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Polarization signatures of local parity breaking in central heavy ion collisions

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Abstract. In this talk we describe a possibility of local spatial parity breaking (LPB) emerging in a dense hot baryon medium (in a fireball) in heavy-ion collisions at high energies. The phenomenology of origin local spatial parity breaking in the fireball is based on introducing a topological (axial) charge and a topological (chiral) chemical potential. A signal (phase) with spatial parity breaking in heavy-ion collisions can be sought in experiments with an excess yield of dilepton pairs with different circular polarizations outside the resonance region of the ρ and ω- meson invariant masses. In these experiments, the asymmetry of longitudinal and transverse polarized states for different values of the invariant mass can serve as a characteristic indicating the possible existence of local spatial parity breaking.

Phenomenology of local spatial parity breaking (LPB) in strong interactions and chiral chemical potential

It is currently known that the spatial parity in QCD is a well established global symmetry of strong interactions [1]. But it was found some time ago that under different extreme conditions (high temperatures and baryon densities, strong electromagnetic fields) spatial domains in the QCD vacuum can arise with metastable non-zero topological density which leads to a spatial parity (P-parity) violation [2]. The formation of a parity-breaking phase can occur in a finite reaction volume (fireball) in heavy-ion collisions. This phase is manifested in the so-called chiral magnetic effect when strong electric and magnetic fields arise and result in chiral charge separation in the reactions for peripheral ion collisions [3]. On the contrary, an isosinglet pseudoscalar condensate can be formed as a result of creating large, "long-lived" topological fluctuations ($t \sim 5 - 10 fm/c$, where c is the speed of light) of gluon field configurations in the fireball in central collisions (see [4] for details). 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 [5]–[9] (see the reviews in [10]), which can be thought of as a result of local spatial parity breaking in the medium (the details can be found in [11]). To describe various effects of hadron matter in a fireball with parity breaking, we must introduce the different chemical potentials and primarily the axial or chiral chemical potential [4].

The change of QCD vacuum properties in matter, and different vacuum transitions mediated by sphalerons can arise under the influence of external conditions [12]. In particular, in heavy-ion collisions at high energies, with raising temperatures and baryon densities, metastable domains can appear in the so-called fireball with a nontrivial topological charge T_5, which is related to the gluon gauge field G_i:

$$T_5(t) = \frac{1}{8\pi^2} \int_{\text{vol.}} d^3x\, \varepsilon_{jkl}\, \mathrm{Tr}\Big(G^j \partial^k G^l - i\frac{2}{3} G^j G^k G^l\Big), \quad j,k,l = 1,2,3, \tag{1}$$

where the integration is over a finite part of the fireball volume. This is not a gauge-invariant object under global gauge transformations. Nevertheless, its jump ΔT_5 can be associated with the space-time integral of the gauge-invariant

Chern-Pontryagin density:

$$\begin{aligned} \Delta T_5 &= T_5(t_f) - T_5(0) = \frac{1}{16\pi^2}\int_0^{t_f} dt \int_{\text{vol.}} d^3x \ \mathrm{Tr}(G^{\mu\nu}\widetilde{G}_{\mu\nu}) == \frac{1}{4\pi^2}\int_0^{t_f} dt \int_{\text{vol.}} d^3x \, \partial^\mu K_\mu, \\ K_\mu &= \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}\,\mathrm{Tr}\Big(G^\nu\partial^\rho G^\sigma - i\frac{2}{3}G^\nu G^\rho G^\sigma\Big). \end{aligned} \tag{2}$$

We suppose a comparably long lifetime of domains and accordingly neglect a topological current flux through the fireball boundary during the corresponding thermodynamic phase.

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 axial current conservation affected by the gluon anomaly:

$$\partial^\mu J_{5,\mu} - 2i\widehat{m}_q J_5 = \frac{N_f}{2\pi^2}\partial^\mu K_\mu; \quad J_5 = \overline{q}\gamma_5 q \tag{3}$$

This relation allows to find the connection of a nonzero topological charge with a non-trivial quark axial charge Q_5^q. Namely, integrating (4) over a finite volume of fireball we come to the equality

$$\begin{aligned} &\frac{d}{dt}(Q_5^q - 2N_f T_5) \simeq 2i\int_{\text{vol.}} d^3x \, \widehat{m}_q \overline{q}\gamma_5 q, \\ &Q_5^q = \int_{\text{vol.}} d^3x \, q^\dagger\gamma_5 q = \langle N_L - N_R\rangle, \end{aligned} \tag{4}$$

where $\langle N_L - N_R\rangle$ stands for the vacuum averaged difference between left and right chiral densities of baryon number. Therefrom it follows that in the chiral limit (when the masses of light quarks are taken zero) 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 order $L = 5-10$ 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 [4] for neglected light u, d quarks. Thus we have

$$\langle\Delta T_5\rangle \simeq \frac{1}{2N_f}\langle Q_5^q\rangle \iff \mu_5 \simeq \frac{1}{2N_f}\mu_\theta, \tag{5}$$

Thus adding to the QCD lagrangian the term $\Delta\mathcal{L}_{\text{top}} = \mu_\theta\Delta T_5$ 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. In the Lorentz invariant form the field dual to fluctons is described by means of the classical pseudoscalar field $a(t)$, depending on time so that

$$\Delta\mathcal{L}_a = \frac{N_f}{2\pi^2}K_\mu\partial^\mu a(x) = \frac{1}{4\pi^2}\mu_\theta K_0 \iff \mu_5\overline{q}\gamma_0\gamma_5 q, \quad \mu_5 \simeq \dot{a}(t) \simeq \text{const.} \tag{6}$$

Thus in a quasi-equilibrium situation the appearance of a nearly conserved chiral charge can be incorporated with the help of a chiral chemical potential μ_5.

Effective meson theory in a medium with local spatial parity breaking

The model of vector dominance [13],[14] can serve as a basis for describing local parity breaking in the hadron fireball with electromagnetic interactions taken into account. Moreover, we assume that a time-dependent but approximately spatially homogeneous pseudoscalar field $a(t)$ induced at densities accessible in heavy-ion collisions arises in the fireball, and we define it as a four-vector$\zeta_\mu \simeq \partial_\mu a \simeq (\zeta, 0, 0, 0)$. The quark-meson interaction is described by

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

while $Q = \frac{\lambda_3}{2} + \frac{1}{6}\mathbf{I}_q - \frac{1}{3}\mathbf{I}_s$, $g_\omega \simeq g_\rho \equiv g \simeq 6 < g_\phi \simeq 7.8$ and the values of the constants are extracted from the decays of the vector mesons. Here, $\mathbf{I}_q$ and $\mathbf{I}_s$ 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,

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

which describes the mixing of photons and vector mesons under the local spatial parity breaking. With our definitions we can obtain the relation $\zeta = N_c\, g^2\mu_5/8\pi^2$ where N_c is a number of colors, and numerically $\zeta \simeq 1.5\mu_5$. The analysis of the massive Chern-Simons electrodynamics [4] has shown that in the case of an isosinglet pseudoscalar background field, the spectrum of massless photons is not distorted when they are mixed with massive vector mesons, while the spectrum of massive vector mesons splits into three polarizations with the masses $m^2_{V,+} < m^2_{V,L} < m^2_{V,-}$. This splitting might be an indication of a possible parity breaking and also of a Lorentz-invariance breaking because the background field depends on time. Moreover, 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 [15]). A question hence arises. Could the splitting be measured in experiments with heavy-ion collisions?

Manifestation of local spacial parity breaking in heavy ion collisions

An effect of anomalous dilepton pair production in the range of low invariant masses and rapidities and moderate transverse momenta was established in a series of experiments with heavy-ion collisions in recent years [5]-[8]. Characteristically, this effect was observed only for central or nearly central collisions and is an effect of the nuclear medium [9].

Such an anomalous yield of dilepton pairs has not yet been satisfactorily explained from the standpoint of hadron phenomenology. A detailed consideration of the decay processes and their contributions to the dilepton yield can be found in [11], [15].

We present graphic results of calculating the anomalous yield of dilepton pairs in the vicinity of the polarized vector ρ- and ω -meson resonances. In Fig. 1, we show the excess of dilepton pairs for the ρ-meson spectral function (there is a similar effect for the ω meson too) and its corresponding contributions with different polarizations for the values of the parameter inducing the spatial parity breaking, $\zeta = 400$ MeV compared to $\zeta = 0$ MeV. Because of the mass dependence of polarizations on wave vector, the original Breit-Wigner resonance actually splits in three different peaks. This is shown in in Fig.1.

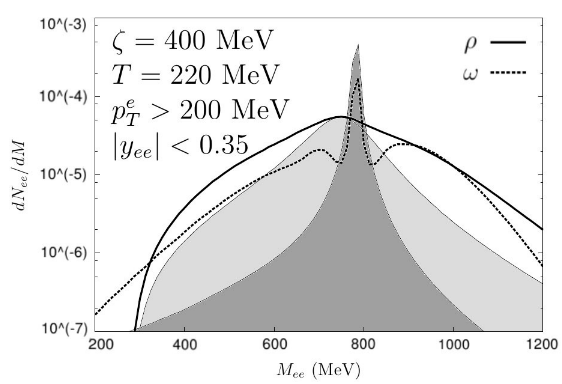

FIGURE 1. In-medium ρ and ω channels (solid and dashed line) and their vacuum contributions (light and dark shaded regions) for $\mu_5 = 290$ MeV.

It is well known that the angular distribution of leptons carries the information on the polarization. However, the current angular distribution studies based on full angular average do not seem to detect possible parity-odd effects.

Instead we define an angle as described in Fig. 2.

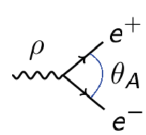

FIGURE 2. θ_A is the angle between the two outgoing leptons in the laboratory frame.

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. θ_A is the angle between the two outgoing leptons in the laboratory frame. A quite visible secondary peak appears in a P-odd medium! To isolate the transverse polarizations in the spectrum, we selected different angle sectors and studied the changes in the ρ-meson spectral function (analogously for ω -mesons). The results are shown in Fig.3. The appearance of the second peak in the parity-odd medium is quite obvious. Various experimental possibilities for its identification were discussed in [15] and also in the PhD theses [16].

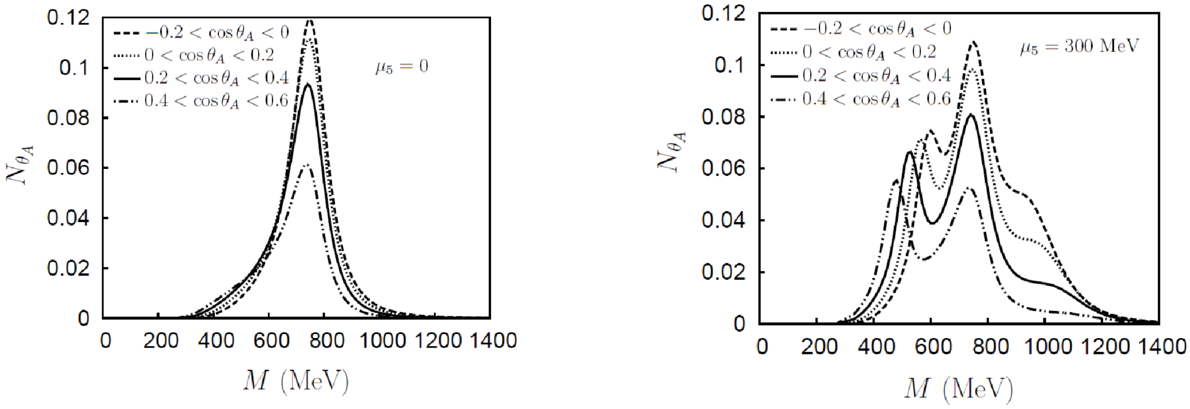

FIGURE 3. Angle θ_A between the two outgoing leptons in the laboratory frame. ρ spectral function depending on the dielectron invariant mass M in vacuum ($\mu_5 = 0$) and in a parity-breaking medium with $\mu_5 = 300$ MeV for different ranges of θ_A.

It turns out that as this parameter increases the contributions of circular polarizations of the resonance become even more noticeable as compared with the vacuum situation. On this basis, we can assume that the magnitude of pseudoscalar condensate gradient in the fireball can serve as a measure of the anomalous yield of polarized dilepton pairs. The corresponding contributions for ρ- and ω -mesons in the medium and in the vacuum are shown in Fig.1, whence it follows that the excess of lepton pairs can occur aside the ρ -meson resonance peaks (analogously for ω-mesons) because of the momentum dependent mass shift in the circular polarizations of resonances in the phase of local spatial parity breaking.

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. The asymmetry of longitudinal and transverse polarized states for different values of the invariant mass can serve as a characteristic indication of the existence of local spatial parity breaking in these experiments. Of course, it should be kept in mind that there are also other possible contributions from processes occurring in the region under study and also in the thermal evolution of the medium in fireball, but we have here restricted ourself only to the dominant contributions from ρ- and ω -mesons and thus tried to quantitatively describe the mechanism for an anomalous excess yield of lepton pairs in the experiments CERES, PHENIX, STAR, NA60, and ALICE.

Conclusions and outlook

In this talk 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 finite temperature/density. The phenomenology of local spatial parity breaking in a fireball is based on introducing a topological (axial) charge and a topological (chiral) chemical potential. Topological charge fluctuations transmit their influence to hadronic physics via an axial chemical potential. We suggested a generalized Lagrangian of the vector meson dominance model in the presence of the Chern-Simons interaction with a spatially homogeneous pseudoscalar field $a(t)$ for describing the electromagnetic interactions of hadrons in a fireball. An analysis showed that in the case of an isosinglet pseudoscalar background field $a(t)$, the spectrum of massless photons is not distorted when they are mixed with massive vector mesons. At the same time, the spectrum of massive vector mesons splits into three components with different polarizations and with different effective masses $m^2_{V,+} < m^2_{V,L} < m^2_{V,-}$. The positions of the resonance poles for transverse polarizations of the corresponding ρ, ω -mesons are shifted depending on the wave vector $|\vec{k}|$, and a resonance broadening occurs that leads to an increase of the spectral contribution to the dilepton production as compared with the situation where the resonances are in the vacuum state. A signal (phase) with spatial parity breaking in heavy-ion collisions (in a fireball) can be sought in experiments with an excess yield of dilepton pairs with different circular polarizations outside the resonance region of the ρ and ω -meson invariant masses. In these experiments, the asymmetry of longitudinal and transverse polarized states for different values of the invariant mass can serve as a characteristic indication of possible existence of local spatial parity breaking. 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, and the identification of its physical origin might serve as a base for a deeper understanding of QCD properties in a medium under extreme conditions. Experimental collaborations should definitely check this possibility.

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