Quark-gluon plasma: from superstrings and supercomputers to superfluids*

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In this talk I briefly review our recent results related to the physics of strongly coupled quark-gluon plasma (sQGP). The methods we used include AdS/CFT-correspondence, lattice QCD simulations and condensed-matter-inspired models such as superfluidity and anisotropic hydrodynamics.

1. Holography for sQGP-like systems

In [1] we study the D3/D7-brane model at finite temperature T describing a boost-invariant viscous expanding $\mathcal{N}$=2 plasma. In presence of a magnetic field B the chiral symmetry of the system is broken down and a finite chiral condensate $c(T, B)$ is formed. The value of the condensate can be read off from the profile of the probe D7-brane embeddings. The results (apart of the description of time dynamics) are the following:

1) $c(T, B) \sim B^{3/2}$ at $T = 0$
2) $c(T, B) \sim B$ at high T
3) Critical temperature $T_c \sim \sqrt{B}$
4) Viscosity changes the moment of time when the transition occurs, see [1].

In [2] we construct a gravity dual of a boost-invariant $\mathcal{N} = 4$ $SU(N)$ super Yang-Mills plasma with a chemical potential. The resulting background takes the form of a time-dependent AdS Reissner-Nordström-type black hole. We further extend this model in [3] to the case of two chemical potentials (ordinary one μ and the chiral one μ_5) and obtain a fluid-gravity model for certain CP-odd transport coefficients hypothetically present in the quark gluon plasma at strong magnetic field B^μ and vorticity $\omega^\mu \equiv \frac{1}{2}\varepsilon^{\mu\nu\alpha\beta}u_\nu\partial_\alpha u_\beta$. The result is given by the expressions for the electric j^μ and axial j_5^μ currents in the plasma,

$$j^\mu = \rho u^\mu + \kappa_\omega \omega^\mu + \kappa_B B^\mu \,,$$

$$j_5^\mu = \rho_5 u^\mu + \xi_\omega \omega^\mu + \xi_B B^\mu \,,$$

with coefficients

$$\kappa_\omega = 2C\mu\mu_5 \left(1 - \frac{\mu\rho}{\epsilon + P}\right) \text{ - chiral vortical effect,}$$

$$\kappa_B = C\mu_5 \left(1 - \frac{\mu\rho}{\epsilon + P}\right) \text{ - chiral magnetic effect,}$$

$$\xi_\omega = C\mu^2 \left(1 - 2\frac{\mu_5\rho_5}{\epsilon + P}\right) \text{ - quark vortical effect,}$$

$$\xi_B = C\mu \left(1 - \frac{\mu_5\rho_5}{\epsilon + P}\right) \text{ - chiral separation effect,}$$

where u^μ is the four-velocity of the fluid (e.g. strongly-coupled plasma), ρ and ρ_5 are the densities of the electric and axial charges, respectively. $C = \frac{N_c}{2\pi^2}$ is the chiral anomaly, ϵ and P are the energy density and pressure of the plasma. Finally, we study anisotropic hydrodynamics with multiple anomalous U(1) currents [4] and find the following correction to the chiral magnetic effect

$$\kappa_B \approx C\mu_5 \left(1 - \frac{\mu\rho}{\epsilon + P}\left[1 - \frac{v_2}{3}\right]\right) \,,$$

where v_2 is the elliptic flow coefficient. We obtain the result first within the hydrodynamics and then reproduce it using our fluid-gravity model.

2. Lattice QCD

In [5] we study some properties of the non-Abelian vacuum induced by strong external magnetic fields, $B > m_\pi^2$. We perform calculations

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in the quenched SU(3) lattice gauge theory with tadpole-improved Lüscher-Weisz action and chirally invariant lattice Dirac operator. The following results are obtained

1) The chiral symmetry breaking is enhanced by the magnetic field. The chiral condensate is given by $\Sigma(B) = \Sigma_0 + const \cdot B^\nu$ at $T = 0$, where $\Sigma_0 = [(228 \pm 3) MeV]^3$ and the exponent $\nu = 1.6 \pm 0.2$

2) There is a paramagnetic polarization of the vacuum with the corresponding magnetic susceptibility $\chi = -4.2 \pm 0.2\, GeV^{-2}$

3) Magnetic field induces a local electric dipole moment of quarks $d_i(x) = \bar{\psi}(x)\sigma_{0i}\psi(x)$ along the field.

4) There are non-zero local fluctuations of the chirality $\rho_5(x) = \bar{\psi}(x)\gamma_5\psi(x)$ and electromagnetic current $J_i(x) = \bar{\psi}(x)\gamma_i\psi(x)$, both of which grow with the magnetic field strength. These fluctuations are present at all T and can be a manifestation of the chiral magnetic effect (CME).

In [6–8] we consider a similar setup but with two colors. We measure the Euclidean time correlator of two vector quark currents,

$$G_{ij}(\tau) = \int d^3\vec{x} \langle J_i(\vec{x}, \tau) J_j(\vec{0}, 0)\rangle$$

and restore corresponding spectral function. The latter provides us with the value of electric conductivity of the system by means of the Kubo formula. In summary, we obtain

1) At $T > T_c$ QCD vacuum is a conductor

2) At $T < T_c$ the vacuum is either an insulator (for $B = 0$) or an anisotropic conductor (for strong B)

Both facts are in favor of CME, allowing us to interpret the fluctuations of current J_i as a macroscopic current. The primary consequence of the second fact is that one can expect an enhancement of the dilepton and soft photon production rates in direction transverse to $\vec{B}$ [8].

Finally in [9] we measure the Hausdorff dimension d of the chirality distribution $\rho_5(x)$ and conclude that it depends on the resolution of a measurement. Lattice calculation without cooling ("high resolution") gives us $d = 2 \div 3$, i.e. presumably the vortex/domain-wall nature of the localization. In opposite, the cooling procedure ("resolution lowering") increases the dimensionality towards $d = 4$, i.e. restore the instanton picture of the QCD vacuum.

3. Chiral superfluidity

In [10] we argue that the sQGP can be considered as a chiral superfluid. The "normal" component of the fluid is the thermalized matter in common sense, while the "superfluid" part consists of long wavelength (chiral) fermionic states moving independently. We use several non-perturbative techniques to demonstrate that. First, we analyze the fermionic spectrum in the deconfinement phase ($T_c < T < 2\,T_c$) using lattice (overlap) fermions and observe a gap between near-zero modes and the bulk of the spectrum. Second, we use the bosonization procedure with a finite cut-off and obtain a dynamical axion-like field out of the chiral fermionic modes. Third, we use relativistic hydrodynamics for macroscopic description of the effective theory obtained after the bosonization. Finally, solving the hydrodynamic equations in gradient expansion, we find that in presence of external electromagnetic fields the motion of the "superfluid" component gives rise to the chiral magnetic, chiral electric and dipole wave effects. Latter two effects are specific for a two-component fluid, which provides us with crucial experimental tests of the model.

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