CERN-PPE/96-111
31 July 1996

LOW MASS DILEPTON PRODUCTION AT THE SPS: PROBING HOT AND DENSE NUCLEAR MATTER.

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Abstract

CERES and HELIOS-3 have detected a significant enhancement of low–mass dileptons in nuclear collisions at 200 GeV/nucleon with respect to the expected "conventional" sources. The onset of the excess, starting at a mass of $\sim 2m_\pi$, and the possibility of a quadratic dependence on the event multiplicity suggest the opening of the $\pi^+\pi^- \rightarrow e^+e^-(\mu^+\mu^-)$ annihilation channel. This would be the first observation of thermal radiation from dense hadronic matter. Possible interpretations of these results are presented, including the reduction of the ρ mass due to partial restoration of chiral symmetry in the dense fireball formed in the collision.

*) Talk given at the XXXIst Rencontres de Moriond on QCD and High Energy Hadronic Interactions, Les Arcs, France, March 23-30, 1996.

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1 Dileptons as a probe of dense nuclear matter.

The reason for the spontaneous breaking of chiral symmetry and the origin of confinement are probably the least understood features of QCD and one of the standing unresolved problems in particle physics. However it seems clear that any confining theory must break chiral symmetry [1] and therefore these are closely related phenomena. Heavy ion collisions at high energies are expected to produce a hot and dense region, or *fireball*, of hadronic matter where these topics can be studied.

In particular, dileptons provide a clean probe of the dynamics of relativistic heavy ion collisions since they do not interact strongly and can leave the interaction region without final-state rescattering [2]. They therefore provide a window to the early stages of the collision, when the system reaches its hottest and most dense stage, with a possible phase transition to QGP [3]. They also provide a means of studying another of the interesting predictions of QCD: the restoration of chiral symmetry at high temperatures or densities [4, 5]. Typical values of the temperature, T, and energy density, ε, at which these transitions are expected to occur are $T \sim 200$ MeV or $\varepsilon \sim 15 - 20\varepsilon_{nuclear}$.

2 Chiral symmetry restoration in dense matter.

If we neglect the heavy-quark sector, which is not relevant for the following discussions, the QCD Lagrangian almost possesses chiral symmetry due to the small masses of the u and d quarks. However the QCD vacuum is definitely *not* chirally symmetric as can be seen from the vacuum expectation value of the quark condensate, $\langle 0|\bar{\psi}\psi|0\rangle \sim -(240 \text{ MeV})^3$. Therefore the vacuum expectation value of the operator $\langle\bar{\psi}\psi\rangle$ is a good measure of the effects of chiral symmetry breaking since in a chirally symmetric world $\langle 0|\bar{\psi}\psi|0\rangle = 0$. This spontaneous breaking of chiral symmetry has important consequences for QCD phenomenology at the hadronic level. We expect the appearance of the massless Goldstone bosons associated with the symmetry breaking, and these are indeed found in the π isospin triplet. The small mass of the pion can be expressed as $m_\pi^2 = k\,(m_u + m_d) + O(m^2)$. [1)] The proportionality constant k absorbs the strength of the symmetry breaking effect through the quark condensate $\langle\bar{\psi}\psi\rangle$, $k \propto \langle\bar{\psi}\psi\rangle/f_\pi^2$.

The behaviour of the quark condensate with density (or temperature) provides then a means to study the conditions in which the spontaneously broken chiral symmetry is restored. The effects of the dense medium in hadronic properties can be addressed within several approaches: QCD sum rules, effective Lagrangians or lattice QCD (LQCD). The general result is that $\langle 0|\bar{\psi}\psi|0\rangle$ decreases with increasing density or temperature, reaching a symmetry restoration phase transition where it becomes 0. This translates into a reduction of the hadronic masses in the dense medium, a "melting" effect, as we approach the critical point.[2)] A well known example is the reduction of the nucleon mass within the nucleus as calculated by Walecka [6] using a scalar mean-field model. Calculations by Brown and Rho [7] with an effective Lagrangian and Hatsuda and Lee [8] within the sum rule framework, show that a similar effect is expected in dense nuclear matter for the vector mesons.

Experimentally one would like to have access to the properties of hadrons in a dense medium

[1)] Similar relations hold for the K and η mesons if one includes the s quark in the game. However, for the η' we are faced with the U(1) anomaly and such a simple relation fails.

[2)] The effect is expected to be more pronounced in the density axis than along the temperature axis. In the limit of zero baryon density and high temperature the reduction of the hadronic masses is due to the presence of baryon-antibaryon pairs. At lower temperatures, the density effect dominates.

to test these predicted effects. The production of the ρ meson in heavy ion collisions provides an excellent tool to this end [9]. Due to its much shorter lifetime ($\tau_\rho = 1.3$ fm/c) compared with typical fireball lifetimes of 10-20 fm/c, several generations of ρ mesons are produced and decay during a nuclear collision at SPS energies. The most important aspect is that they decay inside the dense interaction region, while they retain their reduced mass. Thus, their decay through the dilepton channel provides a unique experimental window to the dense-medium effects on the ρ meson. This effect is not so clear for the other mesons, ω, ϕ or J/ψ because of their much longer lifetimes: they will be re-absorbed in the medium or they will decay well outside the interaction region when they have regained their vacuum masses.

3 Dilepton production in relativistic nuclear collisions.

There are several processes contributing to dilepton production in nuclear interactions at different space-time points of the collision history. I will mention here only the decays of the light hadrons and dilepton production from the hot hadronic fireball, since these are the relevant dilepton sources to the problem I am discussing in this paper.

We expect the dilepton sources known from p-p collisions to be an important source of dileptons also in nucleus-nucleus collisions. These include the decay of the resonances ρ, ω and ϕ, the Dalitz decays of the ω, η and η' and, in the case of dielectrons, the Dalitz decay of the π^o .

The most differential aspect of nucleus-nucleus collisions with respect to nucleon-nucleon collisions is the formation of a (thermalized?) dense fireball. This opens new dilepton production mechanisms through interactions of the fireball constituents, which are absent in the nucleon-nucleon case. The most important of them is pion annihilation. According to the Vector-Meson Dominance model (VMD), $\pi^+\pi^-$ annihilation proceeds through an intermediate ρ state, $\pi^+\pi^- \to \rho^o \to \ell^+\ell^-$, and the cross section can be written as

$$\sigma_{\pi^+\pi^-\to\ell^+\ell^-} = \frac{4\pi\alpha^2}{3M^2}\left(1-\frac{4m_\pi^2}{M^2}\right)^{1/2}\left(1-\frac{4m_\ell^2}{M^2}\right)^{1/2}\left(1+\frac{2m_\ell^2}{M^2}\right)\times\left|F_\pi(M)\right|^2 \qquad (1)$$

where M is the dilepton invariant mass and $F_\pi(M)$ is the pion form factor, given by

$$\left|F_\pi(M)\right|^2 = \frac{m_\rho^4}{(M^2-m_\rho^2)^2+m_\rho^2\Gamma_\rho^2} \qquad (2)$$

From the expression of F_π we see that any modification of the ρ parameters in a dense medium will bear an important change into the shape of $\sigma_{\pi^+\pi^-\to\ell^+\ell^-}$. There are other processes producing dileptons in the fireball, though their contribution to the final spectrum is not dominant. A complete treatment can be found in [10] (see also the discussion in section 5).

4 Results on dilepton production in relativistic nuclear collisions.

We turn now to the current experimental understanding of the dilepton spectrum from nuclear collisions. Figure 1 shows the measured dilepton spectrum both from CERES [11] on dielectrons in S+Au collisions at 200 GeV/nucleon and from HELIOS-3 [12] on dimuons in S+W collisions at the same energy. The results of CERES are compared with the expected dielectron yield from the p-p sources, normalized to the charged-particle rapidity density. The shaded area in the plot represents the uncertainty in the theoretical calculation of the dilepton yield, while the vertical bars in each bin represent the statistical error. The small brackets represent the statistical and systematic errors added quadratically. The results from HELIOS-3 are compared with their measured p+W spectrum, normalized to the charged particle multiplicity.[3)]

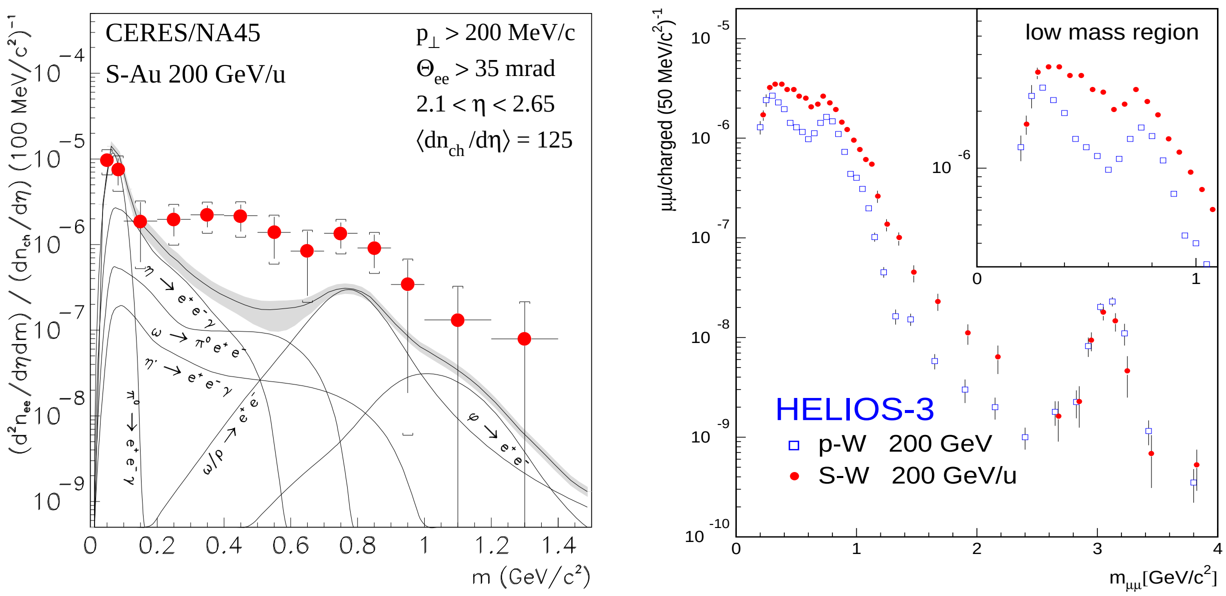

Figure 1: Dilepton spectra from CERES (dielectrons) and HELIOS-3 (dimuons) from S+Au and S+W collisions at 200 GeV/nucleon respectively.

The message from these results is clear. There is a significant enhancement of dileptons over the expected scaled p-p yield in the invariant mass range $0.2 < m_{\ell^+\ell^-} < 1.5$ GeV/c^2, extending up to $m_{\mu^+\mu^-} \sim 2.5$ GeV/c^2 in the case of dimuons due to the wider mass coverage of HELIOS-3. Moreover, the enhancement sets in at masses $m_{\ell^+\ell^-} \sim 2m_\pi$ which would indicate that we are observing $\pi^+\pi^-$ annihilation from a dense fireball. The shape of the spectrum from both experiments is also revealing since it does not simply follow that from the p-p sources. I will discuss possible interpretations of this feature in the next section.

First note that the global excess is somewhat different in both experiments. If we concentrate in the invariant mass region common to both experiments, $0.2 < m_{\ell^+\ell^-} < 1.5$ GeV/c^2, CERES finds an enhancement of a factor of $5.0 \pm 0.8_{sta} \pm 2_{sys}$, while HELIOS-3 obtains a factor of ~ 1.6. This discrepancy could be a consequence of the different rapidity windows accessible to each experiment. CERES measures at mid-rapidity, $2.1 < \eta < 2.6$, while HELIOS-3 covers the forward region, $3.7 < \eta < 5.5$. Therefore the average particle multiplicities seen by the two experiments differ by at least a factor of two. If the dilepton yield scales non-linearly with multiplicity this discrepancy could be accounted for. Such an effect would provide a test of the type of emitting source, since different dilepton production mechanisms are expected to scale differently with multiplicity [13]. Though CERES sees an increase of the dielectron yield with multiplicity compatible with a quadratic dependence, the present errors do not allow us to rule out a conventional linear dependence [14].

[3)]Results from CERES on p+Au collisions at 450 GeV/c show that the dielectron yield in p-nucleus collisions is well reproduced by the p-p yield [11]. We can then assume that the results from HELIOS-3 on p+W represent the p-p data with some degree of confidence.

5 Theoretical interpretations.

Several models have been proposed to explain the data presented in the previous section. I will summarize here three approaches which reflect the current theoretical efforts on this topic.

There are two calculations which use a microscopic approach to the nuclear collision. Li *et al.* [15] use the RQMD model while Cassing *et al.* [16] use the HSD model. These are similar models where the colliding nuclei are described in terms of their constituent nucleons and particle production is described from the collisions of such nucleons using a string fragmentation approach. Reinteractions among the produced particles are also taken into account in both cases. The main contribution to dilepton production in these calculations comes from $\pi^+\pi^-$ annihilation and from the decays of produced resonances.

A more unconventional approach is that proposed by Srivastava *et al.* [17]. In this model it is assumed that QGP is initially formed in the collision at a typical time of $\tau = 1$ fm. The initial temperature is calculated to be $T_i = 199$ MeV. The system expands and cools through hydrodynamical longitudinal expansion, reaching a mixed phase at a transition temperature $T_c = 160$ MeV. Further expansion brings the hadron gas to a freeze-out temperature $T_f = 140$ MeV where the hadrons decouple. Dilepton emission from the QGP phase proceeds through $q\bar{q}$ annihilation, whereas in the hadronic system dilepton production comes from meson annihilation and the decays of the resonances. The relatively low initial temperature results in a very short lived QGP and, therefore, the main contribution to dilepton production comes from the mixed and hadronic phases.

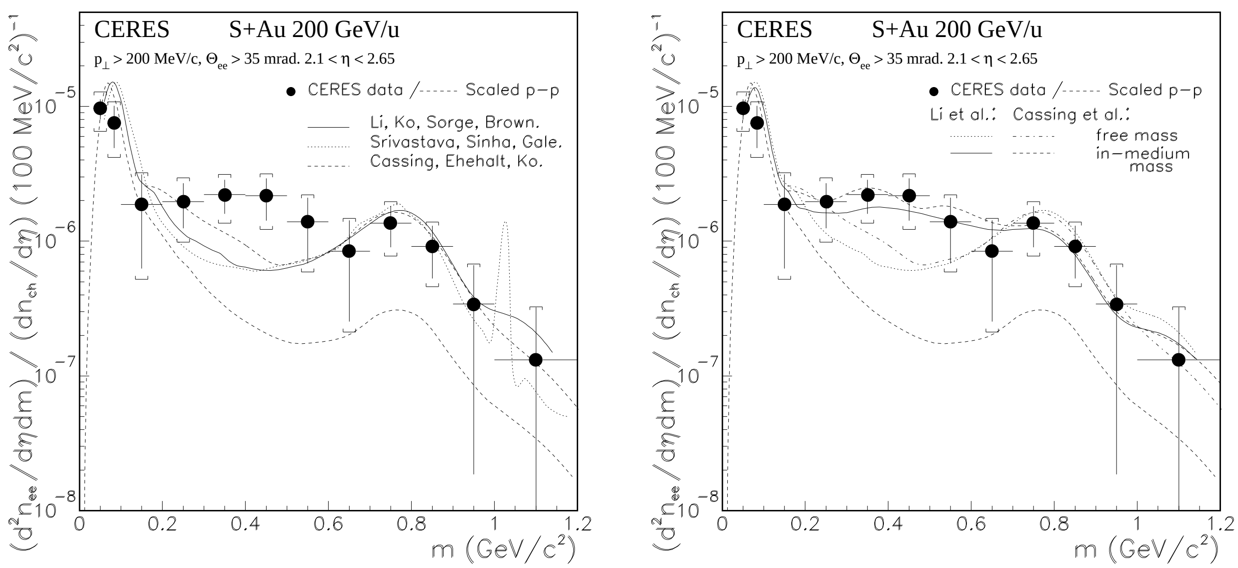

Figure 2: Comparison of several theoretical calculations with the CERES data. See the text for details.

These three models give remarkably similar results as is shown in the left plot of Figure 2.[4)] They reproduce the observed dilepton excess in the ρ region due to the $\pi^+\pi^-$ annihilation channel (eq. 1) but, although they account for a sizeable fraction of the excess at lower masses, they fail to reproduce the data in the mass region $0.2 < m_{e^+e^-} < 0.5$ GeV/c^2.

[4)] Note that Srivastava *et al.* have not convoluted their prediction with the CERES mass resolution and therefore the ϕ peak appears as the bare resonance.

The right plot in Figure 2 shows an extension of the models of Li *et al.* and Cassing *et al.* where the effect of the reduction of the ρ mass is included. Li *et al.* calculate the in-medium ρ mass, m_ρ^*, using an extended Walecka model, where the vector mesons are allowed to couple to the scalar field. In this approach $m_\rho^* = m_\rho - g_s\langle S\rangle$. The scalar field S is determined self-consistently from the energy density of the fireball. Cassing *et al.* calculate the reduction of the ρ mass from QCD sum rules where, in an obvious notation, $m_\rho^*/m_\rho^o = 1 - 0.18(\rho^*/\rho^o)$. In both cases the reduction of the ρ mass opens pion annihilation channels at lower $\pi^+\pi^-$ invariant masses, giving rise to an enhanced dilepton yield below the nominal ρ peak. The agreement with the CERES result when this effect is considered is remarkable. Though I have concentrated here on CERES results, recent calculations by Li *et al.* (unpublished) and Cassing *et al.* [18] including the in-medium modification of the ρ mass reproduce also the results of HELIOS-3 shown in Figure 1.

6 Summary

I have presented several models proposed recently to explain the enhancement of dileptons in nuclear collisions seen by CERES and HELIOS-3. The dilepton enhancement in the ρ peak region seems to be well understood from $\pi^+\pi^-$ annihilation, whereas the enhancement at lower invariant masses ($0.2 < m_{\ell^+\ell^-} < 0.5$ GeV/c^2) is not reproduced by any conventional effect. The explanation of the enhancement in this region seems to call for partial restoration of chiral symmetry in the dense fireball and in its effects on the vector mesons' masses.

Acknowledgments: I would like to thank Y. Nir for his useful comments and G. Li and W. Cassing for providing the theoretical curves and explanations about their models.

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