Abnormal dilepton yield from parity breaking in dense nuclear matter

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Abstract. At finite density parity can be spontaneously broken in strong interactions with far reaching implications. In particular, a time-dependent pseudoscalar background would modify QED by adding a Chern-Simons term to the lagrangian. As a striking consequence we propose a novel explanation for the dilepton excess observed in heavy ion collisions at low invariant masses. The presence of local parity breaking due to a time-dependent pseudoscalar condensate substantially modifies the dispersion relation of photons and vector mesons propagating in such a medium, changing the ρ spectral function and resulting in a potentially large excess of dileptons with respect to the predictions based in a ‘cocktail’ of known processes.

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INTRODUCTION

The appearance of parity violation via pseudoscalar condensation for sufficiently large values of the chemical potential has been attracting much interest during the last decades to search it both in dense nuclear matter (in neutron/quark stars and heavy ion collisions at intermediate energies) and in strongly interacting quark-gluon matter (“quark-gluon plasma” in heavy ion collisions at very high energies). At finite baryon density was conjectured by A. Migdal in [1] long ago. While it was argued in [2] that parity, and vector flavor symmetry could not undergo spontaneous symmetry breaking in a vector like theory such as QCD, the conditions under which the results of [2] hold (positivity of the measure) are not valid for non-zero chemical potential.

We have investigated[3] the possibility of parity being spontaneously violated in QCD at finite baryon density and temperature. The analysis is done for an idealized homogeneous and infinite nuclear matter where the influence of density can be examined with the help of constant chemical potential. QCD is approximated by a generalized σ model with two isomultiplets of scalars and pseudoscalars. The interaction with the chemical potential is introduced via the coupling to chiral quark fields as nucleons are not considered as point-like degrees of freedom in our approach (for a semi-quantitative discussion this should suffice). This mechanism of parity violation is based on interplay between lightest and heavy meson condensates and it cannot be understood in simple models retaining the pion and nucleon sectors solely; in particular is essentially different from the old idea of pion condensation advocated originally by Migdal. We argue that, in the appropriate environment (dense nuclear matter of a few normal densities where quark percolation does not yet play a significant role), parity violation may be the rule rather than the exception.

Let us mention several experimental signatures of parity violation in strong interactions[3]: a) Resonances do not have a definite parity and therefore the same resonance can decay into even and odd number of pions. b) At the very point of the phase transition leading to parity breaking one has six massless pion-like states. After crossing the phase transition, in the parity broken phase, apart from the usual pions, two scalar charged states remain massless. c) Changes in the nuclear equation of state. d) Additional isospin breaking effects in the pion decay constant and substantial modification of $F_π'$. However all these dramatic effects are nevertheless difficult to observe in the environment of heavy ion collisions. We would like to find an effect that showed up in simpler probes such as photons, electrons or muons.

During the last decade several experiments in heavy ion collisions have indicated an abnormal yield of lepton pairs with invariant mass $M < 1$ GeV in the region of small rapidities and moderate transversal momenta [4, 5] (reviewed in [6, 7]). This effect is visible only for collisions that are central or semi-central. From a comparison to pp collisions it has been established beyond doubt that such an enhancement is a nuclear medium effect[6]. For the energies accessible at CERN SPS and BNL RHIC the abnormal dilepton yield has not been yet explained satisfactorily by known processes in hadronic physics[6, 7]. In this region the ρ meson, directly via
\[ m_{ab}^2 = m_V^2 \left( \begin{array}{ccc} \frac{10e^2}{9g} & -\frac{\zeta}{3g} & -\frac{\zeta}{g} \\ -\frac{\zeta}{3g} & 1 & 0 \\ -\frac{\zeta}{g} & 0 & 1 \end{array} \right), \] (3)

with \( \det (m^2) = 0 \) and \( m_V^2 = m_{\rho}^2 = 2g_\rho^2 f_\rho^2 \approx m_\omega^2 \). Finally, in a pseudoscalar time-dependent background the Lagrangian contains a parity-odd Chern-Simons (CS) term

\[ \mathcal{L}_{CS}(k) = -\frac{1}{4} e^{\nu}_{\sigma} \sigma_{\mu \nu} \text{tr} [\hat{V}_c(x)] V_{\rho \sigma}(x) \]

\[ = \frac{1}{2} \text{tr} [\hat{\zeta} e_{ijkl} V_j \partial_k V_l] = \frac{1}{2} \zeta e_{ijkl} V_{j,a} N_{ab} \partial_k V_{l,b}, \] (4)

which additionally mixes photons and vector mesons due to LPB. For isosinglet pseudoscalar background (the only possibility we shall consider here) \( e^2 \zeta = \frac{g}{2} \xi I \), and \( N \propto m^2 \). Simple order-of-magnitude considerations indicate that \( \zeta \sim \alpha \tau^{-1} \sim 1 \text{ MeV} \), taking the time of formation of pseudoscalar condensate \( \tau = 1 \text{ fm} \) and the value of condensate of order of \( f_\pi \).

Particularizing to the case \( \zeta_{\mu \lambda} \approx (\zeta, 0, 0, 0) \) we find the following spectrum

\[ N = \text{diag} \left[ 0, \frac{9g^2}{10e^2}, \frac{9g^2}{10e^2} + 1 \right] \sim \text{diag} [0, 1, 1] \]

\[ m^2 = m_V^2 \text{ diag} \left[ 0, 1, 1 + \frac{10e^2}{9g^2} \right], \] (5)

namely vector mesons have the dispersion relation

\[ k_0^2 - k^2 = m_V^2 \pm \frac{9g^2}{10e^2} \zeta |\hat{k}| \approx m_V^2 \pm 360 \zeta |\hat{k}| \equiv m_{\phi \pm}^2. \] (6)

Thus in the case of isosinglet background the massless photons are not distorted when mixed with massive vector mesons. In turn, massive vector mesons split into three polarizations with masses \( m_{V_{\perp}}^2 < m_{V_L}^2 < m_{V_{\parallel}}^2 \), signifying local parity as well as Lorentz invariance breaking. Note that the position of resonance poles for \( \pm \) polarized mesons is moving with wave vector \( |\hat{k}| \) and therefore they reveal themselves as “giant” resonances. The enlargement of the resonant region potentially leads to a substantial enhancement of their contribution to dilepton production away from their nominal vacuum resonance position. See [16] for more details.

**THE NA60 RESULTS**

Here we shall limit our discussion to a comparison with the determination of the ‘abnormal’ rho spectral function from the NA60 experiment [4, 17, 18]. The production rate of dileptons pairs mediated by \( \rho \) mesons takes a form similar to the one given in [14] but with modified propagators due to LPB, according to our previous
and for local parity breaking with \( \omega \) and local \( \omega \) pole and Dalitz decay (shown separately), after adjusting the coefficients for an optimal fit. \( \xi = 1.9 \) MeV, \( T = 270 \) MeV. The overall fit is excellent giving strong plausibility to the possibility of LPB.

(see [16] for possible experimental signals) the consequences could be far reaching.

\[
\frac{dN}{d^4\omega} \simeq \frac{c_0}{M^3} \left( \frac{M^2 - m_\omega^2}{m_\omega^2 - 4m_\pi^2} \right)^{3/2} \sum \int \frac{dk}{2k} \sqrt{\frac{\zeta_0^2 - M^2}{\zeta_0^2 - k^2}} \times \frac{m_\pi^2}{(M^2 - m_\omega^2)^2 + m_\pi^2 k^2 \epsilon}.
\]

Finite lepton mass corrections are not shown. For \( \omega \) mesons a similar expression is used but without the two pion threshold, characteristic of the dominant coupling of the \( \rho \) to hadronic matter. A simple thermal average is assumed but we remark that the temperature \( T \) is an effective one that may in fact depend on the range of \( M \), \( p_T \) and centrality. The coefficients \( c \) parameterize the total cross-sections for vector meson creation. Because they are not known with precision in the present setting, particularly their off-shell values, the relative weights are used as free parameters in the hadronic ‘cocktail’\(^4\) and \( p-A \). For semi-central and central collisions, particularly at low \( p_T \) the \( \rho / \omega \) ratio needs to be enhanced by a factor 1.6 in the case of NA60 \(^4\) or approximately 1.8 in PHENIX \(^19\).

The result is shown in fig. 1 showing that LPB provides a much better description of the \( \rho \) shape than the fitted hadronic cocktail. This can be further improved by including the (much smaller) modifications due to LPB on the contribution from the \( \omega \) pole and the \( \omega \) Dalitz decay \( \omega \rightarrow \mu^+ \mu^- \pi^0 \). This is tentatively shown in fig. 2.

From these results we conclude that local parity breaking seems capable of explaining in a natural way the PHENIX/CERES/NA60 ‘anomaly’. If LPB is confirmed

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