Phenomenology of (local) parity breaking in nuclear matter

Alexander A. Andrianov
on behalf of collaboration with
D. Espriu, V. A. Andrianov, and X. Plannels

Saint-Petersburg State University, Russia
Institut de Ciències del Cosmos, Universitat de Barcelona, Spain

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Motivation of local parity breaking (LPB): $P$-odd bubbles, neutral pion condensate, cold axion background

Axial baryon charge and chiral chemical potential

Vector Meson Dominance (VMD) approach to LPB (with V. A. Andrianov, D. Espriu and X. Planells)

Manifestation of LPB in heavy ion collisions (HIC)

Finite volume effects: passing through a boundary (with S.S. Kolevatov)

Conclusions: in hunting for LPB.
Motivation of LPB

Parity: well established global symmetry of strong interactions. Reasons to believe it may be broken in a finite volume?!

Recent investigations:


- **New QCD phase** characterized by a spontaneous parity breaking due to formation of neutral pion-like background [A. A. Anselm ... A. A. Andrianov, V. A. Andrianov & D. Espriu]

- **Axion background** in dense stars and/or as the dark matter [E. W. Mielke, P. Sikivie et al, A. A. Andrianov, D. Espriu, F. Mescia et al]

- **Our special interest**: LPB background inside a hot dense nuclear fireball in HIC !?
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PHENIX anomaly: abnormal $e^+e^-$ excess in central HIC at low $p_t$ !?

Hint to LPB?  [PHENIX Data Plot (id p1147) 2011]
Topological charge

\[ T_5(t) = \frac{1}{8\pi^2} \int_{\text{vol.}} d^3x \varepsilon_{jkl} \text{Tr} \left( G^j \partial^k G^l - i \frac{2}{3} G^j G^k G^l \right) \]

in a finite volume it may arise from quantum fluctuations in hot QCD medium
(due to sphaleron transitions!? [Manton, Rubakov, Shaposhnikov, McLerran])
and survive for a sizeable lifetime in a heavy-ion fireball,

\[ \langle \Delta T_5 \rangle \neq 0 \quad \text{for} \quad \Delta t \simeq \tau_{\text{fireball}} \simeq 5 - 10 \text{ fm}, \]

For this period one can control the value of \( \langle \Delta T_5 \rangle \) introducing into the QCD Lagrangian a topological chemical potential

\[ \Delta L = \mu_\theta \Delta T_5, \quad \Delta T_5 = T_5(t_f) - T_5(0) = \frac{1}{8\pi^2} \int_0^{t_f} \int_{\text{vol.}} d^3x \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right) \]

in a gauge invariant way.
Topological charge fluctuations, QCD with 2+1 flavors

Domain Wall Fermions on a lattice of size $16^3 \times 8$,
T. Blum et al. LAT2009, 0911.1348 [hep-lat]
Chiral (axial) baryon charge

Partial conservation of isosinglet axial current broken by gluon anomaly (consider the light quarks only),

$$\partial_\mu J^{\mu}_5 - 2i m_q J_5 = \frac{N_f}{8\pi^2} \text{Tr} \left( G^{\mu\nu} \tilde{G}_{\mu\nu} \right)$$

predicts the induced chiral (axial) charge

$$\dot{Q}^q_5 - 2N_f T_5 \simeq 0, \quad m_q \simeq 0, \quad Q^q_5 = \int_{\text{vol.}} \bar{q} \gamma_0 \gamma_5 q = N_L - N_R$$

to be conserved $\dot{Q}^q_5 \simeq 0$ (in the chiral limit $m_q \simeq 0$) during $\tau_{\text{fireball}}$. 
Chiral chemical potential

Chiral chemical potential can be associated with approximately conserved $Q^q_5$ (for $u, d$ quarks!)

$$\Delta L_q = \mu_5^q Q^q_5,$$

to reproduce a corresponding

$$\langle \Delta T_5 \rangle \simeq \frac{1}{2N_f} \langle Q^q_5 \rangle, \iff \mu_5^q \simeq \frac{1}{2N_f} \mu_\theta$$

For the $s$ quark introducing of $\mu_5^q$ is problematic as $1/m_s \sim 1$ fm and several left-right oscillations occur during the fireball lifetime $\sim 5 - 10$ fm, i.e. one cannot consider the $s$ quark chiral charge as conserved. As well the heavier is a quark the larger is screening of anomaly ($\rightarrow$ topological charge) by the pseudoscalar density $J_5$ (decoupling effect in vector gauge theories). Thus one expects suppression of strange meson contributions into LPB.
Chiral chemical potential in hadron Lagrangians

LPB to be investigated in e.m. interactions of leptons and photons with hot/dense nuclear matter via heavy ion collisions.

- e.m. interaction implies

\[ Q_5^q \rightarrow \tilde{Q}_5 = Q_5^q - T_5^{em}, \quad T_5^{em} = \frac{1}{16\pi^2} \int_{vol.} d^3x \epsilon_{jkl} A^j \partial^k A^l \]

- \( \mu_5 \) is conjugated to (nearly) conserved \( \tilde{Q}_5 \)

- **Bosonization** of \( Q_5^q \) following VMD prescription

Extra term in Lagrangian

\[ \Delta \mathcal{L} \simeq -\frac{1}{4} \epsilon^{\mu\nu\rho\sigma} \text{Tr} \left[ \hat{\zeta}_\mu V_\nu V_{\rho\sigma} \right], \]

with \( \hat{\zeta}_\mu = \hat{\zeta} \delta_{\mu0} \) due to spatially homogeneous and isotropic background \((^\wedge \equiv \text{isospin content})\) and \( \zeta \sim \alpha \mu_5 \sim \alpha T^{-1} \sim 1 \text{ MeV} \)

\[
\langle \Delta T_5 \rangle \quad \Longleftrightarrow \quad \mu_\theta \quad \Longrightarrow \quad \mu_5 \quad \Longrightarrow \quad \zeta
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\[
\left\langle \Delta T_5 \right\rangle \iff \mu_\theta \implies \mu_5 \implies \zeta
\]
Vector Meson Dominance approach to LPB

\[ \mathcal{L}_{\text{int}} = \bar{q} \gamma_{\mu} \hat{V}^{\mu} q; \quad \hat{V}_{\mu} \equiv -e A_{\mu} Q + \frac{1}{2} g_\omega \omega_{\mu} \Pi_{\text{ns}} + \frac{1}{2} g_\rho \rho^0_{\mu} \tau_3 + g_\phi \phi_{\mu} \Pi_s, \]

\[ (V_{\mu, a}) \equiv (A_{\mu}, \omega_{\mu}, \rho^0_{\mu}, \phi_{\mu}), \quad g_\omega \sim g_\rho \equiv g \sim 6 < g_\phi \sim 7.8 \]

\[ \mathcal{L}_{\text{kin}} = -\frac{1}{4} (F_{\mu\nu} F^{\mu\nu} + \omega_{\mu\nu} \omega^{\mu\nu} + \rho_{\mu\nu} \rho^{\mu\nu} + \phi_{\mu\nu} \phi^{\mu\nu}) + \frac{1}{2} V_{\mu, a} (\hat{m}^2)_{a, b} V^{\mu}_b \]

\[ \hat{m}^2 \approx m_V^2 \begin{pmatrix} \frac{4e^2}{3g^2} & -\frac{e}{3g} & -\frac{e}{g} & \frac{eg_\phi \sqrt{2}}{3g^2} \\ -\frac{e}{3g} & 1 & 0 & 0 \\ -\frac{e}{g} & 0 & 1 & 0 \\ \frac{eg_\phi \sqrt{2}}{3g^2} & 0 & 0 & \frac{g_\phi^2}{g^2} \end{pmatrix} \]

\[ \Rightarrow \text{mixing of } \gamma, \rho, \omega, \phi \]
VDM approach to LPB: reduction of $3 \rightarrow 2$ flavors

$P$-odd interaction

$$\mathcal{L}_{\text{mix}} \propto \frac{1}{2} \text{Tr} \left( \hat{\zeta} \epsilon_{jkl} \hat{V}_j \partial_k \hat{V}_l \right) = \frac{1}{2} \zeta \epsilon_{jkl} V_{j,a} N_{ab} \partial_k V_{l,b}$$

$\tau_\phi \gg \tau_{\text{fireball}}$, non-negligible L-R oscillations due to $s$-quark mass term $\Rightarrow \langle Q_5^s \rangle \approx 0$. Correspondingly the reduction of $3 \rightarrow 2$ flavors makes sense.

$$\hat{\zeta} = a \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} + b \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

VDM approach to Local P-breaking

Mixing matrix $N$:

- Isosinglet pseudoscalar background ($T \gg \mu$) [RHIC, LHC]

$$
(N^\theta_{ab}) \simeq \begin{pmatrix}
1 & -\frac{3g}{10e} & -\frac{9g}{10e} \\
-\frac{3g}{10e} & \frac{9g^2}{10e^2} & 0 \\
-\frac{9g}{10e} & 0 & \frac{9g^2}{10e^2}
\end{pmatrix}, \quad \det (N^\theta) = 0
$$

Different effective masses of vector mesons for different polarizations $L, \pm \epsilon = 0, \pm 1$

$$
m^2_{V,\epsilon} = m^2_V - \epsilon \frac{9g^2}{10e^2} \zeta |\vec{k}| \quad \implies \quad |\zeta|, \quad \epsilon = 0, \pm 1
$$

- Pion-like condensate ($\mu \gg T$) [FAIR, NICA]

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Manifestation of LPB in heavy ion collisions
Enhanced dilepton production

Contribution of different polarizations $L, \pm$ for vector mesons in the hot pion gas:

\[
\frac{dN_{ee}^\epsilon}{d^4x dM} \simeq c_V \frac{\alpha^2 \Gamma_V m_V^2}{3\pi^2 g^2 M^2} \left( \frac{M^2 - n_V^2 m_{\pi}^2}{m_V^2 - n_V^2 m_{\pi}^2} \right)^{3/2} \\
\times \sum_\epsilon \int_{M}^\infty \frac{dk_0}{e^{k_0/T} - 1} \frac{m_{V,\epsilon}^4}{\left( M^2 - m_{V,\epsilon}^2 \right)^2 + m_{V,\epsilon}^4 \frac{\Gamma_V^2}{m_V^2}}
\]

where $n_V = 2, 0; |\vec{k}| = \sqrt{k_0^2 - M^2}$ and $M^2 > n_V^2 m_{\pi}^2$. $c_V$ absorbs combinatorial factors different for $\rho$ and $\omega, \mu_V$, finite volume suppression. Empirically for $\zeta = 0$ the ratio $c_\rho/c_\omega \sim 10$ holds.
Manifestation of LPB in heavy ion collisions

Cocktail of hadron decays

- $\pi^0 \rightarrow \gamma e^+ e^-$
- $\eta \rightarrow \gamma e^+ e^-$
- $\eta' \rightarrow \gamma e^+ e^-$
- $\rho \rightarrow e^+ e^-$
- $\omega \rightarrow e^+ e^-$
- $\omega \rightarrow \pi^0 e^+ e^-$
- background $\bar{c}c$

PHENIX data for Au-Au collisions
Polarization splitting in $\rho$ spectral function for LPB $\zeta = 2$ MeV.

POLARIZATION ASYMMETRY!!
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**POLARIZATION ASYMMETRY!!**
Comparison of $\rho$ spectral function in vacuum and for LPB $\zeta = 2$ MeV. In-medium calculation is pushed up by factor 1.8 due to $\pi\pi$ recombination into $\rho$. 
Comparison of $\omega$ spectral function in vacuum and for LPB $\zeta = 2$ MeV.
Numerical results for dilepton excess around $\rho + \omega$ peak

$T = 220$ MeV, $\rho + \omega$ contributions

$\zeta = 0$ MeV
$\zeta = 2$ MeV

$\rho + \omega$ contributions in vacuum and for LPB $\zeta = 2$ MeV (normalization given by the $\omega$ peak).

ENHANCEMENT OF DILEPTON YIELD!!
Numerical results for dilepton excess around $\rho + \omega$ peak

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**ENHANCEMENT OF DILEPTON YIELD!!**
Numerical results for dilepton excess

PHENIX anomaly

Comparison of PHENIX cocktail with modified cocktail using $\rho + \omega$ contributions for LPB with $\zeta = 1, 2$ MeV.
Mean free paths for vector mesons:

- \( L_\rho \sim 0.8 \text{fm} \)
  \( \ll L_{\text{fireball}} \sim 5 - 10 \text{fm} \)

- \( L_\omega \sim 16 \text{fm} \gg L_{\text{fireball}} \)

Why it is relevant in medium?
(PHENIX confirms!)

LPB "vacuum"

\( \neq \) empty vacuum
= coherent state of vacuum mesons
Bogoliubov transformation!

Matching on \( \zeta \cdot x = 0 \)

\[ \delta(\zeta \cdot x) \left[ A_{\text{vacuum}}^\mu(x) - A_{\text{LPB}}^\mu(x) \right] = 0 \]

Thus to save energy-momentum conservation transmission must be accompanied by reflection back. For \( M_{ee} < m_{\text{vec}} \) the classical reflection \( \sim 100\% \). Enhancement of in-medium decays of \( \omega \) mesons!
Reflection from boundary depending on effective mass
Conclusions

▶ LPB not forbidden by any physical principle in QCD at finite temperature/density

▶ The effect leads to unexpected modifications of the in-medium properties of vector mesons and photons

▶ LPB seems capable of explaining in a natural way the PHENIX 'anomaly'

▶ *Event-by-event* measurements of the lepton polarization asymmetry may reveal in an unambiguous way the existence of LPB

▶ Boundary enhancement of in-medium $\omega$ decays + LPB $\rightarrow$ broadening of $\omega$ resonance in fireballs

▶ Lattice simulations triggered by topological vs. chiral chemical potentials could shed light on the local P-breaking in QCD (work in progress with M. D’Elia, D. Espriu and A. Papa)

▶ LPB enhancement in vertices, like $\omega \rightarrow \eta\pi\pi \Longrightarrow \omega \rightarrow \pi\pi \times \zeta$?
Back up slides
Manifestation of LPB in heavy ion collisions

Acceptance

**Experimental detector cuts:**
$|\vec{p}_t| > 200 \text{ MeV}, |y| < 0.35$

Invariant mass smearing: gaussian with width 10 MeV

Acceptance correction breaks Lorentz invariance. Phase space calculation becomes a non-trivial task $\implies$ VEGAS
Explicit formula for the simulation with acceptance correction:

\[ \frac{dN}{d^4xdM} = \int d\tilde{M} \frac{1}{\sqrt{2\pi\Delta}} \exp \left[ -\frac{(M - \tilde{M})^2}{2\Delta^2} \right] c_V \frac{\alpha^2}{24\pi\tilde{M}} \left( 1 - \frac{n_V^2 m_V^2}{\tilde{M}^2} \right)^{3/2} \]

\[ \times \sum \int_{\text{acc.}} \frac{k_t dk_t dyd^2p_t}{|E_k p_\parallel - k_\parallel E_p|} \frac{1}{e^{\tilde{M}_t/T} - 1} P^\mu_\nu (\tilde{M}^2 g_{\mu\nu} + 4p_\mu p_\nu) \]

\[ \times \frac{m_{V,\epsilon}^4}{\left( \tilde{M}^2 - m_{V,\epsilon}^2 \right)^2 + m_{V,\epsilon}^4 \frac{r_{V}^2}{m_V^2}} \]
Numerical results for dilepton excess

PHENIX anomaly

ρ and ω contributions to dilepton yield for LPB $\zeta = 2$ MeV.