Meson Mixing and Dilepton Production in Heavy Ion Collisions

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Abstract. We study the possibility of $\rho - a_0$ mixing via N-N excitations in dense nuclear matter. This mixing is found to induce a peak in the dilepton spectra at an invariant mass equal to that of the $a_0$. We calculate the cross section for dilepton production through mixing and we compare its size with that of $\pi - \pi$ annihilation. In-medium masses and mixing angles are also calculated. Some preliminary results of the mixing effect on the dilepton production rates at finite temperature are also presented.

Electromagnetic radiation, especially lepton pairs, constitutes a class of valuable probes in the context of heavy ion collisions. This owes to the fact that the leptons couple to hadrons via vector mesons and therefore hadronic processes involving $\ell^+\ell^-$ in the final channel are expected to reveal their properties in the dilepton spectra. Furthermore, the $\ell^+\ell^-$ pairs suffer minimum final state interactions and are thus likely to bring information to the detectors essentially unscathed. We will only consider dielectrons in this work.

Several experiments have measured, or are planning to measure, the lepton pairs produced in nucleus-nucleus collisions. They have been carried out by the DLS at LBL [1], and by HELIOS [2] and CERES [3] at CERN. Two new initiatives that will focus on electromagnetic probes will be PHENIX at RHIC [4] and HADES at GSI [5]. The density-dependent characteristics of vector mesons can also be highlighted through experiments performed at TJNAF [6].

We explore here the possibility of $\rho-a_0$ mixing via n-n excitations in nuclear matter. This is a pure density-dependent effect and is forbidden in free space on account of Lorentz symmetry. We show that such a mixing opens up a new channel in dilepton production and will modify the spectrum in the $\phi$ mass region. The details of the calculation will only be sketched here. The interested reader is invited to consult [7].

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The interaction Lagrangian we will use can be written as
\[
\mathcal{L}_{\text{int}} = g_\sigma \bar{\psi} \phi_\sigma \psi + g_{a_0} \bar{\psi} \phi_{a_0} \tau^a \psi + g_{\omega NN} \bar{\psi} \gamma_\mu \psi \omega^\mu \\
+ g_\rho [\bar{\psi} \gamma_\mu \tau^a \psi + \frac{\kappa_\rho}{2m_n} \bar{\psi} \sigma_{\mu\nu} \tau^a \partial^\nu] \rho^\mu ,
\]
(1)
where \( \psi, \phi_\sigma, \phi_{a_0}, \rho \) and \( \omega \) correspond to nucleon, \( \sigma, a_0, \rho \) and \( \omega \) fields, and \( \tau_a \) is a Pauli matrix. The values used for the coupling parameters are obtained from Ref. [8].

The polarization vector through which the \( a_0 \) couples to \( \rho \) via the n-n loop is given by
\[
\Pi_\mu(q_0, |q|) = 2ig_{a_0}g_\rho \int \frac{d^4k}{(2\pi)^4} \text{Tr}[G(k)\Gamma_\mu G(k + q)].
\]
(2)
where 2 is an isospin factor and the vertex for \( \rho \)-nn coupling is
\[
\Gamma_\mu = \gamma_\mu - \frac{\kappa_\rho}{2m_n} \sigma_{\mu\nu} q^\nu.
\]
(3)

\( G(k) \) is the in-medium nucleon propagator [9].

With the evaluation of the trace and after a little algebra Eq. (2) could be cast into a suggestive form:
\[
\Pi_\mu(q_0, |q|) = \frac{g_\rho g_{a_0}}{\pi^3} 2q^2(2m_n^* - \frac{\kappa q^2}{2m_n}) \int_{k_F} d^3k \frac{k_\mu - \frac{q_\mu}{q^2}(k \cdot q)}{E^*(k) q^4 - 4(k \cdot q)^2}.
\]
(4)
It easily can be seen that it obeys current conservation: \( q^\mu \Pi_\mu = 0 = \Pi_\nu q^\nu \). This implies that only one component of \( \Pi_\mu \) is independent. In fact, only the longitudinal component of the \( \rho \) meson couples to the scalar meson while the transverse mode remains unaltered.

In presence of mixing the combined meson propagator might be written in a matrix form where the dressed propagator would no longer be diagonal:
\[
\mathcal{D} = \mathcal{D}^0 + \mathcal{D}^0 \Pi \mathcal{D} \quad \mathcal{D}^0 = \begin{pmatrix} D^0_{\mu
u} & 0 \\ 0 & \Delta_0 \end{pmatrix}.
\]
(5)
The noninteracting propagator for the \( a_0 \) and \( \rho \) are given respectively by
\[
\Delta_0(q) = \frac{1}{q^2 - m_{a_0}^2 + i\epsilon}, \quad D^0_{\mu\nu}(q) = \frac{-g_{\mu\nu} + \frac{g_{a_0}q_{\mu\nu}}{q^2}}{q^2 - m_\rho^2 + i\epsilon}.
\]
(6)
The mixing is characterised by the polarization matrix which contains non-diagonal elements
\[
\Pi = \begin{pmatrix} \Pi^\rho_{\mu\nu}(q) & \Pi^\rho_{\nu\sigma}(q) \\ \Pi^\rho_{\mu\sigma}(q) & \Pi^\rho_{\sigma\nu}(q) \end{pmatrix}.
\]
(7)
Π_{a_0}^0$ and $Π_{\rho}^\mu_\nu$ refer to the diagonal self-energies of the $a_0$ and $\rho$ meson induced by the n-n polarization.

The $\rho$ meson being a vector, one can write the longitudinal and transverse polarization as $\Pi_L = -\Pi_{00} + \Pi_{33}$ and $\Pi_T = \Pi_{11} = \Pi_{22}$. To determine the collective modes and their dispersion relation, one can define the dielectric function and look for its zeroes [10]. The left panel of Fig. 1 shows the relevant dispersion curves with

![Dispersion curves and mixing angle](image)

**FIGURE 1.** The dispersion curve and mixing angle at $\rho=2.5\rho_0$.

and without mixing at density $\rho=2.5\rho_0$. As only the L mode mixes with the scalar mode, we do not consider the T mode. The later in fact is the same as presented in Ref. [11] for the $\rho$ meson, and in Ref. [12] for $\sigma-\omega$ mixing. The effect of mixing on the pole masses, as evident from Fig. 1, are found to be small. However, the mixing could be large when the mesons involved go off-shell.

To calculate the mixing angle, one diagonalises the mass matrix [11] with the mixing and obtains

$$\theta_{mix} = \frac{1}{2} \arctan \left( \frac{2\Pi_{\rho a_0}^{\rho a_0}}{m_{a_0}^2 - m_{\rho}^2 - \Pi_L + \Pi_{a_0}} \right)$$

In Eq. (8) $\Pi_{mix}^{\rho a_0} = M_q/|q|\Pi_0$ which increases with density. $\Pi_0$ is the zero'th component of Eq. (4). The momentum dependence for a density of 1.5 times higher than the normal nuclear matter density is shown in the right panel of Fig. 1. This shows that for momenta beyond $|q| \approx 0.2$ GeV/c the mixing is quite appreciable. It should also be noted that the mixing angle vanishes at $|q| = 0$ as it should.

The $\rho-a_0$ mixing opens a new channel, $\pi + \eta \to e^+ + e^-$, in dense nuclear matter through n-n excitations. The cross-section for this process is expressed in terms of the mixing amplitude ($\Pi_0$) [7] and is plotted in Fig. 2.

One can notice in Fig. 2 that the process, $\pi + \eta \to e^+ + e^-$, at densities higher than $\rho_0$, not only enhances the overall production of lepton pairs but also induces an additional peak near the $\phi$ mass region. The contribution at the $a_0$ mass is
FIGURE 2. Dilepton production cross section for $\pi + \eta \rightarrow e^+ + e^-$ through matter-induced $\rho - a_0$ mixing, and for $\pi + \pi \rightarrow e^+ + e^-$. Similar cross sections are obtained for $\pi + \eta \rightarrow e^+ + e^-$ through matter-induced $\rho - a_0$ mixing, and for $\pi + \pi \rightarrow e^+ + e^-$. The cross sections are well below that of $\pi + \pi \rightarrow e^+ + e^-$ near the $\rho$ peak, for densities higher than $\rho_0$. Fig. 2 also shows that as the density goes even higher the dilepton yield arising out of the mixing also increases further.

FIGURE 3. Dilepton production rates for $T=50$ MeV.

Further studies are in progress to assess finite temperature effects and to incorporate the necessary many-body machinery. We will show here only some preliminary results for the dilepton production rate including the effect of $\rho - a_0$ mixing. We work the independent particle approximation of kinetic theory. We assume a thermal gas of mesons at $T = 50 MeV$. Fig. 3 shows the dilepton production rate as compared with the standard $\pi\pi$ and $K\bar{K}$ annihilation. One can observe from Fig 3 that even at density $\rho/\rho_0 = 1.5$ the contribution of the mixing wins over the $\pi\pi$...
annihilation rate in the vicinity of $M = 1.0$ GeV. Naturally at higher density this goes up as evident from the right panel of Fig. 3.

We have highlighted the possibility of $\rho$-$a_0$ mixing in dense nuclear matter. We observe the appearance of an additional peak at a dilepton invariant mass that corresponds to that of the $a_0$. With sufficient experimental resolution, this effect could be observed. Maybe not as an individual peak, but probably more realistically as a shoulder in the $\phi$ spectrum. This feature would then be exclusively temperature and density-dependent and would thus be the reflection of a genuine in-medium effect.

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