DECAYS OF LIGHT MESONS TRIGGERED BY CHIRAL CHEMICAL POTENTIAL*

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Light meson (π, σ, a_0) properties in the environment with chiral imbalance are analyzed with the help of meson effective Lagrangian associated with QCD. New spatial parity violating decays of scalar mesons arise as a result of mixing of π and a_0 mesons under the influence of chiral charge density. The pion electromagnetic form factor gets an unusual parity-odd contribution. Pion effective masses depend on their velocities and may vanish in flight. The possible determination of chiral chemical potential in heavy-ion collisions based on the above-mentioned phenomena is discussed.

1. Chiral imbalance after nuclear collisions

The properties of nuclear (quark) matter in heavy-ion collisions are subjects of great interest which is supported by several running and planned heavy-ion collider programs [1, 2]. New phases of QCD can be tested in current and future accelerator experiments at RHIC, SPS and the LHC [3] and soon at FAIR and NICA. A fireball generated in these collisions brings new data for experimental and theoretical studies of various phases of strong interactions.

Study of hadron correlations in non-central heavy-ion collisions at RHIC [4] and the LHC [5] provide [6–8] the clue for understanding of the so-called "chiral magnetic effect" (CME) in the reactions for peripheral ion collisions [9].

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 Local Parity Breaking (LPB), we must introduce the axial/chiral chemical potential [10]. 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 [11]), which can be partially thought of as a result of LPB in the medium (the details can be found in [12]). In particular, in heavy-ion collisions at high energies, with raising temperatures and baryon densities, a 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.

Its jump, ΔT_5, can be associated with the space-time integral of the gauge-invariant Chern–Pontryagin density

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

where the integration is over the finite fireball volume.

It is known that the divergence of isosinglet axial quark current $J_{5,\mu} = \bar{q}\gamma_\mu\gamma_5 q$ is locally constrained via the relation of partial conservation of axial current (PCAC), affected by the gluon anomaly [10]. It allows to find the connection of a non-zero topological charge with a non-trivial quark axial charge Q_5^q

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

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

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*). Therefrom, it follows that in the chiral limit, the generation of non-zero topological charge in a finite fireball volume is accompanied by creation of chiral imbalance. Then if for the lifetime of fireball and the size of hadron fireball of the order of $L = 5$–10 fm the induced topological charge is non-zero, $\langle \Delta T_5 \rangle \neq 0$, then it may be associated with a topological potential μ_θ. Equivalently, the axial charge can be controlled by an axial chemical potential μ_5 [10]. Thereby, we have

$$\langle \Delta T_5 \rangle \simeq \frac{1}{2N_{\mathrm{f}}} \langle Q_5^q \rangle \iff \mu_5 \simeq \frac{1}{2N_{\mathrm{f}}} \mu_\theta. \tag{4}$$

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.

2. Effective meson theories in the presence of chiral imbalance

For the detection of LPB in the hadron fireball, one considers the effective Lagrangian describing mass spectra and decays of scalar/pseudoscalar mesons in a fireball carrying a chiral imbalance.

In the environment with chiral chemical potential μ_5, the scalar sector can be described in the meson Lagrangian [14]

$$D_\nu \implies \bar{D}_\nu - i\{\boldsymbol{I}_q \mu_5 \delta_{0\nu}, \star\} = \partial_\nu - iA_\nu[Q_{\text{em}}, \star] - 2i\boldsymbol{I}_q \mu_5 \delta_{0\nu}, \qquad (5)$$

where A_μ, Q_{em} are the electromagnetic field and charge respectively.

The axial chemical potential is introduced as a constant time component of an isosinglet axial–vector field. An effective Lagrangian includes the lightest scalar degrees of freedom σ and $a_0(980)$, the latter being mixed with its pseudoscalar chiral partners π.

The effective Lagrangian of the extended σ model with two flavors contains the following set of operators (see a similar Lagrangian in [13, 14]):

$$
\begin{aligned}
\mathcal{L} = {} & \frac{1}{4} \, \text{Tr} \left(D_\mu H \, (D^\mu H)^\dagger \right) \\
& + \frac{b}{2} \, \text{Tr} \left[m \left(H + H^\dagger \right) \right] + \frac{M^2}{2} \, \text{Tr} \left(HH^\dagger \right) - \frac{\lambda_1}{2} \, \text{Tr} \left[\left(HH^\dagger \right)^2 \right] \\
& - \frac{\lambda_2}{4} \left[\text{Tr} \left(HH^\dagger \right) \right]^2 + \frac{c}{2} \left(\det H + \det H^\dagger \right) + \mathcal{L}_{\text{WZW}}(U).
\end{aligned} \qquad (6)
$$

In the chiral parametrization, they contain two types of fields in $H = \xi \Sigma \xi$ — the scalar isosinglet and isotriplet as well as the pseudoscalar isotriplet

$$
\begin{aligned}
\Sigma &= \begin{pmatrix} v + \sigma + a_0^0 & \sqrt{2}a^+ \\ \sqrt{2}a_0^- & v + \sigma - a_0^0 \end{pmatrix}, \\
U &= \xi\xi = \exp\left\{ \frac{i}{f_\pi} \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix} \right\},
\end{aligned}
$$

where v is a v.e.v. of isoscalar field in the minimum of effective potential. From spectral characteristics of scalar mesons in vacuum, one fixes the Lagrangian parameters, $\lambda_1 = 16.4850$, $\lambda_2 = -13.1313$, $c = -4.46874 \times 10^4 \text{ MeV}^2$, $b = 1.61594 \times 10^5 \text{ MeV}^2$.

The Lagrangian is supplemented by the Wess–Zumino–Witten term describing parity-odd vertices [15]. They contain light pseudoscalar fields and covariant derivatives and, therefore, are sensitive to chiral imbalance. The relevant WZW vertices for our purpose are

$$\frac{ie\,\mu_5 N_c}{6\pi^2\,v^2}\,\epsilon_4^{\;5\sigma\lambda\rho}\,A_\rho\partial_\sigma\pi^+\,\partial_\lambda\pi^- - \frac{e^2 N_c}{24\,\pi^2 v}\,\epsilon^{5\nu\sigma\lambda\rho}\,\partial_\sigma A_\lambda\partial_\nu A_\rho\pi^0\,. \tag{7}$$

3. Mass spectrum with chiral imbalance

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:

$$\mathcal{L} = \tfrac{1}{2}\left(\partial_\mu a_0^j\right)^2 + \tfrac{1}{2}\left(\partial_\mu \pi^j\right)^2 - \tfrac{1}{2}m_{a,\text{bare}}^2\left(a_0^j\right)^2 - \tfrac{1}{2}m_{\pi,\text{bare}}^2\left(\pi^j\right)^2 - 4\mu_5\,\dot\pi^j a_0^j\,. \tag{8}$$

Due to the last term in Eq. (8), new eigenstates arise from the mixture of scalars and pseudoscalars

$$a_0 = C_{a\tilde a}\tilde a + C_{a\tilde\pi}\tilde\pi\,, \qquad \pi = C_{\pi\tilde a}\tilde a + C_{\pi\tilde\pi}\tilde\pi\,. \tag{9}$$

For large 3-momentum, $\tilde\pi$ becomes massless and then tachyonic [14]. Such a behaviour does not represent a serious physical obstacle as it can be checked that the energies remain positive and no vacuum instabilities appear. For the same 3-momentum, the new scalar states $\sigma, \tilde a_0$ prove to increase in masses. In Fig. 1, we present the results for the evolution of effective masses of $\tilde\pi$ and $\sigma, \tilde a_0$ with respect to 3-momentum.
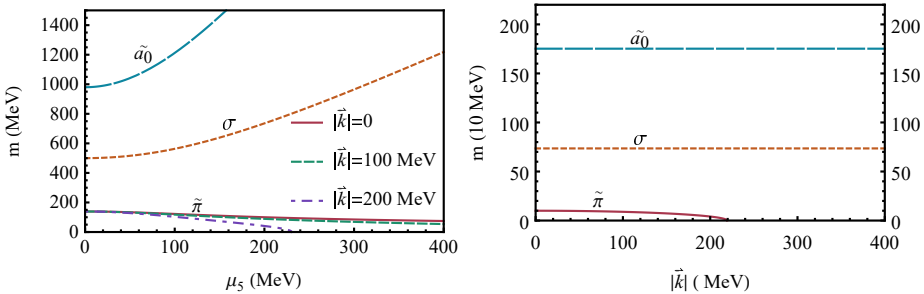

Fig. 1. Effective inflight masses at different values of 3-momentum and chiral chemical potential μ_5 (in the right plot $\mu_5 = 200$ MeV.)

4. Exotic radiative decays in the environment with chiral imbalance

The mixture of light pseudoscalars and heavy scalars Eq. (9) in trilinear vertices, parity-even Eq. (6) and parity-odd ones Eq. (7), generate exotic

decays of $\tilde{a}_0$ states, $a_0^{\pm} \to \pi^{\pm}\gamma$, which may serve as a "smoking gun" of strong parity breaking in a fireball produced in heavy-ion collisions. The partial width of this decay is growing when chiral imbalance increases (see the left plot in Fig. 2). As well the second vertex in Eq. (7) induces the decay $a_0^0 \to \gamma\gamma$ which becomes stronger with the increase of chiral imbalance (see the right plot in Fig. 2).
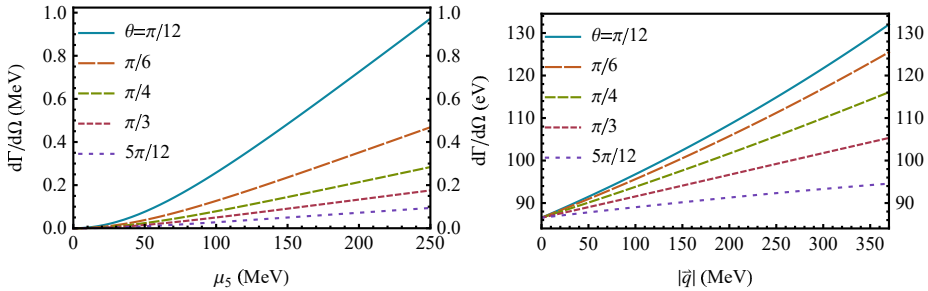

Fig. 2. Decay widths of $\tilde{a}_0^{\pm}$ mesons at $|\vec{q}| = 200$ MeV and of $\tilde{a}_0^0$ mesons at $\mu_5 = 200$ MeV in different angular sectors.

Inverting the process $a_0^{\pm} \to \pi^{\pm}\gamma$, one may conclude that the exotic a_0 resonance decay in the intermediate state will considerably enhance the $\pi\gamma \to \pi\gamma$ scattering around 1 GeV in the medium with chiral imbalance.

5. Conclusions and outlook

Strong CP violation is quite a challenging possibility to be discovered in heavy-ion collisions both at high-energy densities (temperatures) and when triggered by large-baryon densities. For that purpose, we suggest to detect peculiar effects generated in CP odd background (chiral chemical potential), measuring the probability of production of the scalar states with indefinite CP parity.

The influence of chiral imbalance on thermodynamics of hadron(quark) matter can be efficiently established in lattice computations by the chiral chemical potential method [16].

At the previous conference "eQCD2016" [17], we declared also a manifestation for LPB in the presence of chiral imbalance in the sector of ρ and ω vector mesons. It turns out [10] that the spectrum of massive vector mesons splits into three components with different polarizations having different effective masses $m_{V,+}^2 < m_{V,L}^2 < m_{V,-}^2$. Then a resonance broadening occurs that leads to an increase of the spectral contribution to the dilepton production as compared with the vacuum vector-meson states. The latter mechanism for generating local spatial parity breaking helps to (partially) saturate the anomalous yield of dilepton pairs in the CERES, PHENIX, STAR, NA60, and ALICE experiments.

We also draw attention to the recent interesting proposal to measure the photon polarization asymmetry in $\pi\gamma$ scattering [18] as a way to detect LPB due to chiral imbalance.

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