Electromagnetic superconductivity **of vacuum** induced by (very) strong magnetic field

M. N. Chernodub

1) CNRS, University of Tours, France
2) Department of Physics and Astronomy, University of Gent, Belgium

Based on:

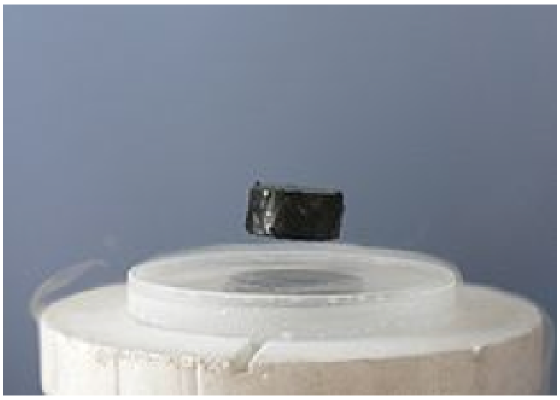
Phys. Rev. D 82, 085011 (2010) [arXiv:1008.1055]

Phys. Rev. Lett. 106, 142003 (2011) [arXiv:1101.0117]

Published on April 8, 2011 (symbolic?...)

Superconductivity

Discovered by Kamerlingh Onnes
at the Leiden University
100 years ago
at 4:00 p.m. April 8, 1911 (Saturday).

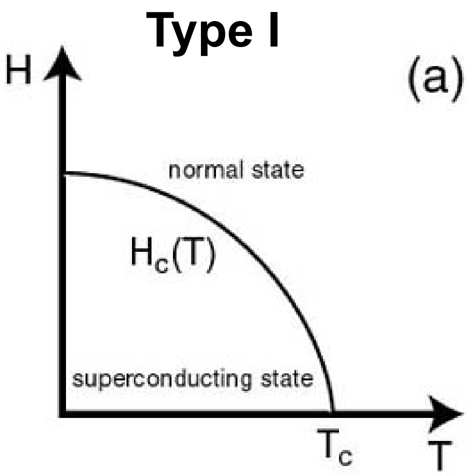


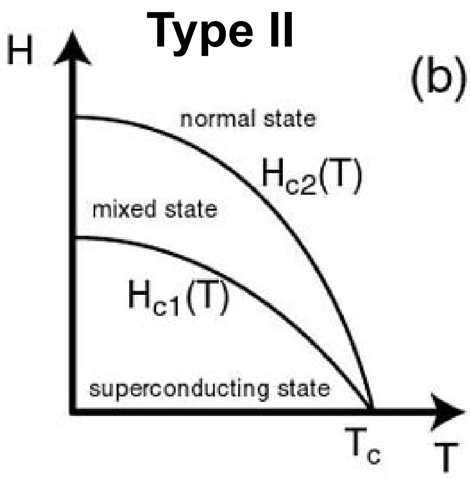
I. Any superconductor has zero electrical DC resistance

II. Any superconductor is an enemy of the magnetic field:

1) weak magnetic fields are expelled by all superconductors (the Meissner effect);

2) strong magnetic field always kills superconductivity.





Our claims:

In a background of strong enough magnetic field the vacuum becomes an electromagnetic (= "real") superconductor.

The superconductivity emerges in empty space. Literally, "nothing becomes a superconductor".

Some features of the superconducting state of vacuum:

1. spontaneously emerges above the critical magnetic field $B_c \simeq 10^{16}$ Tesla, or
$$eB_c \simeq m_\rho^2 \simeq 31\, m_\pi^2 \simeq 0.6\ \mathrm{GeV}^2$$
2. conventional Meissner effect (which usually screens the magnetic field) does not exist in the vacuum superconductor

The claim seemingly contradicts textbooks which state:

1. Superconductor is a material (= a form of matter, not an empty space)
2. Weak magnetic fields are suppressed by superconductivity
3. Strong magnetic fields destroy superconductivity

1+4 arguments in favor of the existence of this ~~crazy~~ exotic effect:

0. General handwaving arguments; (this poster)

1. Effective bosonic model for electrodynamics of ρ mesons based on vector meson dominance
[M.Ch., Phys.Rev.D 2010]; (this poster)

2. Effective fermionic model of QCD vacuum (the Nambu-Jona-Lasinio model)
[M.Ch., Phys.Rev.Lett. 2011]; (not this poster)

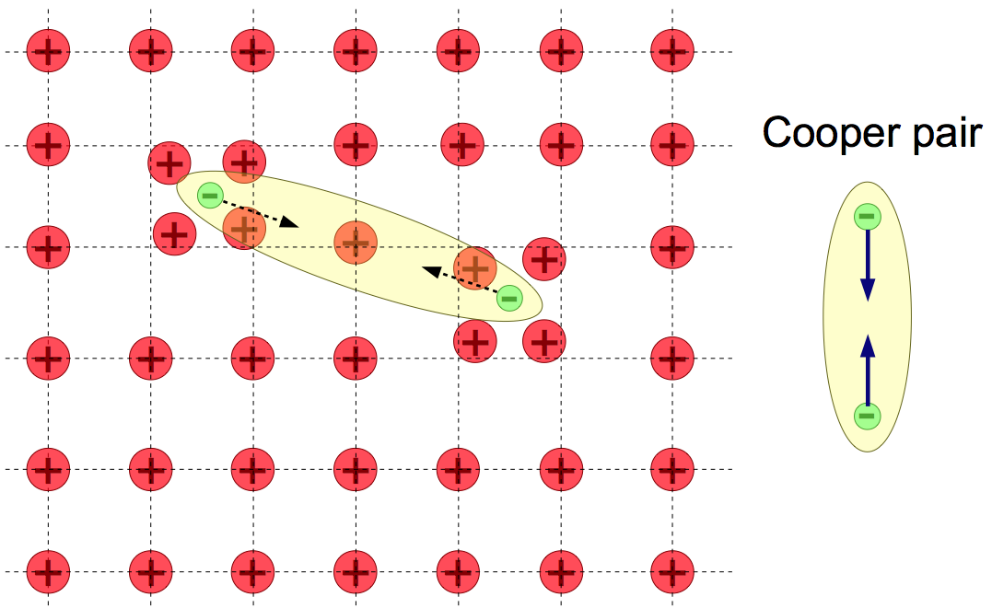
3. Nonperturnative effective models based on gauge/gravity duality (AdS/CFT)
[Callebaut, Dudal, Verschelde (Gent U.), arXiv:1102.3103 and arXiv:1105.2217];
[Erdmenger, Kerner, Strydom (Munich), 2010]
(not this poster)

4. Numerical simulation on the lattice
[ITEP (Moscow) Lattice Group, arXiv:1104.3767]
(this poster)

Conventional superconductivity

1) The Cooper pair (made of two electrons) is the relevant degree of freedom!

2) The electrons are bounded into the Cooper pairs by the (attractive) phonon exchange.



Basic ingredients (requirements) for the conventional superconductivity to occur:

A. presence of (almost free) carriers of electric charge
(otherwise electric current would not arise)

C. even weakest attractive interaction between the particles of the same electric charge
(otherwise the bound states would not form)

B. reduction of physics from (3+1) to (1+1) dimensions
(otherwise the weak attraction would not be effective)

Real vacuum, no magnetic field

1) Boiling soup of everything.

Virtual particles and antiparticles (electrons, positrons, photons, gluons, quarks, antiquarks ...) are created and annihilated every moment.

2) Net electric charge is zero.

An insulator, obviously.

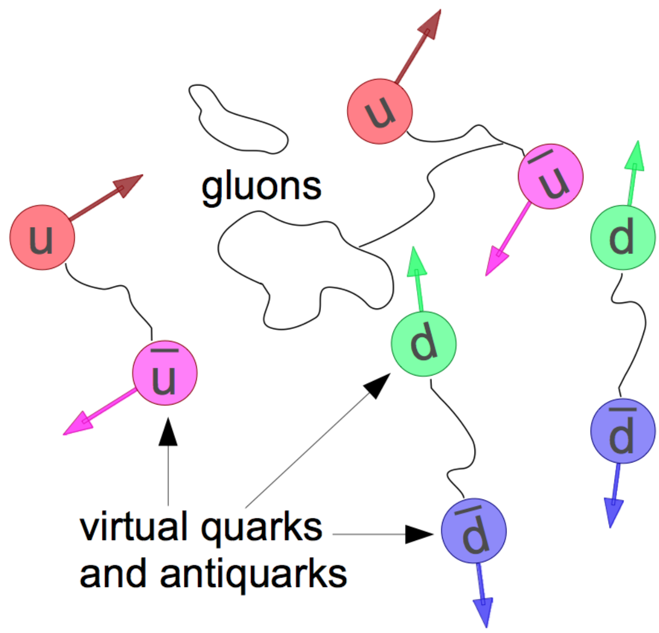
3) Strongly interacting sector of the theory:

a) quarks and antiquarks,

i) u quark has electric charge $q_u=+2\ e/3$

ii) d quark has electric charge $q_d=-\ e/3$

b) gluons (an analogue of photons, no electric charge) "glue" quarks into hadronic bounds states



Vacuum in strong magnetic field

A. **Presence of electric charges?**

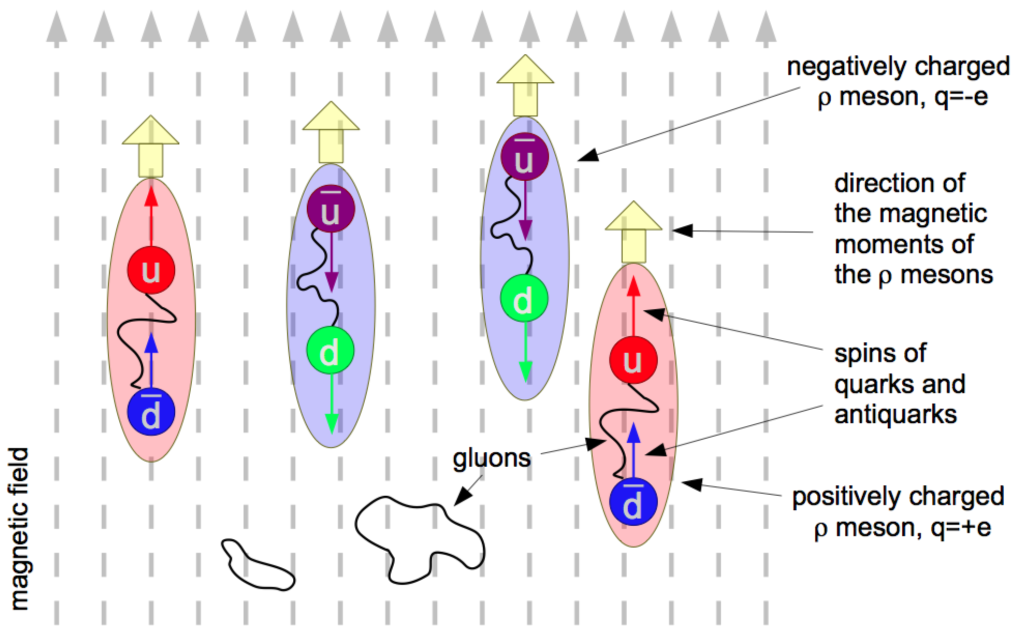
Yes: there are virtual particles which may potentially become "real" (= pop up from the vacuum) and make the vacuum superconducting.

B. **Attractive interaction between the like-charged particles?**

Yes: gluons lead to attraction of the quarks and antiquarks with the same sign of electric charges (i.e., $q_u=+2\,e/3$ and $q_{\bar{d}}=+e/3$).

C. **Dimensional reduction?**

Yes: in a very strong magnetic field the motion of electrically charged particles (i.e, quarks) becomes effectively one-dimensional, because the particles tend to move along the magnetic field.



Free electrically charged relativistic particles in magnetic field

- Energy of a relativistic particle in the external magnetic field B_{ext}:

$$\varepsilon^2_{n,s_z}(p_z) = p_z^2 + (2n - 2s_z + 1)eB_{\text{ext}} + m^2$$

momentum along the magnetic field axis

nonnegative integer number

projection of spin on the magnetic field axis

(the external magnetic field is directed along the *z*-axis)

ρ mesons: electrically charged and neutral vector particles with the quark content:

$\rho^+ = u\bar{d}$, $\rho^- = d\bar{u}$, $\rho^0 = (u\bar{u} - d\bar{d})/2^{1/2}$

mass: 775.5 MeV, lifetime: 1.35 fm/*c*

- Masses of ρ mesons and pions in the external magnetic field

$$m^2_{\pi^\pm}(B_{\text{ext}}) = m^2_{\pi^\pm} + eB_{\text{ext}}$$ becomes heavier

$$m^2_{\rho^\pm}(B_{\text{ext}}) = m^2_{\rho^\pm} - eB_{\text{ext}}$$ becomes lighter

- Dominant decay mode: $\rho^\pm \to \pi^\pm \pi^0$

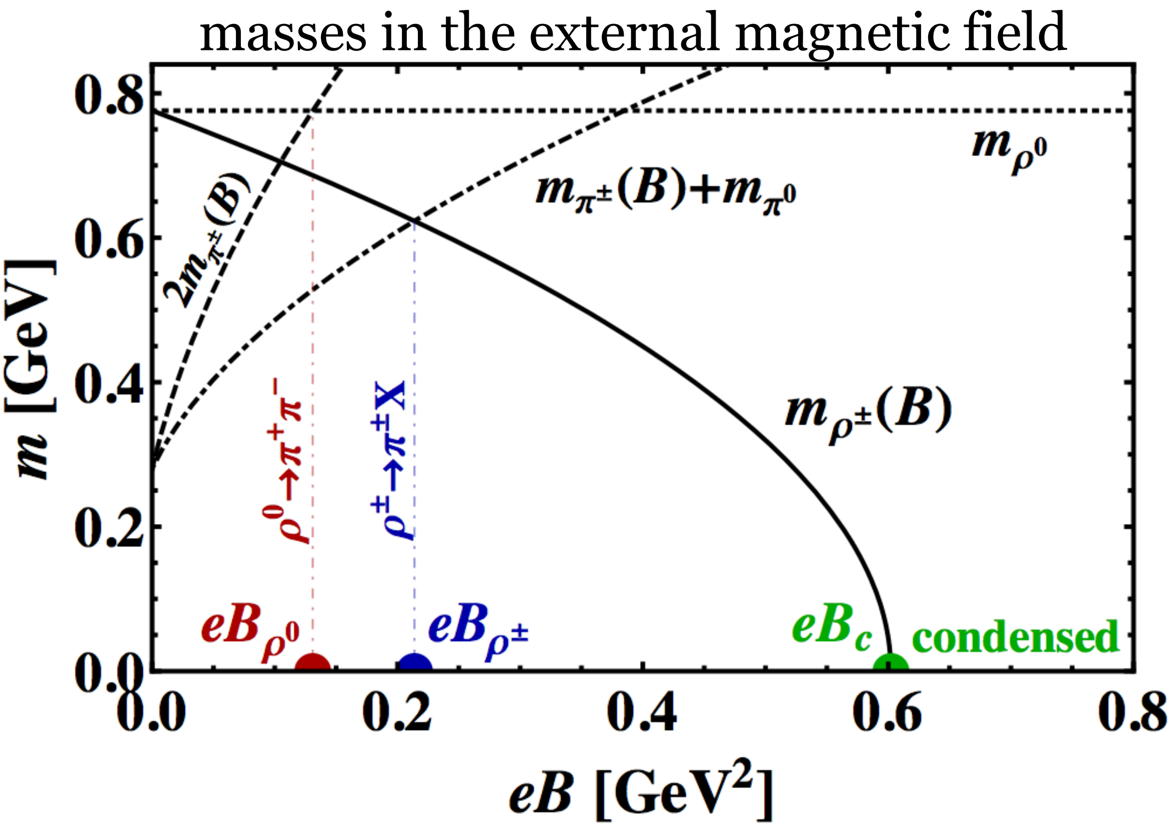
- Masses of ρ mesons and pions:

$$m_\pi = 139.6\,\text{MeV}\,, \qquad m_\rho = 775.5\,\text{MeV}$$

Condensation of ρ mesons

The $\rho^{\pm}$ mesons become massless and condense at the critical value of the magnetic field

$$eB_c \approx 0.6\,\mathrm{GeV}^2$$



Kinematical impossibility of dominant decays

The pion becomes heavier while the rho meson becomes lighter

- The decay $\rho^{\pm} \to \pi^{\pm}\pi^{0}$ stops at certain value of the magnetic field $m_{\rho^{\pm}}(B_{\rho^{\pm}}) = m_{\pi^{\pm}}(B_{\rho^{\pm}}) + m_{\pi^{0}}$
- A similar statement is true for $\rho^{0} \to \pi^{+}\pi^{-}$

Electrodynamics of ρ mesons

- Lagrangian:

Nonminimal coupling leads to *g=2*

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{2} \rho^\dagger_{\mu\nu}\rho^{\mu\nu} + m_\rho^2 \rho^\dagger_\mu \rho^\mu - \frac{1}{4} \rho^{(0)}_{\mu\nu}\rho^{(0)\mu\nu} + \frac{m_\rho^2}{2} \rho^{(0)}_\mu \rho^{(0)\mu} + \frac{e}{2g_s} F^{\mu\nu}\rho^{(0)}_{\mu\nu}$$

- Tensor quantities

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \,,$$
$$f^{(0)}_{\mu\nu} = \partial_\mu \rho^{(0)}_\nu - \partial_\nu \rho^{(0)}_\mu \,,$$
$$\rho^{(0)}_{\mu\nu} = f^{(0)}_{\mu\nu} - ig_s(\rho^\dagger_\mu \rho_\nu - \rho_\mu \rho^\dagger_\nu)$$
$$\rho_{\mu\nu} = D_\mu \rho_\nu - D_\nu \rho_\mu \,,$$

- Covariant derivative

$$D_\mu = \partial_\mu + ig_s \rho^{(0)}_\mu - ieA_\mu$$

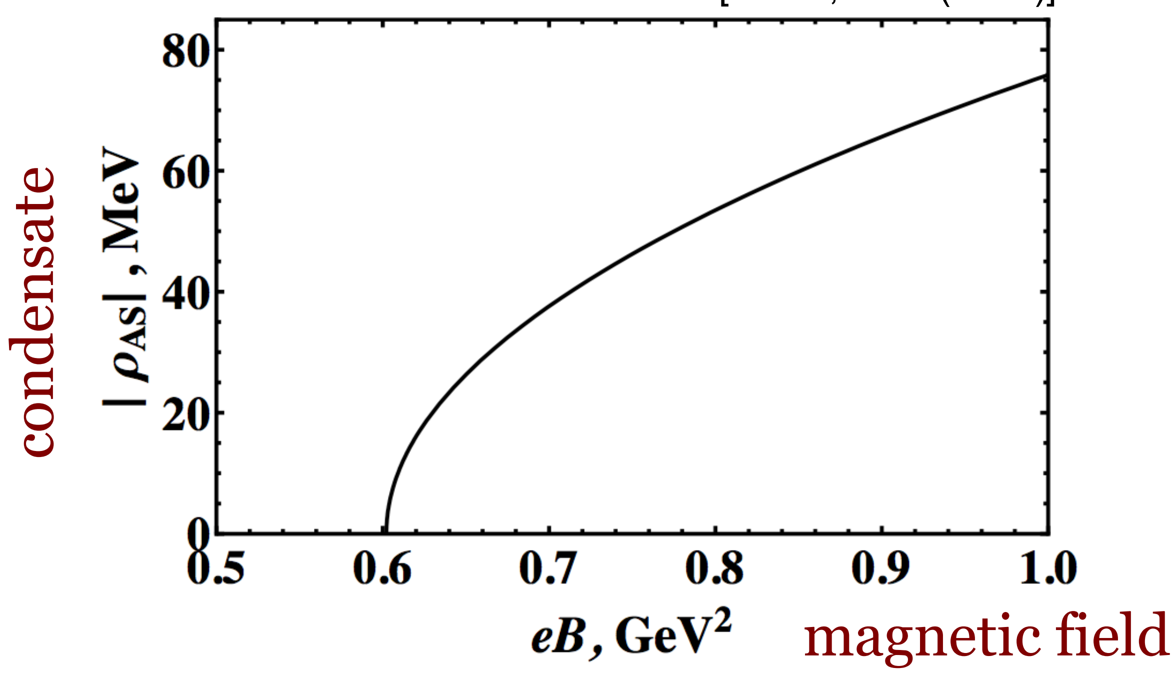
- Coupling:

$$g_s \equiv g_{\rho\pi\pi} = \frac{m_\rho}{\sqrt{2} f_\pi} = 5.88$$

[D. Djukanovic, M. R. Schindler, J. Gegelia, S. Scherer, PRL (2005)]

- Condensation of ρ mesons emerges spontaneously at strong field:

[M.Ch., PRD (2010)]



Structure of the condensates

Anisotropic inhomogeous state:

$$\rho_\mu = \begin{pmatrix} \rho_0(x) \\ \rho_1(x) \\ \rho_2(x) \\ \rho_3(x) \end{pmatrix} \to \begin{pmatrix} 0 \\ \rho_1(0,x^1,x^2,0) \\ \rho_2(0,x^1,x^2,0) \\ 0 \end{pmatrix}$$

The condensed state: $\rho_1 = -i\rho_2 = \rho$

$$\langle \bar{u}\gamma_1 d\rangle = \rho(x_\perp)\,, \qquad \langle \bar{u}\gamma_2 d\rangle = i\rho(x_\perp)$$

Depend on transverse coordinates only

$$\vec{B} = (0,0,B)$$

Locking of symmetries:

$$U(1)_{\text{e.m.}} \times O(2)_{\text{rot}} \to U(1)_{\text{locked}}$$

Abelian gauge symmetry

$$U(1)_{\text{e.m.}}: \qquad \rho(x) \to e^{i\omega(x)}\rho(x)$$

is locked with

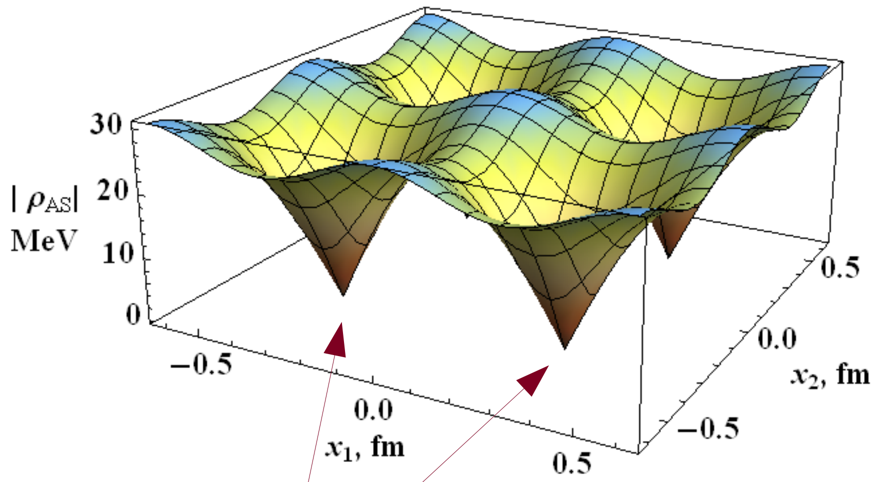
Rotations around B-axis

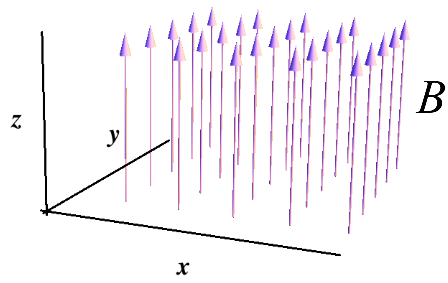
$$O(2)_{\text{rot}}: \qquad \rho(x) \to e^{i\varphi}\rho(x)$$

Condensates of ρ mesons in strong magnetic field

Example for $B = 1.06\,B$

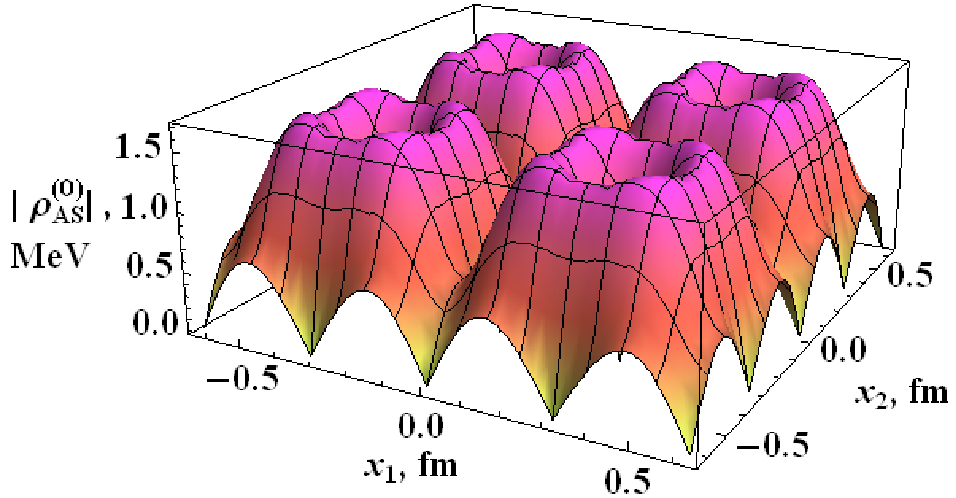
Superconducting condensate
(charged ρ mesons)





New objects, topological vortices, made of the ρ condensates
(the phase of the ρ field winds around the ρ-vortex center, the ρ-condensate vanishes)

Superfluid condensate
(neutral ρ mesons)



much weaker compared to the condensate of the charged ρ mesons

(four elementary lattice cells of the vortex lattice are shown)

Anisotropic superconductivity
(an analogue of the London equations)

- Apply a weak electric field ***E*** to an ordinary superconductor. Then one discovers accelerating electric current along the direction of the electric field:

$$\frac{\partial \vec{J}_{\rm GL}}{\partial t} = m_A^2 \vec{E} \qquad \text{[London equation]}$$

- In the QCD vacuum, we get an accelerating electric current if the electric field ***E*** is directed along the magnetic field ***B***:

$$\frac{\partial}{\partial t}\langle J_3 \rangle = -\frac{2e^3}{g_s^2}(B_{\rm ext} - B_c)E_3$$

$$\frac{\partial}{\partial t}\langle J_1 \rangle = \frac{\partial}{\partial t}\langle J_2 \rangle = 0 \qquad (\text{for } B \geqslant B_c)$$

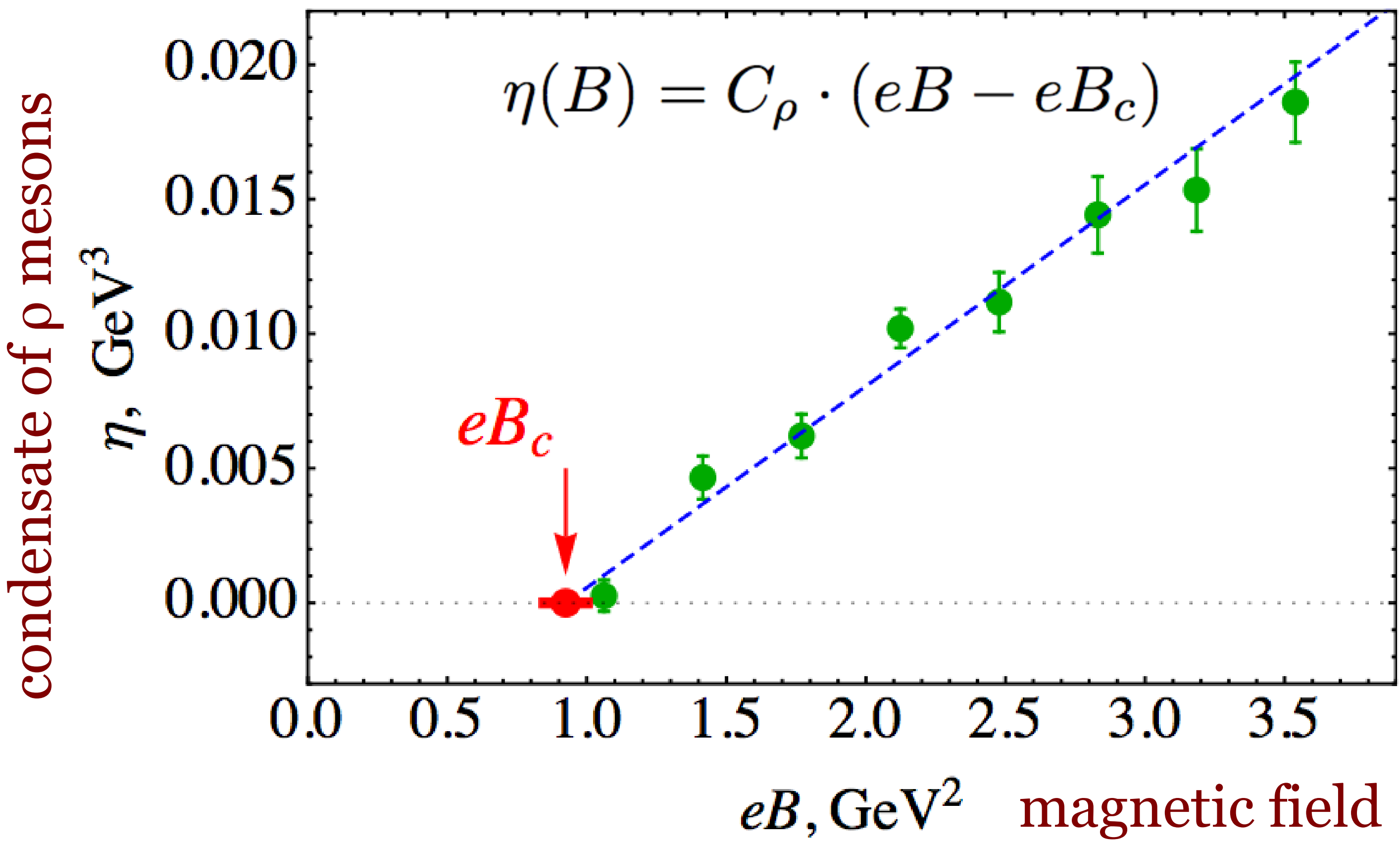
- The Lorentz-covariant form:

$$\partial_{[\mu,} j_{\nu]} = \kappa \frac{(F \cdot \widetilde{F})}{(F \cdot F)} \widetilde{F}_{\mu\nu}$$

Numerical simulation in magnetic field background

[V.Braguta, P. Buividovich, M. Polikarpov, M.Ch., arXiv:1104.3767]

Confirmation!



Numerical simulation of quenched QCD vacuum:

$$eB_c = 0.924(77)\,\mathrm{GeV}^2$$

[qualitatively realistic vacuum, quantitative results may get corrections (20%-50% typically)]

Theory:

$$eB_c \approx 0.6\,\mathrm{GeV}^2$$

$$\eta \sim \sqrt{B - B_c} \quad \text{for } B \geqslant B_c$$

Signatures of superconductivity in heavy-ion collisions???

The strength of the magnetic field required for the emergence of the superconductivity:

$$eB_c \approx 0.6\,\mathrm{GeV}^2$$

Ultra peripheral collisions

[cold vacuum is exposed to strong magnetic field]

Maximal magnetic field at the "near-misses":

$$eB^{LHC}_{\max} \approx 32\pi\gamma^{LHC}\frac{Z\alpha_{e.m.}}{b^2}$$

Dec'2010 heavy-ion run: $\gamma^{LHC} \approx 1500$

Take imact parameter: $b = 10\,\mathrm{fm}$

The peak-magnetic field at the LHC is huge:

$$eB^{LHC}_{\max} \approx 35\,\mathrm{GeV}^2 \quad \gg eB_c$$

... but short in time. Still:

$$\int eB^{LHC}dt \approx 1.2\,\mathrm{GeV} \sim \sqrt{eB_c}$$

Prediction: superconductivity is seen as abundance of $\rho^{\pm}$ mesons (in preparation)

Conclusions

- In a sufficiently strong magnetic field condensates with $\rho^{\pm}$ meson quantum numbers are formed spontaneously via a second order phase transition with the critical exponent 1/2.

- The vacuum (empty space, or, “nothing”) becomes electromagnetically superconducting.

- The superconductivity is anisotropic: the vacuum behaves as a superconductor only along the axis of the magnetic field.

- New type of topological defects,"ρ vortices", emerge. The ρ vortices form Abrikosov-type lattice in transverse directions.

- The Meissner effect is absent.

- **Signatures of the electromagnetic vacuum superconductivity in heavy-ion collisions?**

Prediction: abundance of $\rho^{\pm}$ mesons in ultra peripheral *Pb-Pb* collisions

(in preparation)