Dilepton excess from local parity breaking in baryonic matter

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Outline

- Introduction
- Parity breaking at large densities
- Parity breaking from topological fluctuations
- Some consequences of LPB
- How hadronic physics is modified by LPB
- Can this possibility be tested in HIC?
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- Enhanced dilepton production explained?
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Introduction

Parity is one of the well established symmetries of strong interactions. Yet there are reasons to believe that it may be broken in some circumstances.

The Vafa-Witten theorem does not apply at $\mu \neq 0$. No fundamental principle forbids spontaneous parity breaking.

- $P$-and CP-odd condensates = “pion” condensates
Local large fluctuations in the topological charge probably exist in a hot environment.

For *peripheral* collisions they lead to the Chiral Magnetic Effect (CME): Large $\vec{B} \Rightarrow$ large $\vec{E} \Rightarrow$ charge separation

For *central* collisions (and light quarks) they correspond to an ephemeral phase with chiral chemical potential $\mu_5 \neq 0$

- **Topological fluctuations**
Thus the generic situation in heavy ion collisions could be described by a combination of baryon and chiral chemical potentials

\[ \mu \Rightarrow V_0, \quad \mu_5 \Rightarrow A_0 \]

Both \( A_0 \) and \( V_0 \) will be isosinglets but the latter may trigger a pseudoscalar condensate in a non-singlet channel as we will see below.

We will present an effective meson theory description of both phenomena.
Parity breaking at large densities

Take a model with two scalar doublets $H_j = \tilde{\sigma}_j \mathbf{1} + i \hat{n}_j$, $j = 1, 2$

$$V_{\text{eff}} = \frac{1}{2} \text{Tr}\{- \sum_{j,k=1}^{2} H_j^\dagger \Delta_{jk} H_k + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2$$

$$+ \frac{1}{2} \lambda_4 (H_1^\dagger H_2 H_1^\dagger H_2 + H_2^\dagger H_1 H_2^\dagger H_1) + \frac{1}{2} \lambda_5 (H_1^\dagger H_2 + H_2^\dagger H_1) H_1^\dagger H_1$$

$$+ \frac{1}{2} \lambda_6 (H_1^\dagger H_2 + H_2^\dagger H_1) H_2^\dagger H_2\} - \bar{q}_R H_1 q_L + \bar{q}_L H_1^\dagger q_R$$

The constants $\Delta_{ij}$, $\lambda_i$ are constrained by QCD properties at low energies.

At least two scalar doublets are necessary to trigger a pseudoscalar condensate.
This model provides a fairly accurate description of many aspects of hadronic and nuclear physics: condensation point, absence of chiral collapse, nuclear compressibility, ...

The vacuum structure of this model is quite complex.

It is a generic feature of the model that, after imposing all QCD constraints, a phase with a pseudoscalar condesate appears

$$\langle \hat{\pi}_2 \rangle = \rho \tau^3 \neq 0$$

The transition of is of second order (may be an artifact of the approximation).
Parity breaking at large densities

Spontaneous P-parity breaking (2nd order phase transition)

\[ \sigma_1(\mu) \quad \rho^2(\mu) \quad \sigma_1(0) \]

Nuclear matter forms (saturation point)
No chiral collapse

\[ \sigma_1(0) \equiv M_{\text{dyn}} \simeq 300 \text{MeV} \]

SPB

Jumps of derivatives

Beyond the range of validity of chiral expansion

With increasing \( \mu \) one enters SPB phase and leaves it before (?) encountering any new phase (CSR, CFL ...)

Order of the phase transition?

P and CP-odd effects in hot and dense matter - BNL April 2010
Parity breaking at large densities

The transition is located at intermediate densities (from 3 to $6 \times \rho_N$), where using several isomultiplets seems particularly justified.
Some consequences of parity breaking

Some features:

- Parity is no longer a good quantum number in strong interactions: $S \leftrightarrow P$
- Genuine mass eigenstates do not possess a definite parity in the decays
- Isospin symmetry broken: $SU(2) \rightarrow U(1)$ if $\langle \hat{\pi}_2 \rangle \neq 0$
- Two new Goldstone bosons may appear
- Likely to influence the equation of state of neutron stars
Phenomenological consequences of SPB

P-breaking phase

Mixing with massless pions is different for neutral and charged ones because vector isospin symmetry is broken

\[ \tilde{\pi}^\pm = \pi^\pm + \zeta \Pi^\pm, \quad \tilde{\pi}^0 = \pi^0 + \frac{F_0^2}{F_0^2 + A_{22} \rho^2} \left( \zeta \Pi^0 - \frac{\rho}{F_0} \sum_{j=1}^{2} A_{j2} \partial_\mu \Sigma_j \right). \]

Partially diagonalized kinetic term

\[ \mathcal{L}_{\text{kin}}^{(2)} = \partial_\mu \tilde{\pi}^\pm \partial^\mu \tilde{\pi}^{\mp} + (A_{22} - \zeta^2) \partial_\mu \Pi^\pm \partial^\mu \Pi^{\mp} + \frac{1}{2} \left( 1 + \frac{A_{22} \rho^2}{F_0^2} \right) \partial_\mu \tilde{\pi}^0 \partial^\mu \tilde{\pi}^0 + \frac{1}{2} \sum_{j,k=1}^{2} A_{jk} \frac{F_0^2}{F_0^2 + A_{22} \rho^2} \delta_{1j} \delta_{1k} \partial_\mu \Sigma_j \partial^\mu \Sigma_k \]

\[ - \frac{F_0 \rho}{F_0^2 + A_{22} \rho^2} \zeta \partial_\mu \Pi^0 \sum_{j=1}^{2} A_{j2} \partial^\mu \Sigma_j \]

Isospin breaking \( SU_V(2) \to U(1) \)
Phenomenological consequences of SPB

Mass spectrum of “pseudoscalar” states

(Parity no longer a good quantum number in strong interactions!)

\[ m^2_{\Pi_0} \quad m^2_{\Pi_{\pi}} \]

\[ (1.3 GeV)^2 \]

\[ \mu^* \quad \mu_c^- \quad \mu_c^+ \]

\[ \text{SPB} \quad \rho(\mu) \neq 0 \]

\[ \pi_0 \quad \pi_{\pm} \quad \Pi_{\pm} \]

pseudoscalar mesons
Physical scenario

In a HIC the nuclear matter is first compressed and heated during $< 0.5$ fm, then cools down for 5-10 fm until freeze-out. We shall assume that a situation of quasi-equilibrium is established and that the fireball can be approximately described by a spatially homogeneous but time dependent pseudoscalar background.

The scalar meson effective theory has already been shown (the pseudoscalar condensate will be time dependent: $\langle \hat{\pi}_2 \rangle = \rho(t)\tau^3$)

In addition we get a new contribution via the anomaly

$$\Delta \mathcal{L} \simeq \varepsilon^{\mu\nu\rho\sigma} \text{Tr} \left[ \hat{\zeta}_\mu V_\nu V_{\rho\sigma} \right]$$

with $\hat{\zeta}_\mu \simeq (\hat{\zeta}, \vec{0})$ for a homogenous fireball. $\hat{\zeta}_0 \propto \partial_0 \rho(t)$ and it could be either $SU(3)_f$ singlet or diagonal part of $SU(3)_f$ octet or a mixture of the two

This term influences the properties of vector mesons.
Parity breaking from topological fluctuations

During the compression and heating period a topological charge may emerge. This can be treated by including a term

$$\Delta \mathcal{L}_{\text{top}} = \mu_\theta \Delta T_5$$

Until freeze-out the topological charge is approximately conserved.

For light quarks the creation of topological charge leads to the generation of an axial charge (anomaly equation). The axial charge is conserved too provided that the quark mass term remains subdominant.

The characteristic oscillation time is governed by inverse quark masses. For $u, d$ quarks $1/\hat{m}_q \sim 1/5 \text{ MeV}^{-1} \sim 40 \text{ fm} \gg \tau_{\text{fireball}}$ and the left-right quark mixing can be neglected. For strange quarks as $1/m_s \sim 1/200 \text{ MeV}^{-1} \sim 1 \text{ fm} \ll \tau_{\text{fireball}}$ and the mean value of strange quark axial charge is around zero due to left-right oscillations.
For $u, d$ quarks QCD with a topological charge $\langle \Delta T_5 \rangle \neq 0$ can be equally described at the Lagrangian level by topological chemical potential $\mu_\theta$ or by axial chemical potential $\mu_5$

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

$$\Delta L_{\text{top}} = \mu_\theta \Delta T_5 \iff \Delta L_q = \mu_5 Q^q_5$$

We have to account for the photon contribution to the singlet axial anomaly

$$Q^q_5 \rightarrow \tilde{Q}_5 = Q^q_5 - T^\text{em}_5, \quad T^\text{em}_5 = \frac{N_c}{8\pi^2} \int_{\text{vol.}} d^3x \varepsilon_{jkl} \text{Tr} \left( \hat{A}^j \partial^k \hat{A}^l' \right).$$

The following term appears

$$\Delta L \simeq \varepsilon^{\mu\nu\rho\sigma} \text{Tr} \left[ \hat{\zeta}_\mu V_\nu V_{\rho\sigma} \right]$$

with $\hat{\zeta}_\mu = \hat{\zeta}_\delta \delta_{\mu 0}$ for a spatially homogeneous fireball and $\zeta \propto \mu_5$. 
The scalar part of the lagrangian can be estimated by using the spurion technique

\[ D_\nu \mapsto D_\nu - i\{\mu_5 \delta_{0\nu}, \cdot\} = D_\nu - 2i\mu_5\delta_{0\nu} \]

Two new processes are then likely to be most relevant inside the fireball thermodynamics: the decays \( \eta, \eta' \rightarrow \pi\pi \) that are strictly forbidden in QCD on parity grounds.

Dimension four terms in the chiral lagrangian lead to couplings such as

\[ \sim \frac{16\mu_5}{F_\eta f_\pi^2} L \partial\eta \partial\pi \partial\pi \]

A rough estimate of the partial width gives values comparable to \( \Gamma_{\rho \rightarrow \pi\pi} \): if \( \rho \)'s are in thermal equilibrium in the pion bath, so will the \( \eta \).
Effective lagrangian:

\[
\mathcal{L} = \frac{1}{4} \text{Tr} \left( D_\mu H D^\mu H^\dagger \right) + \frac{b}{2} \text{Tr} \left[ M (H + H^\dagger) \right] + \frac{M^2}{2} \text{Tr} \left( HH^\dagger \right) \\
- \frac{\lambda_1}{2} \text{Tr} \left[ (HH^\dagger)^2 \right] - \frac{\lambda_2}{4} \left[ \text{Tr} \left( HH^\dagger \right) \right]^2 + \frac{c}{2} (\text{det} H + \text{det} H^\dagger) \\
+ \frac{d_1}{2} \text{Tr} \left[ M (HH^\dagger H + H^\dagger HH^\dagger) \right] + \frac{d_2}{2} \text{Tr} \left[ M (H + H^\dagger) \right] \text{Tr} \left( HH^\dagger \right)
\]

with

\[
H = \xi \Sigma \xi, \quad \xi = \exp \left( i \frac{\Phi}{2f} \right), \quad \Phi = \lambda^a \phi^a, \quad \Sigma = \lambda^b \sigma^b
\]
New eigenstates of strong interactions with LPB

\[ \Phi = \begin{pmatrix} \eta_q + \pi^0 & \sqrt{2}\pi^+ & 0 \\ \sqrt{2}\pi^- & \eta_q - \pi^0 & 0 \\ 0 & 0 & \sqrt{2}\eta_s \end{pmatrix}, \quad \Sigma = \begin{pmatrix} \nu_u + \sigma + a_0^0 & \sqrt{2}a_0^+ & 0 \\ \sqrt{2}a_0^- & \nu_d + \sigma - a_0^0 & 0 \\ 0 & 0 & \nu_s \end{pmatrix} \]

\[
\begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix} = \begin{pmatrix} \cos \psi & \sin \psi \\ -\sin \psi & \cos \psi \end{pmatrix} \begin{pmatrix} \eta \\ \eta' \end{pmatrix}
\]

For \( \mu_5 = 0 \), we assume \( \nu_u = \nu_d = \nu_s = \nu_0 \equiv f_\pi \approx 93 \text{ MeV} \).

For non-vanishing \( \mu_5 \) we assume isospin symmetry and thus, we impose to our solutions to be \( \nu_u = \nu_d = \nu_q \neq \nu_s \).

The coupling constants are fitted to phenomenology (MeV):

\[
b = -3510100, \quad M^2 = 1255600, \quad c = 1252.2, \quad d_1 = -1051.7,
\]

\[
d_2 = 523.21, \quad \lambda_1 = 67.007, \quad \lambda_2 = 9.3126
\]
New eigenstates of strong interactions with LPB

\[ \mathcal{L} = -\frac{1}{2} \begin{pmatrix} \sigma & \eta_q & \eta_s \end{pmatrix} \begin{pmatrix} -k^2 + 2\Sigma & i\Theta k_0 & 0 \\ -i\Theta k_0 & -k^2 + 2Q_v & g_n \\ 0 & g_n & -k^2 + 2S \end{pmatrix} \begin{pmatrix} \sigma \\ \eta_q \\ \eta_s \end{pmatrix} + \text{interaction terms} \]

\[ \Sigma = -(M^2 + 6d_1mv_q + 12d_2mv_q + cv_s + 2d_2msv_s - 6v_q^2\lambda_1 \\ - 6v_q^2\lambda_2 - v_s^2\lambda_2 + 2\mu_5^2) \]

\[ Q_v = bm/v_q + d_1mv_q + 2d_2mv_q + 2cv_s + d_2mv_s^2/v_q \]

\[ S = bm_s/v_s + cv_q^2/v_s + 2d_2msv_q^2/v_s + d_1msv_s + d_2msv_s \]

\[ \Theta = 4\mu_5, \quad g_n = 2\sqrt{2}cv_q \]

After diagonalization new eigenstates are defined: \( \tilde{\sigma}, \tilde{\eta}, \text{ and } \tilde{\eta} \).
\( \pi \) and \( a_0 \) are also included and lead to new states \( \tilde{\pi} \) and \( \tilde{a}_0 \).
Mass dependence on $\mu_5$ for two values of the 3-momenta

\begin{align*}
\tilde{\eta}' & \quad \tilde{\sigma} \\
\tilde{\eta} & \quad \tilde{\bar{\eta}} \\
|k| = 0
\end{align*}

\begin{align*}
|k| = 200 \text{ MeV}
\end{align*}
The dependence of $\tilde{\pi}$ and $\tilde{a}_0$ masses on $\mu_5$ for $\vec{k} = 0$
Widths depend strongly on $\mu_5$ and (unfortunately) on the details of the effective theory. $\tilde{\eta}'$ shows clear violations of unitarity $\Rightarrow$ more hadronic d.o.f. are needed
\[ \mathcal{L}_{\text{int}} = \bar{q} \gamma_{\mu} \hat{V}^{\mu} q; \quad \hat{V}_{\mu} \equiv -eA_{\mu} Q + \frac{1}{2} g_\omega \omega_{\mu} \mathbb{I} + g_\rho \rho_{\mu} \frac{\tau_3}{2} \]

\[ (V_{\mu,a}) \equiv (A_{\mu}, \omega_{\mu}, \rho_{\mu} \equiv (\rho_0)_{\mu}), \]

where \( Q = \frac{\tau_3}{2} + \frac{1}{6} \); \( g_\omega \simeq g_\rho \equiv g \simeq 6 \)

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

\[ (\hat{m}^2)_{a,b} = m^2_V \begin{pmatrix} \frac{10e^2}{9g^2} & -\frac{e}{3g} & -\frac{e}{g} \\ -\frac{e}{3g} & 1 & 0 \\ -\frac{e}{g} & 0 & 1 \end{pmatrix}, \quad \det(\hat{m}^2) = 0. \]
The parity-odd interaction affecting vector mesons is given by the term

\[ \mathcal{L}_{\text{mixing}}(k) = -\frac{1}{4} \varepsilon^{\mu\nu\rho\sigma} \text{tr} \hat{\zeta}_\mu \hat{V}_\nu(x) \hat{V}_\rho(x) = \frac{1}{2} \zeta \epsilon_{jkl} V_{j,a} N_{ab} \partial_k V_{l,b} \]

For isosinglet pseudoscalar background the mixing matrix is

\[ (N_{ab}) \simeq \begin{pmatrix} \frac{10e^2}{9g^2} & -\frac{e}{3g} & -\frac{e}{g} \\ -\frac{e}{3g} & 1 & 0 \\ -\frac{e}{g} & 0 & 1 \end{pmatrix}, \quad \text{det} (N) = 0 \]

For iso-triplet condensate (not considered in the following)

\[ (N_{ab}) \simeq \begin{pmatrix} \frac{2e^2}{3g^2} & -\frac{e}{g} & -\frac{e}{3g} \\ -\frac{e}{g} & 0 & 1 \\ -\frac{e}{3g} & 1 & 0 \end{pmatrix}, \quad \text{det} (N) = 0 \]
Physical states:

\[ \varepsilon_L^\mu = \frac{\zeta^\mu k^2 - k^\mu (\zeta \cdot k)}{\sqrt{k^2 ( (\zeta \cdot k)^2 - \zeta^2 k^2 )}}; \quad \varepsilon_{\mu, L} \varepsilon_L^\mu = -1, \]

\[ K_{\mu \nu} \varepsilon_\pm^\nu = (k^2 I - \hat{m}^2 \pm \sqrt{(\zeta \cdot k)^2 - \zeta^2 k^2} \hat{N}) \varepsilon_\pm^\mu; \quad \varepsilon_- \cdot \varepsilon_+ = -1. \]

After the simultaneous diagonalization of matrices \( \hat{m}^2, \hat{N} \)

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

\[ \hat{m}^2 = m_V^2 \text{ diag} \left[ 0, 1, 1 + \frac{10e^2}{9g^2} \right] \simeq \text{diag} [0, 1, 1] \]
After diagonalization

\[ m^2_{V,\pm} \equiv m^2_V \pm \zeta |\vec{k}| \]

The photon itself is unaffected by a singlet \( \zeta \)

The position of the poles for \( \pm \) polarized mesons is moving with wave vector \( |\vec{k}| \)

Massive vector mesons split into three polarizations with masses

\[ m^2_{V,-} < m^2_{V,L} < m^2_{V,+}. \]

*This splitting unambiguously signifies LPB. Can it be measured?*
Separation of helicities

\[ \rho \text{ channel} \]
\[ \zeta = 400 \text{ MeV} \]
\[ T = 220 \text{ MeV} \]
\[ p_T^e > 200 \text{ MeV} \]
\[ |y_{ee}| < 0.35 \]

Corresponds to \( \mu_5 = 290 \text{ MeV} \)
Bouncing back to the medium

(A.Andrianov, S.Kolevatov, R.Soldati)

Mean free paths for vector mesons:

- $L_\rho \sim 0.8\text{fm} \ll L_{\text{fireball}} \sim 5 - 10\text{fm}$
- $L_\omega \sim 16\text{fm} \gg L_{\text{fireball}}$

LPB ”vacuum”
\neq \text{empty vacuum}
= coherent state
of vacuum mesons

Mesons have different dispersion relations on both sides of the wall: continuity of the wave function implies that transmission will be accompanied by reflection back to the medium.
The reflection coefficient approaches 1 for large $p_T$ and close to the vacuum on-shell condition. Many $\omega$ will decay inside the firewall, in the LPB vacuum.

The $\omega$ much like the $\rho$ will show a distorted shape. The emission of mesons at large $p_T$ should be suppressed. *Can this be experimentally quantitatively verified?*
Mixing of vector mesons with their axial counterparts has not been considered. This mixing is however expected to be relatively small due to the relatively large mass differences and that $m_V \gg \mu_5$. 

\[ \zeta = 400 \text{ MeV} \]
\[ T = 220 \text{ MeV} \]
\[ p_T^e > 200 \text{ MeV} \]
\[ |y_{ee}| < 0.35 \]
How to test these ideas?

Electromagnetic probes (electrons, positrons, and photons, but also muons) are best suited to extract information about the possible existence of a LPB phase (and also other properties of hot/dense nuclear matter).

Do we understand the electromagnetic properties of hot and dense nuclear matter and/or the QGP?
The CERES/NA60/PHENIX/STAR 'anomaly'

FIG. 27: (Color online) Invariant mass spectrum of $e^+e^-$ pairs inclusive in $p_T$ compared to expectations from the model of hadron decays for $p+p$ and for different Au + Au centrality classes.

From: 0912.0244v1 [nucl-ex]
(PHENIX Collaboration)

TABLE IX: The enhancement factor, defined as the ratio between the measured yield and the expected yield for $0.15 < m_{ee} < 0.75$ GeV/$c^2$, for different centrality bins. The meaning of the errors is defined in the text.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Enhancement (±stat ±syst ±model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00-10 %</td>
<td>7.6 ± 0.5 ± 1.5 ± 1.5</td>
</tr>
<tr>
<td>10-20 %</td>
<td>3.2 ± 0.4 ± 0.1 ± 0.6</td>
</tr>
<tr>
<td>20-40 %</td>
<td>1.4 ± 1.3 ± 0.02 ± 0.3</td>
</tr>
<tr>
<td>40-60 %</td>
<td>0.8 ± 0.3 ± 0.03 ± 0.2</td>
</tr>
<tr>
<td>60-92 %</td>
<td>1.5 ± 0.3 ± 0.001 ± 0.3</td>
</tr>
<tr>
<td>Min. Bias</td>
<td>4.7 ± 0.4 ± 1.5 ± 0.9</td>
</tr>
</tbody>
</table>
The CERES/NA60/PHENIX/STAR ‘anomaly’
The CERES/NA60/PHENIX/STAR 'anomaly'

This is an old puzzle...

Theoretical interpretations have so far failed...

Enhanced dilepton production

**Fig. 1.** Background-subtracted mass spectrum before (dots) and after subtraction of the known decay sources (triangles).

**Fig. 2.** Excess dimuons compared to theoretical predictions [16], renormalized to the data in the mass interval $M<0.9$ GeV. No acceptance correction applied.


The contribution from hadron decays is independently normalized based on meson measurements.
Modified $\rho + \omega$ contribution

Comparison with NA60 measurements (no acceptance correction)

A large value of $\mu_5$ required for best fit. $\mu_5$ is meant to be an average, experiment dependent quantity.

LPB gives a good description for $M^2 > m_V^2$ but 'something is missing' for $M^2 < m_V^2$.

This region could receive additional contributions from the states $\tilde{\eta}, \tilde{\eta}'$ in thermal equilibrium now as well as from $\omega$ Dalitz decay.
Modified Dalitz contribution

We only show the contribution of particles in thermal equilibrium. The $\omega$ Dalitz decay is not included. The green line represents the new contribution due to $\mu_5 \neq 0$. On top of this one has to include the contribution from the direct $\eta \eta'$ and $\omega$ decays.
Conclusions and outlook

- Local parity breaking is not forbidden by any physical principle in strong interactions at finite chemical potential.
- Topological fluctuations transmit their influence to hadronic physics via a chiral chemical potential.
- LPB leads to unexpected modifications of the in-medium properties of scalar and vector mesons.
- Measurement event-by-event of the lepton polarization may reveal in an unambiguous way the existence of parity violation.
- The ‘bouncing back effect’ may change the high $p_T$ spectrum and reinforce thermal equilibration.
- LPB may help explaining the observed lepton spectrum in the LMR of PHENIX and STAR.
- The possibility of breaking a fundamental symmetry is quite open!
- Other implications?