

Precision studies of dilepton spectra in heavy-ion collisions

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The spontaneous breaking of chiral symmetry (SBCS) in the QCD vacuum is believed to be at the origin of more than 95% of the visible mass in the Universe. The underlying mechanism is intimately related to the formation of zero-temperature condensates. Unlike the Higgs condensate in electroweak interactions, the QCD condensates are composites of quark and gluons, most notably the scalar quark-antiquark condensate. However, the condensates themselves are not physical observables, and thus information about the ground-state structure has to be deduced from its excitations. In the present context the latter are nothing but the hadronic spectrum. In particular, chiral multiplets (e.g. $\pi(140)$ - $\sigma(500)$, $\rho(770)$ - $a_1(1260)$ or $N(940)$ - $N^*(1535)$) exhibit a massive ($\Delta M \sim 0.5\text{GeV}$) splitting corroborating the notion of SBCS. At finite temperatures and baryon densities the condensates are expected to melt giving rise to a chiral phase transition in hot/dense QCD matter. Clearly, such phase changes must be accompanied by a major reshaping (chiral restoration) of the hadron spectrum as we know it in the vacuum.

Three decades of high-energy heavy-ion collision experiments have demonstrated that hot and dense QCD matter close to equilibrium can be created and studied in these reactions. Dilepton invariant-mass spectra are the only known observable to directly extract information on the spectral modifications of hadrons, specifically vector mesons through their exclusive decays $V \rightarrow e^+e^-$ ($V=\rho,\omega,\phi$) [1]. The ρ meson is of particular interest since it dominates the dilepton emission rate in thermal equilibrium. Its vacuum line shape has been predicted to undergo a strong broadening in hot and dense hadronic matter [2], leading to a “melting” of the resonance ($\Gamma_\rho \rightarrow m_\rho$) close to the expected phase transition temperature of $T_c \sim 180\text{MeV}$, cf. left panel of Fig. 1. These predictions can now be tested quantitatively with the

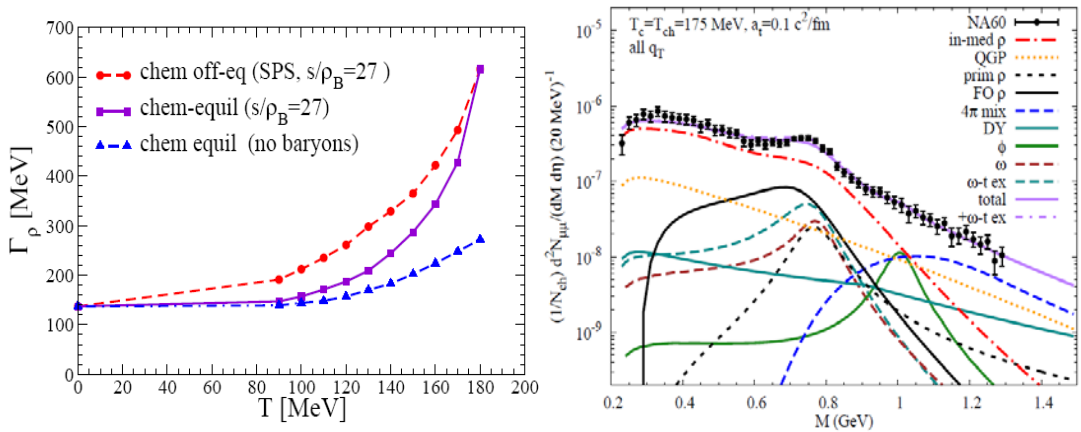


FIG. 1. Left panel: In-medium ρ -meson width as a function of temperature under CERN-SPS conditions (i.e., the baryon density increases with T as well) [1,2]. Right panel: Predictions for dilepton emission from a thermal fireball (plus “non-thermal” sources) [4], compared to fully acceptance-corrected NA60 dimuon data [3] in semi-central 158 AGeV In-In collisions.

newest fully acceptance-corrected dimuon spectra measured by NA60 in In-In collisions at the CERN-SPS [3], cf. right panel of Fig. 1. Note that since the mass spectra are invariant, details of the modeling of the medium expansion in the heavy-ion reaction do not matter. Therefore, the shape of the data directly reflects the theoretical thermal emission rate at the input level (which is basically given by the thermal Bose factor times the in-medium ρ spectral function). The quantitative agreement of the theory predictions [1,4] with the NA60 data allows to extract a (time-) average in-medium ρ width of $\Gamma_\rho = 350\text{-}400$ MeV, realized at an average temperature of about $T \sim 150\text{-}160$ MeV (with a baryon density close to that of normal nuclear matter). This necessarily implies contributions from higher temperatures and densities where the ρ width is indeed approaching its mass. The behavior of the ρ -width toward “ T_c ” may be closely related to the well-known Hagedorn limit of the hadron resonance gas which was one of the first arguments for the existence of a phase transition in hot hadronic matter. Schematically, the ρ -width may be written as $\Gamma_\rho^{\text{med}} \sim \sum_h \sigma_{\rho h} n_h v_{\text{rel}}$, where the summation is over all hadrons, h , with their respective densities in the medium. If the ρ - h cross section is finite, a divergence of the total hadron density (Hagedorn catastrophe) implies the divergence of the in-medium ρ width [1].

The theory comparisons to NA60 data enable further insights into the medium produced in heavy-ion collisions. The combined analysis of invariant-mass and transverse-momentum (q_t) spectra in the mass region of the narrow vector resonances ω and ϕ reveals a sequential freezeout pattern. The relatively soft q_t spectra of the ϕ require its kinetic decoupling close to the critical temperature which, in turn, is consistent with the (near) absence of an in-medium ϕ contribution in the dimuon excess spectra (right panel of Fig. 1 around $M \sim 1.02$ GeV). The ω is inferred to decouple somewhat later, at a temperature of about 150 MeV. On the contrary, the main emission yield driven by the in-medium ρ decays requires a significantly lower freezeout at about $T \sim 130$ MeV. This, in turn, enables a determination of the total lifetime of the interacting fireball in In-In collision at unprecedented accuracy, $\tau_{\text{FB}} = 6.5 \pm 1$ fm/c.

Current applications of this framework to (less accurate) dilepton data at RHIC indicate marked discrepancies for central Au-Au collision in the mass region around 0.3 GeV. Whether this requires a new production mechanisms (e.g. a disoriented chiral condensate due to supercooling through the chiral phase transition) is one of the exciting open question at this point.

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