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A holographic model of quantum Hall transition

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Abstract

We consider a phenomenological holographic model, inspired by the D3/D7 system with a $(2+1)$-dimensional intersection, at finite chemical potential and magnetic field. At large 't Hooft coupling the system is unstable and needs regularization; the UV cutoff can be decoupled by considering a certain double scaling limit. At finite chemical potential the model exhibits a phase transition between states with filling fractions plus and minus one-half as the magnetic field is varied. By varying the parameters of the model, this phase transition can be made to happen at arbitrary values of the magnetic field.

1. Introduction and summary

In condensed matter physics, the quantum Hall effect (QHE) is a general feature of $(2+1)$-dimensional, low-temperature electron systems subject to strong magnetic field B [1–3]. At zero temperature, by varying the magnetic field B, the transverse conductivity σ_{xy} experiences sudden jumps between quantized values (plateaux)

$$\sigma_{xy} = \nu \frac{e^2}{h} \,, \tag{1.1}$$

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where ν is the filling fraction, defined as the ratio of the charge density to the magnetic field, and it can assume integer (IQHE) or fractional values (FQHE). Although the IQHE is well explained by considering localization–delocalization processes for free electrons moving in a random potential, a complete understanding of the fractional case, which relies on the strong interaction between electrons, is still lacking. Remarkably, in both cases experiments show the presence of scaling behavior with respect to the temperature. Indeed, when the temperature T is increased, the profile of the transition between plateaux is smoothed out and it is described by a power law of the temperature

$$\frac{\partial \sigma_{xy}}{\partial B} \propto T^{-\kappa} \,, \tag{1.2}$$

while at the same critical value of magnetic field the longitudinal conductivity exhibits sharp spikes. Moreover, the width of the region in which the transition occurs (or, equivalently, in which the longitudinal resistivity is different from zero) scales with the temperature

$$\Delta B \propto T^{\kappa} \,. \tag{1.3}$$

The exponent κ has been experimentally measured for different materials and between different pairs of plateaux (both in the integer and fractional case). Initially, the same value $\kappa \sim 0.42$ had been found [4–6] and this was interpreted as a signal of universal behavior. However, further investigations suggested that the value of κ may be in general dependent on the experimental apparatus and the plateau transition considered [7,8] even if, concerning the IQHE, recent papers conjectured that the presence or absence of universality is affected by the range of the disorder potentials in the sample [8].

Due to the presence of strong interactions, it is difficult to understand the physics underneath the plateau transitions in the QHE. Therefore, it would be interesting to have a holographic model of this phenomenon and to investigate the finite temperature behavior. In this paper we focus on the phase transition at zero temperature, leaving the non-zero temperature analysis to future work. There is a wide literature concerning the QHE and its holographic description. Refs. [9,10] studied quantum Hall plateaux using holographic D-brane constructions where the fermions are represented by open strings living on the $2+1$ dimensional intersection of D3 and D7 system. This approach was pursued further by several authors in various D-brane contexts [11–13]. Another interesting approach is based on the observation that some experimental results can be explained by a discrete duality group relating the different quantum Hall states. Refs. [14,15] and, more recently [16], considered a holographic model encoding this feature based on Einstein–Maxwell axion-dilaton action. In this description, the quantum Hall states are represented by dyonic black holes and it is possible to capture the quantization of the Hall plateaux. Other work on holographic quantum Hall physics includes [14–48].

Although these attempts succeeded in explaining some of the features of QHE such as the presence of constant conductivity plateaux, the description of phase transitions between different quantum Hall plateaux remains elusive. In this paper we consider a holographic model that exhibits such a transition. We follow the approach of [49–52] where the physics of interacting three-dimensional fermions was argued to be holographically related to the physics of a tachyon field in the bulk of AdS space. The three-dimensional fermions coupled to four-dimensional $\mathcal{N}=4$ super Yang Mills are realized as a low energy theory of the D3/D7 branes configuration in which a small number of D7 branes intersects a large number of D3-branes along $2+1$ dimensions. The holographic description involves finding a profile of the D7 brane propagating in the $AdS_5 \times S^5$ space; there is a (below Breitenlohner–Freedman bound) tachyon mode which