Testing of QCD Plasma Formation by Dilepton Spectra in Relativistic Nuclear Collisions

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If a colored plasma is produced in ultrarelativistic collisions of heavy nuclei, its presence can be inferred by observing that the ρ-meson peak in the mass spectrum of emitted dileptons disappears as their transverse energy increases.

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The hope that nuclear collisions at ultrarelativistic energies may lead to the creation of a colored plasma, in which quarks and gluons move freely within a confinement volume much larger than hadronic sizes, is tempered by the difficulty of observing a signature to prove that the deconfinement has taken place. Since the plasma will rapidly expand and cool, it will soon turn into a hot dense gas of hadrons similar to the final state expected if the deconfinement had not occurred. Thus most traces of the plasma will be obscured by final-state interactions of hadrons. This problem will not disturb the photons and leptons emitted by the plasma; in their case, the challenge is to distinguish them from electroweak products of the hadronic gas. We show that the dependence of the mass spectrum of dilepton pairs on their transverse energy permits the separation of possible plasma products from the hadronically produced background.

The production of lepton pairs in relativistic nuclear collisions has been studied extensively.[1-4] These studies have shown that the spectrum of dileptons emitted from the plasma would be smooth and featureless, extending from the threshold dilepton mass $2m$ to very high masses of several gigaelectronvolts. By contrast, the dilepton spectrum from hadrons is dominated by a strong peak at the mass $M_\rho = 0.775$ GeV of the ρ meson, a feature known for decades as "vector dominance." Since even if a plasma is formed, the accompanying hadronic processes will surely also produce many dileptons with masses near M_ρ, previous workers[2-4] have suggested searching for signals of plasma formation in mass regimes above or below M_ρ. The high-mass region has the advantage[4] of being closely related to the quark correlation function at short distances and over short time scales; unfortunately, this regime does not directly bear the signals of deconfinement, which is an infrared phenomenon, so that only secondary features such as temperature can be inferred. The low-mass region is sensitive to confinement or deconfinement since it probes longer scales of distance[2]; there, however, the infrared properties of the hot dense hadronic gas also are important.[3] Sophisticated models of the hadronic gas would be necessary; for example, the simplest model of dilepton production by annihilation of two pions would lead to a threshold at a dilepton mass of $2m_\pi$, where instead observations show many dimuons produced near or below this mass[5-7] in ordinary hadronic collisions. We conclude that the extraction of a smooth plasma-produced component from the complicated dilepton mass spectrum would require a precise, quantitative theoretical understanding of hadronic interactions at a few times the pion mass in dense hot nuclear matter.

We propose a more direct, phenomenological method for separating the plasma's dileptons from those of the hadrons. Since the plasma phase, if it is produced, will be hotter than the accompanying hadronic phase, the plasma's dileptons will have, on the average, a greater total energy than the hadronic dileptons of the same mass. Thus the most energetic dilepton pairs will have a greater than average likelihood of coming from the plasma. We therefore expect that the peak at M_ρ in the dilepton mass spectrum will subside as the total energy of the pair increases, provided that a plasma has been formed. If only hadronic processes were present, the ρ peak would persist independent of the pair's energy. Since most scenarios of relativistic nuclear collisions lead[8,9] to a distribution of velocities of the hot matter along the beam direction, the thermal energy of the dilepton pair will be undetermined. Instead, we have to take the perpendicular energy $E_\perp = (p_\perp^2 + M^2)^{1/2}$ which is the same in all these frames.

We believe that the feature just described would provide a qualitative test of plasma formation, valid in any reasonable model of plasma and hadron dynamics. The vector mesons, whose quantum numbers are the same as the photon, are typical quark-antiquark bound states (ρ and ω have about the same mass). As long as confinement is present, there should be such resonances, though their masses and widths may be modified by their interactions with nearby hadrons. The disappearance of these resonances would be a signal of deconfinement.[10]

To illustrate this result in a simple model, we calculate the double-differential cross section $d^2\sigma/dM\, dE_\perp$ for emission of dilepton pairs of mass M and perpendicular energy $E_\perp = (p_\perp^2 + M^2)^{1/2}$, where $p_\perp$ is the to-

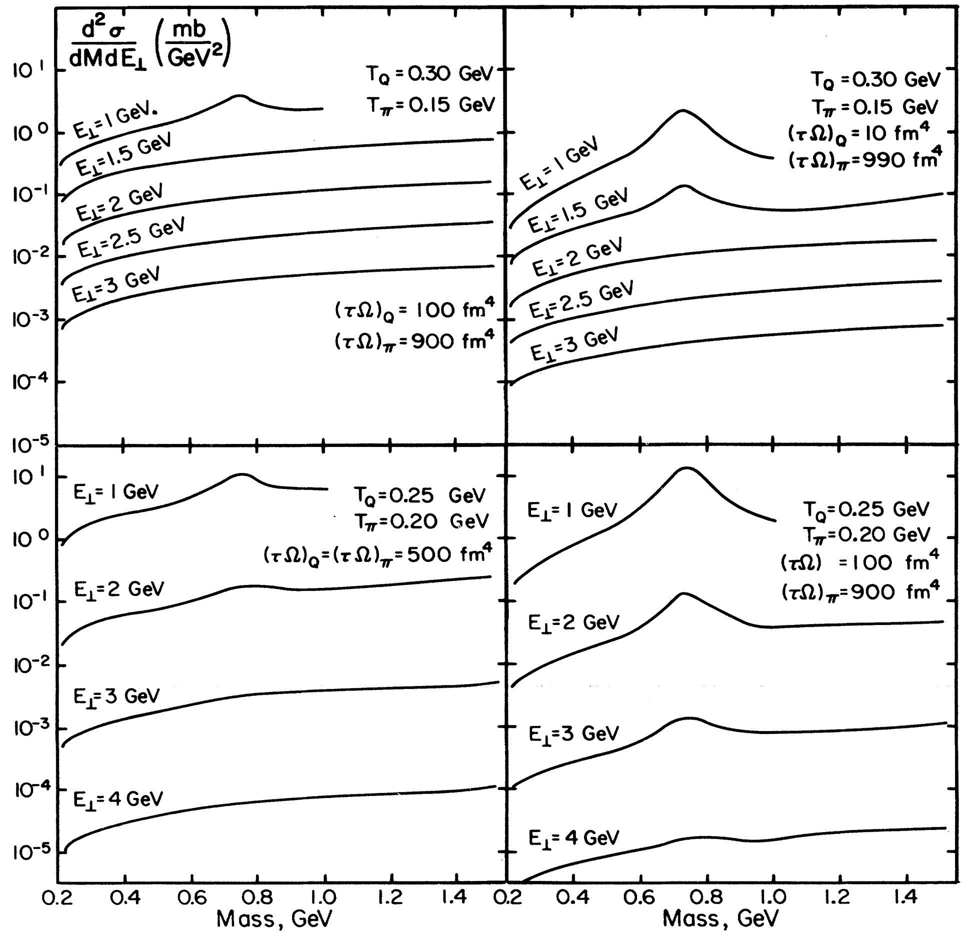

FIG. 1. Differential cross section $d^2\sigma/dM\,dE_\perp$ in millibarns per squared gigaelectronvolt for production of dimuons in ultrarelativistic nuclear collisions, as a function of mass M for various perpendicular energies $E_\perp$. A geometric cross section of 300 mb was assumed.

tal perpendicular momentum, from a collision in which plasma is produced at temperature T_Q in a space-time proper volume $(\tau\Omega)_Q$, followed by a hadronic gas of temperature T_π occupying a space-time proper volume $(\tau\Omega)_\pi$, for various guesses of these parameters. The differential cross section is then

$$d^2\sigma/dM\,dE = \sigma_G[(\tau\Omega)_Q W_Q^\perp + (\tau\Omega)_\pi W_\pi^\perp], \quad (1)$$

where σ_G is the geometrical cross section for formation of the plasma, here taken as 300 mb, and $W_i^\perp$ is the perpendicular luminance of each phase, the number of pairs per unit proper volume per unit proper time per unit mass M per unit perpendicular energy $E_\perp$. Modeling the plasma and hadronic phases by noninteracting, nondegenerate gases of quarks and pions, respectively, and assuming zero chemical potential for simplicity, we find using standard methods[3,11] that

$$W_i^\perp = f_l(M) f_i(M) w^\perp(E_\perp, T), \quad (2)$$

where

$$f_l(M) = \tfrac{1}{3}\alpha^2(2\pi)^{-5/2}\left(1+\frac{2m_l^2}{M^2}\right)\left(1-\frac{4m_l^2}{M^2}\right)^{1/2}, \quad (3)$$

$$f_Q(M) = (\textstyle\sum e_Q^2) N_c (2s+1)^2, \quad (4)$$

$$f_\pi(M) = F_\pi^2(M)[1-(4m_\pi^2/M^2)]; \quad (5)$$

α is the electromagnetic fine-structure constant, m_l is the lepton mass, e_Q are the quark charges, N_c is the number of colors (3), s is the spin of the quark ($\frac{1}{2}$), and F_π is the electromagnetic form factor of the pion.[12] With two flavors, $f_Q = \frac{20}{3}$.

Figure 1 shows the calculated cross sections for several combinations of temperatures and space-time volumes. In each case, the total four-volume is taken as 1000 fm^4, which corresponds, e.g., to a sphere of 3-fm radius lasting for 10 fm/c (a very conservative estimate). In the top half of Fig. 1, the plasma temperature is twice the hadron temperature, which corresponds to a rapid phase transition without supercooling. In this case we would expect the plasma to exist for a much smaller time, and in a much smaller volume, than the hadron gas; we show the plasma as 1% to 10% of the four-volume of the hadrons. In each case, the ρ-meson peak has disappeared when $E_{\perp}=2$ GeV, while cross sections are about 10 μb GeV^2. A more pessimistic scenario is shown in the bottom half of Fig. 1, with a small difference between T_Q and T_π corresponding to supercooling of the plasma. In this case the plasma would exist for a time comparable to the hadron gas; we show equal four-volumes, and a hadron four-volume 10 times that of the plasma. In the latter, worst case, the ρ peak is still visible, though weakly, when $E_{\perp}=3$ GeV and $d^2\sigma/dM\,dE_{\perp}=1$ μb. We should note, however, that in supercooling scenarios the total space-time volume would probably be at least 10 times larger than we assumed, with a corresponding increase in the cross section for dileptons.

We conclude that the dependence of the dilepton mass spectrum on the transverse energy provides a test of deconfinement. In the absence of a phase transition, the spectrum will be dominated by the vector-meson peak at all transverse energies. If a phase transition has occurred at high temperature, then the vector-meson peak will be suppressed at large transverse energy.

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