilepton emissions from hadronic matter which involve axial vector mesons.

FIG. 2. Dilepton production from the hot hadronic matter at T= 150 MeV; the dotted and dashed curves are contributions from $\pi^+\pi^- \to e^+e^-$ and $\rho^+\rho^- \to e^+e^-$, respectively, while the solid curves are from $\pi^+a_1^-(\pi^-a_1^+) \to e^+e^-$ and $a_1^+a_1^- \to e^+e^-$.

FIG. 3. Same as the Figure 2 for $T = 200$ MeV.