Medium Effects in low-mass dilepton production in ultra-relativistic heavy-ion collisions are investigated using hadronic models. The rescattering of pions and rho mesons within a hot and dense hadron gas leads to substantial modifications in the $\pi^+\pi^-\rightarrow e^+e^-$ annihilation process, which are shown to be important for understanding the recently observed dilepton enhancement at the CERN-SpS. Possible implications for the nature of the chiral phase transition are outlined.

1 Introduction

A thorough understanding of Quantum Chromodynamics (QCD) has to account for the many-body properties of the theory, such as its phase diagram. Already at the level of the ground state (vacuum) this has proven to be a non-trivial task: whereas the fundamental QCD Lagrangian,

$$L_{\text{QCD}} = \bar{q} (\not{D} - m_q) q - \frac{1}{4} G_{\mu\nu}G^{\mu\nu},$$

exhibits (in the limit of vanishing current quark masses $m_q \rightarrow 0$) an exact chiral symmetry, the latter is spontaneously broken in the QCD vacuum, leading to, e.g., a nonzero expectation value of the (chiral) quark condensate $\langle0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle$. The same inter-quark forces which generate the chiral-symmetry-breakdown presumably also govern the structure of the low-lying hadronic spectrum, as e.g. indicated by the appearance of (quasi-) Goldstone bosons (pions) or the non-observance of parity doublets (i.e. $\pi(140) - \sigma(400-1200)$, $\rho(770) - a_1(1260)$, $N(939) - N^*(1535)$, etc., are separated in mass by typically $\Delta m \approx 0.5$ GeV). However, at sufficiently high temperature and/or density one expects chiral symmetry to be restored, within the so-called 'Chiral Phase Transition'. Thus one concludes that medium modifications of hadrons in hot/dense matter are in fact precursors of chiral symmetry restoration.
Experimentally one studies strongly interacting matter in the various heavy-ion collision programs at CERN, BNL, GSI, etc.; to probe the highest density/temperature phases formed in the early stages of central collisions of two heavy nuclei, electromagnetic observables (photons or dileptons \(e^+e^-, \mu^+\mu^-\)) are believed to be particular suitable, since, once produced, they can traverse the hadronic fireball without further (strong) interaction. This, in principle, provides direct access to the vector meson properties in the hadronic medium via their decay modes \(V \rightarrow e^+e^-, \mu^+\mu^- (V = \rho, \omega, \phi, J/\Psi, \ldots)\); note, however, that only the \(\rho\) meson lifetime of \(\tau_\rho = 1.3\) fm/c is substantially smaller than the typical lifetime \(\tau_{FB} = 10-20\) fm/c of the hadronic fireball. In this respect, recent measurements of dilepton invariant mass spectra at the CERN-SpS have drawn remarkable attention: in the high mass region, a substantial suppression of \(J/\Psi\) production has been observed; on the other hand, in the low-mass region, a strong increase in the dilepton yield was found as compared to expectations based on hadronic decays after freeze-out. Although the additional inclusion of \(\pi^+\pi^- \rightarrow e^+e^-\) annihilation in the hadronic fireball substantially increases the dilepton yield, the experimentally observed excess around invariant masses of \(M \approx 0.4\) GeV/c\(^2\) still remains unexplained.

In this talk I will discuss recent developments in understanding the low-mass enhancement in terms of hadronic models and its possible implications for the nature of the chiral phase transition. The key object to be calculated is the so-called electromagnetic (or vector) current correlator (sect. 2), which is directly related to the dilepton production rate in hot/dense matter as needed for evaluating experimentally observed spectra in heavy-ion collisions (sect. 3).

2 Hadronic Models for the Electromagnetic Current Correlator

2.1 Vacuum

The electromagnetic (e.m.) current correlation function in free space,

\[
\Pi_{\mu\nu}^{vac}(M) = i \int d^4x \ e^{iq\cdot x} \langle 0 | T j_\mu(x) j_\nu(0) | 0 \rangle = (g_{\mu\nu} - \frac{q_\mu q_\nu}{M^2}) \Pi_{\mu\nu}^{vac}(M) ,
\]

is determined by a single scalar function \(\Pi_{\mu\nu}^{vac}(M)\) depending on the invariant mass \(M = \sqrt{q_\mu q^\mu}\) only, the tensor structure being fixed by current conservation \((q_\mu \Pi^{\mu\nu} = 0)\). Invoking the well-established vector dominance model (VDM), the hadronic e.m. current is saturated by the low-lying vector mesons, i.e. \(j^\mu = j_{\rho}^\mu + j_{\omega}^\mu + j_{\phi}^\mu\). For what follows, the \(\rho\) meson part (isospin \(I=1\)) will be the most relevant one; it is given by

\[
Im\Pi_{I=1}^{vac}(M) = \frac{Im \Sigma_{\rho}^{vac}(M)}{g_\rho^2} |F_\pi(M)|^2 = \left(\frac{(m_{\rho}^{(0)})^2}{g_\rho^2}\right)^2 Im D_{\rho}^{vac}(M)
\]

with \(F_\pi\): pion electromagnetic formfactor, and \(D_\rho^{vac}(M) = [M^2 - (m_\rho^{(0)})^2 - \Sigma_{\rho}^{vac}(M)]^{-1}\): free \(\rho\) propagator consisting of a bare \(\rho\) of mass \(m_{\rho}^{(0)}\), dressed with intermediate two-pion states ('pion cloud') represented by the \(\rho\) selfenergy \(\Sigma_{\rho\pi\pi}^{vac}\). This model is consistent with experimental data on both \(F_\pi\) and p-wave \(\pi\pi\) scattering (proceeding through the \(\rho\) resonance).

2.2 Medium Modifications

In hadronic matter of temperature \(T\) and baryo-chemical potential \(\mu_B\), the e.m. correlator reads

\[
\Pi_{\mu\nu}(q_0,q;\mu_B,T) = i \int d^4x \ e^{iq\cdot x} Tr[e^{(\hat{H}-\mu_B N)/T} T j_\mu(x) j_\nu(0)]/Z
\]

\[
= \Pi^L(q_0,q;\mu_B,T) P_{\mu\nu}^L + \Pi^T(q_0,q;\mu_B,T) P_{\mu\nu}^T
\]

(4)
where the breaking of Lorentz invariance implies the existence of two independent modes (longitudinal and transverse), depending separately on energy $q_0$ and 3-momentum modulus $q$.

Various approaches have been pursued in the literature to assess medium effects in $\Pi_{\mu\nu}$; the most spectacular one is the so-called Brown-Rho scaling conjecture, where in a mean field type picture the vector meson masses are directly linked to the reduction of the chiral condensate towards the chiral phase transition. Such a scenario leads to good agreement with the observed dilepton spectra at the CERN-SpS. More conventional ones include a "chiral reduction formalism", which ties chiral Ward identities with experimental information, or a combination of chiral SU(3) Lagrangians with VDM, in both these frameworks medium effects are based on a low-density expansion. We here discuss a slightly different approach, where phenomenological information on in-medium $\pi N$ and $\rho N$ interactions is employed within the VDM. Restricting ourselves first to the case of nuclear matter at zero temperature two types of medium effects in the $\rho$ propagator as introduced in sect. 2.1 arise:

(i) renormalization of the pion cloud through pion interactions with the surrounding nucleons, as is well known from the analysis of pion nuclear optical potentials, the dominant contributions stem from p-wave nucleon-nucleonhole and delta-nucleonhole excitations including short-range correlation effects (parametrized by Migdal parameters $g'$);

(ii) direct scattering of the $\rho$ on surrounding nucleons, which, in analogy to (i), we assume to be dominated by s-channel baryon ($B$) resonance graphs, the coupling constants of the corresponding $\rho BN$ vertex can be estimated from the free partial decay width $\Gamma_{B\rightarrow \rho N}^0$; they will be quantitatively fixed in the following section. The resonances included are listed in table 1; note that the finite width of the $\rho$ allows decays of the type $B \rightarrow \rho N \rightarrow \pi \pi N$ well below the rho-nucleon threshold of $m_N + m_\rho$.

Table 1: Baryon resonances with substantial coupling to $\rho N$ that are included in our calculation; the second row gives the spin-parity $J^P$ of the resonance, which determines whether the $\rho N$ coupling is of $p$-wave (for $P = +$) or $s$-$d$-wave (for $P = -$) type; the third row gives the partial decay width (in MeV) for $B \rightarrow \rho N$.

| $B^P$ | $N(939)^+$ | $\Delta(1232)$ | $N(1440)$ | $N(1520)$ | $\Delta(1620)$ | $\Delta(1700)$ | $N(1720)$ | $\Delta(1905)$ |
|-------|------------|----------------|------------|------------|----------------|----------------|------------|----------------|
| $J^P$ | $\frac{1}{2}^+$ | $\frac{3}{2}^+$ | $\frac{1}{2}^+$ | $\frac{3}{2}^-$ | $\frac{1}{2}^-$ | $\frac{3}{2}^-$ | $\frac{3}{2}^+$ | $\frac{5}{2}^+$ |
| $\Gamma_{\rho N}^0$ | $\sim 10$ | $\sim 25$ | $\sim 15$ | $\sim 100$ | $> 100$ | $> 200$ |

Thus the longitudinal and transverse parts of the $\rho$ propagator at nuclear density $\rho_N$ become

$$D_{\rho}^{L,T}(q_0, q; \rho_N) = \left[ q_0^2 - q^2 - (m_{\rho}^{(0)})^2 - \Sigma_{\rho\pi}(q_0, q; \rho_N) - \Sigma_{\rho BN}(q_0, q; \rho_N) \right]^{-1}. \quad (5)$$

The spin-averaged $\rho$ spectral function $ImD_{\rho} = \frac{1}{4}(ImD_{\rho}^L + 2ImD_{\rho}^T)$ is shown in fig. 1: already at normal nuclear matter density $\rho_N = \rho_0 = 0.16$ fm$^{-3}$ one observes a strong broadening of the resonance (right panel) as compared to free space (left panel).

### 2.3 Model Constraints from Experimental Data

To increase the reliability of the model when calculating dilepton production in heavy-ion collisions it is important to check consistency with other related data. Obviously, photoabsorption processes represent the $M \rightarrow 0$ limit of the (timelike) dilepton regime and therefore provide valuable constraints. Within the VDM the total photoabsorption cross section on a single nucleon or on nuclei (normalized to the number of nucleons $A$) can be written as

$$\frac{\sigma_{\text{abs}}^{\gamma}}{A} = \frac{4\pi\alpha}{g_\rho^2 q_0} \frac{1}{\rho_N} \tilde{F}(q_0 = q; \rho_N), \quad (6)$$
Figure 1: $\rho$-meson spectral function versus invariant mass $M$ and 3-momentum $q$ in vacuum (left panel) and in normal nuclear matter (right panel).

where $\bar{F}$ is essentially proportional to the imaginary part of the transverse $\rho$ propagator, Eq. (5). It includes direct resonance formation (encoded in $\Sigma_{\rho BN}$) and interactions via the pion cloud (the so-called meson exchange currents or 'background' contributions encoded in $\Sigma_{\rho \pi \pi}$), see the previous section. In the low-density limit, $\rho_N \to 0$, Eq. (6) corresponds to the absorption process on a single nucleon, the results for which are displayed in the left panel of fig. 2: the spectrum is dominated by the resonance contributions with the background constituting about 20-30% of the strength. For finite nuclei, most of the resonance structure disappears, indicating an in-medium broadening of the higher baryon resonances as well; the similarity of the data over a wide range of atomic numbers suggests that nuclear structure effects are not important, thus justifying to perform our calculation for infinite nuclear matter at an average density of $\rho_N = 0.8\rho_0$ (full curve in the right panel of fig. 2). Apparently, the lowest-order-in-density result (long-dashed curve) does not provide a satisfactory description of the nucleus data.

Further model constraints can be obtained, e.g., from the analysis of $\pi N \to \rho N$ production, which is in fact dominated by 'background' contributions. This imposes stringent constraints on the hadronic formfactor at the $\pi NN$ vertex (included in the results shown in fig. 2).
In URHIC’s at CERN-SpS energies (160-200GeV/u) several hundred secondary particles are produced (mostly pions), together with substantial temperatures of the hadronic fireball of about $T \approx 120-200$ MeV, which has to be accounted for in a realistic application of the ρ propagator. To this end we use retarded (finite temperature) selfenergies for both the pion propagator or the full lines (when using the in-medium ρ propagator).

### 3 Dilepton Production in URHIC’s

In URHIC’s at CERN-SpS energies (160-200GeV/u) several hundred secondary particles are produced (mostly pions), together with substantial temperatures of the hadronic fireball of about $T \approx 120-200$ MeV, which has to be accounted for in a realistic application of the ρ propagator. To this end we use retarded (finite temperature) selfenergies for both the pion cloud and the baryon resonance contributions, and include direct interactions of the ρ meson with pions and kaons from the heat bath via a $\rho$ meson propagator or transport simulations, or simply by an expanding fireball. The latter approach is determined by a temperature and density evolution (with isotropic volume $V_{FB}(t)$), which, after including experimental acceptance, leads to a dilepton spectrum according to

$$\frac{dN_{\pi^+\pi^-\rightarrow e^+e^-}}{d^4x} = \frac{\alpha^2(m_\rho/\pi^3 g_\rho^2)^4}{M^2} f^\rho(q_0;T) \frac{1}{3} \left( ImD^L_\rho + 2 ImD^T_\rho \right), \tag{7}$$

where $f^\rho$ denotes the thermal (bose-) occupation factor for ρ mesons. This rate is to be integrated over the space-time history of a given heavy-ion reaction, which can be modelled by e.g. hydrodynamic or transport simulations, or simply by an expanding fireball. The latter approach is determined by a temperature and density evolution (with isotropic volume $V_{FB}(t)$), which, after including experimental acceptance, leads to a dilepton spectrum according to

$$\frac{dN_{\pi^+\pi^-\rightarrow e^+e^-}}{dM \, d\eta} = \int_0^{t_f} dt \, V_{FB}(t) \int d^3q \, \frac{dN_{\pi^+\pi^-\rightarrow e^+e^-}}{dt \, d^3q}(q_0, q; \rho_B(t), T(t)) \, Acc(q_0, q). \tag{8}$$

Further contributions arise from hadron decays after freezeout (such as Dalitz decays $\pi^0, \eta \rightarrow \gamma e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$ or $\omega, \rho^0 \rightarrow e^+e^-$), taken from the CERES collaboration (dashed-dotted lines in fig. 3), which have to be added to the final spectra. Our final results are compared to CERES/NA45 data for Pb(158GeV/u)+Au collisions in fig. 3 when using the free $\rho$ spectral function in Eq. (5), the low-mass enhancement around $M \approx 0.4$ GeV cannot be explained (dashed curves); however, when including the in-medium effects due to hadronic rescattering as discussed above, reasonable agreement is obtained (full curves) with both the invariant mass (left panel) and transverse momentum spectra (right panel). Note that the major part of the enhancement for $0.2 \text{ GeV} < M_{ee} < 0.6$ GeV is correctly ascribed to rather small pair momenta $q_t \leq 0.7$ GeV. This
might in fact resolve the question why the $\mu^+\mu^-$ spectra measured by the NA50 collaboration show a much less pronounced excess at low $M_{\mu\mu}$: their transverse momentum cut of $p_t>1$ GeV on the single muon tracks will eliminate most of enhancement generated within our model.

4 Summary and Conclusions

We have shown that in-medium hadronic interactions generate a substantial excess of low-mass dileptons, which can essentially account for the experimentally observed enhancement in heavy-ion reactions at CERN-SpS energies. The question whether the 'melting' of the $\rho$ resonance as found in our analysis might signal (partial) restoration of chiral symmetry in strongly interacting matter remains open. Further insight could be gained, e.g., by investigating the in-medium properties of the $a_1(1260)$ meson, which, towards the chiral phase transition, has to become degenerate with its chiral partner, the $\rho$ meson. Experimentally, however, this will be difficult to assess.

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