Translational symmetry breaking in holographic strange metals

Balm, F.A.

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7. Conclusion

The central theme of this thesis has been the exploration of holographic systems where translational symmetry is explicitly broken in an inhomogeneous manner. In particular, we were interested in systems that have some relevance to condensed matter physics, such as the cuprate strange metals. By solving the Einstein equations for a corrugated black hole in negatively curved spacetime, we were able to explore thermodynamical and transport properties of strongly coupled systems where translational symmetry is broken. There have been several results that appear to show similar behaviour to what is observed in physical experiment. But, as we have tried emphasise, the holographic results are not to be interpreted literally, and instead need to be digested carefully in order to properly interpret what holography is telling us.

This is of great importance in chapter 4, which deals with holographic fermions. The spectral function of these fermions can be thought of as an analogue to what is measured in ARPES experiments in the laboratory. We were able show that at weak translational symmetry breaking, the physics of the probe holographic fermions we use is not much different than that of normal fermions undergoing weak potential scattering in a periodic potential. This changes drastically when the lattice strength is raised into the non-perturbative regime. Here instead, we see that the Fermi surface appears to end at a point instead of forming a continuous sheet throughout the $x-y$ plane. The root cause of this turns out to be the proximity of a sheet of poles to a sheet of zeros in the complex frequency-momentum space. This is rather remarkable, as in conventional materials the Fermi surface is typically closed. This phenomenon also appears to be present in ARPES experiments on some cuprates in the pseudogap phase for example.

It is tempting to get excited and take holography as a physical explanation of what is happening in the lab. As we are cautioned, we have to admit that the large-N nature of the dual quantum field theory, the probe status of the fermions and the unidirectional nature of the potential all contribute to our inability to interpret the results of holography in a condended matter physics setting. The line of zeros that causes the Fermi arc-like phenomenon is also purely holographic in origin, relying on some special range of masses that allow us freedom in the choice of quantization for the bulk fermion. Peering through this is perhaps something interesting; namely, if there is some phenomenon that would cause a line of zeros to come close to the Fermi surface, similar extinction effects might be observed in strongly coupled systems where translational symmetry is strongly broken, e.g. the strange metal. Therefore, purely phenomenologically, holographic fermions could make a useful numerical exploration tool.

Chapter 6 takes a different approach. This chapter shows perhaps the deepest and most high-precision test of the application of holography to condensed matter theory yet. It takes aim simultaneously at the three key mysteries to the cuprate strange metal: the linear-in-temperature resistivity at low temperature, the observed Planckian relaxation rate, and the indifference of the DC conductivity to the good-to-bad-metal transition. The holographic Gubser-Rocha model presents an excellent testing grounds for this. By exploring carefully the thermodynamics and conductivity in the weak lattice regime, we were able to show that hydrodynamical flow can not only be used to reproduce the Drude-like line shape, but also the transition into the 'bad metal'/Mid-IR peak that is seen in experiments. Intriguingly, even though the peak appears through an effective diffusive-to-propagating crossover of the poles of the Green's function, we can show that the parameters governing the low-frequency conductivity evolve smoothly and therefore that the DC resistivity cannot be sensitive to this crossover.

The large lattice 'incoherent metal' regime shows a completely different story. Here, nothing of our hydrodynamical intuition remains, as momentum conservation is absolutely not present. The slope of the resistivity appears to saturate with increased lattice potential to some value that is of the order of the Planckian scale. The conductivity in this regime can be understood in terms of the thermal and charge diffusivities. The first of these is rather insensitive to the translational symmetry breaking, showing a universal temperature scaling which can be understood from quantum chaos and rapid scrambling in the black hole, but it disappears as the lattice becomes increasingly strong. On the other hand the charge diffusivity saturates, but it evades such a clear understanding as the thermal diffusivity.

Again, we must ask ourselves, what do these black holes actually tell us about the physical experiment, and where does it fall short? First of all, there are also significant discrepancies. The Umklapped sound peak, which is observed to be the peak responsible for a significant fraction of the large-lattice conductivity, is not seen in experiment. Likewise, quantum critical power law tails seen in experiment are not reproduced directly here. However, both of these discrepancies can be understood, and one can reasonably pose conditions under which these phenomena might match.

What remains underneath then is that the real, number one claim that we can draw from these results is that holography is arguing for a fundamentally different kind of physics than that of the Fermi liquid to be governing the strange metal phase. Is it possible that it is hydrodynamics that governs the physics of the strange metal, and is that rooted in the densely many-body entangled nature of the fermions? There are some ways of exploring this in experiment, but with the currently available data it is not possible to make a conclusive decision either way.

It is my hope that the works presented in this thesis have made a sufficiently strong case that the holographic lattice offers a highly intriguing and suggestive view of condensed matter physics. What is more, the interest on the experimental side into holographic claims seems to be increasing. One can think here of recent data suggesting $z \to \infty$ scaling, and perhaps the soonest revolution will come from the new mesoscopic devices that can potentially be used to detect hydrodynamic behaviour in strongly coupled electronic systems. If the coin falls the right way, the AdS/CFT correspondence will finally be truly cemented as a tool for studying condensed matter physics, in particular in systems where strong correlations and dense entanglement are present. The holographic lattices will then have yet another part to play, and hopefully this work can be of use for future generations of physicists.