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QCD WITH CHIRAL CHEMICAL POTENTIAL: MODELS VERSUS LATTICE*

A.A. Andrianov, V.A. Andrianov

Saint-Petersburg State University, 199034 St. Petersburg, Russia

D. Espriu

ICCUB, University of Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain

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An emergence of local spatial parity breaking (LPB) in central heavy-ion collisions (HIC) at high energies is discussed. The QCD phenomenology of LPB in the fireball is induced by a difference between the number densities of right- and left-handed chiral fermions which is triggered by a chiral (axial) chemical potential. For the description of peculiarities of LPB, a number of QCD-inspired models are considered and confronted to certain lattice results. In particular, from the meson effective Lagrangian, it is found that the lightest states may become massless and some scalars turn out to be stable. In experimental studies, the asymmetry in production of longitudinal and transverse polarized states of ρ and ω mesons for different values of the invariant mass can serve as a characteristic indication of local spatial parity breaking which can be derived from an abnormal yield of dilepton pairs in the PHENIX, STAR and ALICE collaborations.

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1. Chiral imbalance in heavy-ions collisions

The behaviour of baryonic matter under extreme conditions in HIC has received a lot of attention [1,2]. New properties of QCD in the environment were tested in current accelerator experiments on RHIC and LHC [3]. A medium generated in these collisions (a fireball) may serve for experimental and theoretical studies of various phases of a matter.

The dedicated experimental study of hadron correlations in non-central heavy-ion collisions at RHIC [4] and LHC [5] revealed a signal of the separation of electric charges predicted in [6] as a signature of local P- and CP-odd

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fluctuations in QCD matter. The subsequent studies [7, 8] improved the theoretical understanding of the underlying phenomenon, the "chiral magnetic effect" (CME) in the reactions for peripheral-ion collisions (see [9] for a review).

On the contrary, a gradient density of isosinglet pseudoscalar condensate can be formed as a result of large, "long-lived" topological fluctuations of gluon fields in the fireball in central collisions (see [10] for details). To describe various effects of hadron matter in a fireball with parity breaking, we must introduce the axial/chiral chemical potential [10]. At finite temperature, the transitions between the vacuum states with different topological Chern–Simons numbers can be induced by a classical thermal activation process, the so-called "sphaleron" [11]. In QCD matter, sphalerons are abundant [12] and induce the quark chirality non-conservation. There are some experimental indications of an abnormal dilepton excess in the range of low invariant masses and rapidities, and moderate values of the transverse momenta (see the review in [13]), which can be thought of as a result of LPB in the medium (the details can be found in [14]). In particular, in heavy-ion collisions at high energies, with raising temperatures and baryon densities, metastable state can appear in the fireball with a non-trivial topological/axial charge T_5, which is related to the gluon gauge field G_i

$$T_5(t) = \frac{1}{8\pi^2}\int\limits_{\mathrm{vol}} \mathrm{d}^3x\,\varepsilon_{jkl}\,\mathrm{Tr}\left(G^j\partial^k G^l - i\frac{2}{3}G^jG^kG^l\right), \qquad j,k,l = 1,2,3\,, \quad (1)$$

where the integration is over the finite fireball volume. Its jump ΔT_5 can be associated with the space-time integral of the gauge-invariant Chern–Pontryagin density

$$\Delta T_5 \;=\; T_5\left(t_f\right) - T_5(0) = \frac{1}{16\pi^2}\int\limits_0^{t_f}\mathrm{d}t\int\limits_{\mathrm{vol}}\mathrm{d}^3x\,\mathrm{Tr}\left(G^{\mu\nu}\widetilde{G}_{\mu\nu}\right). \quad (2)$$

It is known that the divergence of isosinglet axial quark current $J_{5,\mu} = \overline{q}\gamma_\mu\gamma_5 q$ is locally constrained via the relation of partial conservation of axial current (PCAC) affected by the gluon anomaly

$$\partial^\mu J_{5,\mu} - 2i\widehat{m}_q\overline{q}\gamma_5 q = \frac{N_\mathrm{f}}{2\pi^2}\mathrm{Tr}\left(G^{\mu\nu}\widetilde{G}_{\mu\nu}\right). \quad (3)$$

This relation allows to find the connection of a non-zero topological charge with a non-trivial quark axial charge Q_5^q. Namely, integrating (3) over a finite volume of fireball, we come to the equality

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(Q_5^q - 2N_\mathrm{f}T_5\right) \simeq 2i\int\limits_{\mathrm{vol}}\mathrm{d}^3x\,\widehat{m}_q\overline{q}\gamma_5 q\,, \quad (4)$$

$$Q_5^q = \int\limits_{\text{vol}} \mathrm{d}^3x\, q^\dagger \gamma_5 q = \langle N_\mathrm{L} - N_\mathrm{R} \rangle \ , \tag{5}$$

where $\langle N_\mathrm{L} - N_\mathrm{R} \rangle$ stands for the vacuum averaged difference between left and right chiral densities of baryon number (chiral imbalance). Therefore, it follows that in the chiral limit and for a finite fireball volume, the axial quark current is conserved in the presence of non-zero topological charge. If for the lifetime of fireball and the size of hadron fireball of the order of $L = 5$–10 fm, the created topological charge is non-zero, $\langle \Delta T_5 \rangle \neq 0$, then it may be associated with a topological chemical potential μ_θ or an axial chemical potential μ_5 [10]. Thus, we have

$$\langle \Delta T_5 \rangle \simeq \frac{1}{2N_\mathrm{f}} \langle Q_5^q \rangle \iff \mu_5 \simeq \frac{1}{2N_\mathrm{f}} \mu_\theta \, . \tag{6}$$

Thus, adding to the QCD Lagrangian the term $\Delta\mathcal{L}_\mathrm{top} = \mu_\theta \Delta T_5$ or $\Delta\mathcal{L}_q = \mu_5 Q_5^q$, we get the possibility of accounting for non-trivial topological fluctuations (“fluctons”) in the nuclear (quark) fireball.

2. Effective meson theories in search of LPB

For the detection of LPB in the hadron fireball, let us consider an effective theory describing the electromagnetic interactions in a fireball. In this case, we keep in mind mechanisms of hadron interactions which rely on vector dominance model [15].

The quark–meson interaction is described by the Lagrangian,

$$\mathcal{L}_\mathrm{int} = \bar{q}\gamma_\mu V^\mu q \, ; \qquad V_\mu \equiv -eA_\mu Q + \frac{1}{2} g_\omega \omega_\mu \boldsymbol{I}_q + \frac{1}{2} g_\rho \rho_\mu^0 \lambda_3 + \frac{1}{\sqrt{2}} g_\phi \phi_\mu \boldsymbol{I}_s \, , \tag{7}$$

while $Q = \frac{\lambda_3}{2} + \frac{1}{6}\boldsymbol{I}_q - \frac{1}{3}\boldsymbol{I}_s$, $g_\omega \simeq g_\rho \equiv g \simeq 6 < g_\phi \simeq 7.8$ and the values of the constants are extracted from the decays of the vector mesons. Here, $\boldsymbol{I}_q$ and $\boldsymbol{I}_s$ are the unit matrices in the non-strange and strange quark sectors, and λ_3 is a corresponding Gell-Mann matrix. The parity-odd contribution is given by the Chern–Simons term,

$$\mathcal{L}_\mathrm{CS}(k) = -\tfrac{1}{4} \varepsilon^{\mu\nu\rho\sigma} \, \mathrm{Tr} \left[\hat{\zeta}_\mu \, V_\nu(x) \, V_{\rho\sigma}(x) \right] = \tfrac{1}{2} \mathrm{Tr} \left[\hat{\zeta} \, \epsilon_{jkl} \, V_j \, \partial_k V_l \right] \, , \tag{8}$$

which describes the mixing of photons and vector mesons under the local spatial parity breaking. We can obtain the relation $\zeta = N_\mathrm{c}\, g^2 \mu_5 / 8\pi^2$, where N_c is a number of colours, and numerically $\zeta \simeq 1.5\, \mu_5$.

The analysis of the massive Chern–Simons electrodynamics [10] has shown that in the case of an isosinglet pseudoscalar background field, the spectrum of massive vector mesons splits into three polarizations with the masses $m^2_{V,+} < m^2_{V,L} < m^2_{V,-}$. The position of resonance poles for transverse polarizations of ρ^0, ω mesons is shifted with the wave vector $|\vec{k}|$ and also a resonance broadening occurs that leads to an increased contribution of the dilepton production compared with the situation with resonances in vacuum (for details, see [16]). Then, the question arises. Could the splitting be measured in experiments with heavy-ion collisions?

For this purpose, there should be analysed an effect of anomalous dilepton pair production in the range of low invariant masses and rapidities, and moderate transverse momenta which was established in a series of experiments with heavy-ion collisions in recent years [13]. It is well-known that the angular distribution of leptons carries the information on polarizations. However, the current angular distribution studies based on full angular average do not seem to detect possible parity-odd effects.

In order to isolate the transverse polarizations, we perform different cuts choosing the angle θ_A for the analysis and study the variations of the ρ (and ω) spectral functions. A quite visible secondary peak appears in a P-odd medium (see Fig. 1)! To isolate the transverse polarizations in the spectrum, we selected different angle sectors and studied the changes in the ρ-meson spectral function. Various experimental possibilities for its identification were discussed in [16].

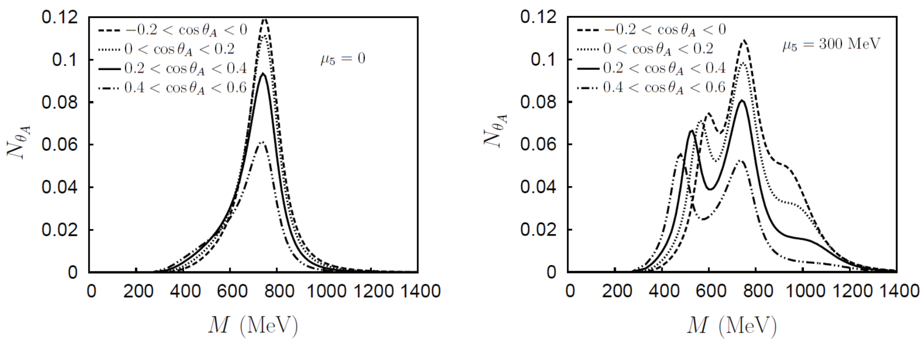

Fig. 1. ρ-spectral function depending on the dielectron invariant mass M in vacuum ($\mu_5 = 0$) and in a parity-breaking medium with $\mu_5 = 300$ MeV for different ranges of the angle θ_A between the two outgoing leptons in the laboratory frame.

Thus, a signal (a phase) with spatial parity breaking in heavy-ion collisions (in a fireball) can be sought in experiments "event by event" using an excess yield of dilepton pairs and predominantly with different circular polarizations outside the resonance region of the ρ- and ω-meson invariant masses.

3. Effective scalar meson Lagrangian with axial chemical potential

Let us now consider the QCD-inspired scalar meson model with axial chemical potential [17] for a description of some properties of low-energy mesons in medium and how it manifests itself in LPB. First of all, the axial chemical potential is introduced and treated as a constant time component of an isosinglet axial-vector field in the non-strange sector. For the lightest isotriplet pseudoscalar π and scalar a_0 states, the piece of the effective Lagrangian that is bilinear in fields looks as follows

$$\mathcal{L} = \frac{1}{2}(\partial a_0)^2 + \frac{1}{2}(\partial \pi)^2 - \frac{1}{2}m_1^2 a_0^2 - \frac{1}{2}m_2^2 \pi^2 - 4\mu_5 a_0 \dot{\pi} \,. \tag{9}$$

Evidently, new eigenstates $\tilde{\pi}$ arise from the mixture of scalars and pseudoscalars, then for big 3-momentum, $\tilde{\pi}$ becomes massless and further on tachyonic [17]. For the same 3-momentum, the quasi-scalar state σ looks stable.

4. Chemical potentials in the NJL model

In [18], we incorporated both a vector and an axial chemical potentials in the Nambu–Jona-Lasinio (NJL) model with the purpose of unravelling the landscape of different stable phases of the theory. It turns out that the inclusion of μ_5 changes radically the phase structure of the model and shows that μ is not a key player in ushering a thermodynamically stable phase where parity is violated in the NJL model, but μ_5 is. It leads to a non-trivial dependence of the scalar condensate (see Fig. 2) in the chirally broken phase.

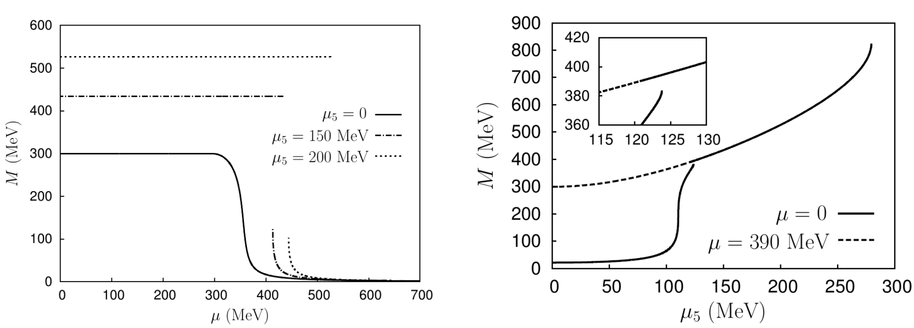

Fig. 2. Evolution of the constituent quark mass M: left panel — depending on μ for different values of the axial chemical potential μ_5; right panel — depending on μ_5 for different values of the chemical potential μ.

Critical temperature with axial potential switched on was computed on lattice [19] and a fairly well correspondence with the results of [18] was established. The main result is that with an increasing chiral chemical potential, the dynamical mass and critical temperature raises up.

5. Conclusions and outlook

In this paper, we described a possibility of local spatial parity breaking emerging in a dense hot baryon medium (fireball) in heavy-ion collisions at high energies. We stress that LPB is not forbidden by any physical principle in QCD at a finite temperature/density. We suggested a generalized Lagrangian of the vector meson dominance model in the presence of the Chern–Simons interaction. It turns out that the spectrum of massive vector mesons splits into three components with different polarizations and with different effective masses $m^2_{V,+} < m^2_{V,L} < m^2_{V,-}$, and a resonance broadening occurs that leads to an increase of the spectral contribution to the dilepton production as compared with the vacuum state. The proposed mechanism for generating local spatial parity breaking helps to explain qualitatively and quantitatively the anomalous yield of dilepton pairs in the CERES, PHENIX, STAR, NA60, and ALICE experiments.

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