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Holographic model of exciton condensation in double monolayer Dirac semimetal

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We consider a holographic model of exciton condensation in double monolayer Dirac semimetal. Exciton is a bound states of an electron and a hole. Being Bose particles, excitons can form a Bose–Einstein condensate. Exciton condensation might be easier to achieve in case we have electrons and holes in different layers of a double layer two dimensional structure. An insulator between the layers prevents electron and holes from annihilation thus increasing exciton lifetime. There are two possible types of condensates. In first case both the electron and the hole forming the exciton are in the same layer (intralayer condensate), in the second case the electron and the hole are in different layers (interlayer condensate). The exciton condensation in double layer systems in magnetic field has been extensively discussed in condensed matter literature (see, for example, [1–3]). In case the electron quasiparticles can be described as massless (gapless) Dirac fermions, exciton condensation is similar to the spontaneous chiral symmetry breaking in Quantum Chromodynamics. The condensate breaks the chiral symmetry of massless fermions creating an energy gap in the spectrum. From this point of view the chiral symmetry of graphene was discussed in [4]. This analogy allows to test some basic notions of Quantum Chromodynamics in condensed matter systems.

We study how the condensates depend on the distance between layers and the mass of the quasiparticles in presence of a strong magnetic field. The electrons and holes in the layers have quasirelativistic dispersion law $\epsilon(p) \sim \sqrt{m^2 + p^2}$. In order to take into account possible strong Coulomb interaction between electrons we use holographic appoach. The holographic model consists of two $D5$ branes embedded into anti de Sitter space. This model was introduced in [5] for zero temperature and mass case. Finite temperature was discussed in [6]. The condensates are described by geometric configuration of the branes. We show that the distance between layers at which interlayer condensate disappears decreases with quasiparticle mass.

The model consists of large number N of $D3$ branes that create $AdS_5 \times S^5$ geometry with metric

$$ds^2 = \frac{d\rho^2}{\rho^2} + \rho^2 \left(-dt^2 + dx^2 + dy^2 + dz^2\right) + \\ + d\psi^2 + \sin^2\psi\, d\Omega_2^2 + \cos^2\psi\, d\hat{\Omega}_2^2. \qquad (1)$$

Here AdS_5 stands for a five-dimensional anti de Sitter space while S^5 is a five dimensional sphere. The two layers of Dirac semimetal are modeled by two $D5$ branes embedded into this geometry. We treat them in probe approximation that is we do not consider the $D5$ branes back-reaction on the geometry. AdS_5 geometry is dual to the $\mathcal{N} = 4$ super Yang–Mills (SYM) theory. Each of the $D5$ branes supports massless Dirac fermions and connected brane configuration gives the fermions mass. The $\mathcal{N} = 4$ SYM leads to the electron interaction energy proportional to $1/r$ and does not take into account screening.

$D5$ branes are stretched along x, y, ρ, t directions and also wrapped around of the two dimensional sphere. Separation between branes and the radius of the sphere depends on the radial coordinate ρ. The energy of the $D5$ brane system is given by Dirac–Born–Infeld action. There is magnetic field B perpendicular to the branes.

Formation of interlayer condensate corresponds to the connected configuration of branes. We compare energies of connected and disconnected branes. The lowest energy configuration corresponds to the equilibrium state of the system. Our numerical analysis yields phase diagram in coordinates m – mass of the quasiparticles, L – layer separation. We find that for large enough separation $L > L_c$ interlayer condensate disappears. Critical layer separation decreases with mass. The results are summarized in Fig. 1. Above the yellow line there is no solution with interlayer condensate and above the blue

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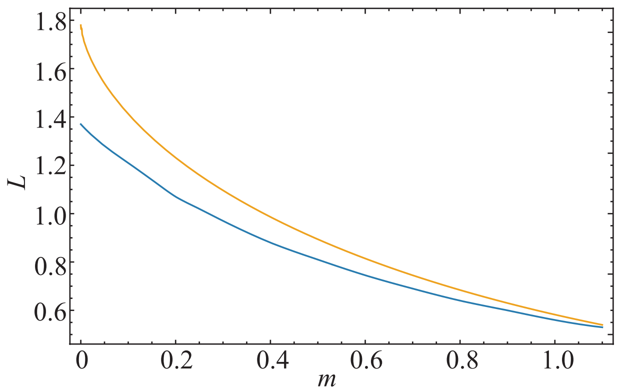

Fig. 1. (Color online) Phase diagram. Above the upper line solution with interlayer condensate does not exist. Below the lower line solution with interlayer condensate has lower energy

(lower) line phase with interlayer condensate is energetically disfavored. As the mass increases, the two lines become closer. Values of mass are given in dimensional units. Units of mass are proportional to $\sqrt{B}$ while units of length are proportional to $1/\sqrt{B}$.

This results cannot be checked directly against experiment because we have not identified the parameters of holographic model in terms of physical parameters of the system. However, the model has some methodological value enabling us to access the properties of the system in strong coupling regime. The holographic model confirms that exciton condensate exists for the finite fermion mass even for the strong coupling case.

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