Deciphering fermionic matter: from holography to field theory

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Citation

Meszéna, B. (2016, December 21). *Deciphering fermionic matter: from holography to field theory*. *Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/45226

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Issue Date: 2016-12-21

Summary

The theoretical description of fermionic system with strong interaction is a very challenging open problem in physics. The most notable (but far from the only) experimental realization of this type of systems are the cuprate superconductors which have zero electric resistivity. Even if one has a good microscopic model for the description of these materials it is very hard to translate it to macroscopic observables which in principle can be experimentally checked.

The problem is that in case of a relevant interaction one can not Taylor expand in the coupling constant in the low-energy regime in which we are most interested. On the other hand, because of the fermion sign problem Monte Carlo numerical techniques (which are succesful with bosonic models) do not work for fermions at finite density.

This thesis is devoted to the applications of several methods to the research area described above. The common theme of these techniques is that they are (partly) motivated from high-energy physics: the research area which deals with particle physics, string theory etc.

In the Introduction chapter of this thesis we review some aspects of Fermi liquids (a state of matter we understand very well) and non-Fermi liquids (where our knowledge is limited). Then we introduce some methods which can be applied to condensed matter system. These include large-N methods, conformal field theories and holography. In the discussion of the last point we also show how these ideas come together in AdS/CFT to form a duality between weakly coupled gravitational theories and strongly coupled large-N systems. After these general ideas we turn to the presentation of several research projects.

In Chapter 2 we consider a holographic model for dynamical pairing in superconductors. The BCS-theory describes succesfully the pairing in superconducting materials when the normal phase of the metal is a weakly interacting Fermi liquid. However, in high-T_c materials the high-temperature phase possesses non-Fermi liquid behavior. As we show in the introduction, AdS/CFT predicts non-Fermi liquid states in some holographic models. It is reasonable therefore to study the superconducting pairing in non-Fermi liquids using AdS/CFT. We take the first step towards this goal by studying the pairing in a holographic Fermi-liquid where

the spacetime geometry is AdS with a hard wall. For this we introduce a pairing interaction between fermions and an order parameter field. Apart from the fixed background geometry we solve the fermion-gauge-scalar system self-consistently. We show that by studying this somewhat simplified model we still find rich, sometimes novel physics. We also argue that in case of interaction terms in the bulk there are subtleties in the usual dicitonary rules between AdS and CFT.

In Chapter 3 we analyze an interesting strongly coupled condensed matter model with a novel field theoretical method. The system at hand consists of fermions at finite density (forming a Fermi-surface therefore) coupled to a dynamical order parameter field in 2+1 dimension. This is the simplest model which displays non-Fermi liquid behavior after tuning the mass of the boson to its critical value (which is zero in our case). As this system is non-perturbative therefore we need to rely on non-standard techniques. We make two approximations. Firstly, we assume that the Fermi surface curvature is small. Secondly, we use the so-called quenched approximation, i.e. we ignore all fermion loops. Formally, this can be systematically achieved by introducing the number of fermion flavors (N_f) and taking the $N_f \to 0$ limit. With these simplification we find the explicit form of the fermion spectral function. This exhibits non-Fermi liquid behavior and also the splitting of the Fermi surface.

In Chapter 4 we continue our investigation by allowing N_f to be nonzero while keeping the Fermi surface curvature small. An important simplification is that it turns out that for small N_f the boson propagator is corrected only at one-loop. This so-called Landau-damping has an important effect to the IR region of the fermion Green's function. We analyze this two-point function in order to understand how it interpolates between the strongly Landau damped form and the quenched result.