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Translational symmetry breaking in holographic strange metals

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Summary

Progress and discoveries in the physical sciences can often come from unexpected places. For several decades now, a part of the theoretical physics community has been faced with a conundrum: certain superconducting compounds, the so-called cuprate strange metals, display characteristics that cannot be explained with the theoretical models that we have available to us. The most striking of this is the electrical resistivity of these metals. This increases linearly with temperature over a very wide range of temperature, from far below freezing to far above boiling temperatures. This is at odds with conventional wisdom regarding metallic compounds, which would for example predict quadratic scaling at low temperatures. This is only one of many observations.

The reason for our limited understanding of the phenomena of the strange metal has several root causes. For one, the mathematical tools we have at our disposal only work well if the electrons in this material are not strongly influenced by either each other or the underlying crystal structure of the material. In the strange metal, both of these conditions are violated. Computers are also of no great help: while our classical computers are great at dealing with classical data, encoded in 1's and 0s, they are spectacularly unsuited to deal with problems where quantum mechanics plays an important role. In the future quantum computers might be able to shed light on these problems, but the technology is simply not there yet.

It may appear we are stuck. However, from the unlikely realm of string theory comes a surprise: the holographic duality. Here string theory is not used as a model of the finest structure of the universe. Instead, it was found that there exists a remarkable duality between the structure of the mathematical equations that describe strongly interacting quantum systems, similar to the strange metal mentioned above, and the theory of General Relativity. The details of this are intricate, but it offers us an olive branch: we are able to translate the original problem that we could not solve, into a problem of General Relativity, one involving black holes and negatively curved space times. Solving this problem is still hard, but no longer impossible. Unfortunately we are not able to model precisely those physical systems of interest, and must always use some proxy that can never be realised in the laboratory. However, thorough investigation of the results can still give rise to universal answers that cannot be arrived at through any other known means.

In this thesis, the duality was investigated with high precision. In particular, we focused on what effects we observe when we try to also pull the crystal structure of the metals through the duality. We looked at several observables such as resistivity and conductivity, but also spectral functions of fermions in the presence of such a lattice. This is a technically difficult thing to accomplish, and we have developed new codes to solve these black hole problems to high accuracy using supercomputers. The main difficulty here comes from the complexity of Einstein's equations, that get monstrously large when a crystal lattice is included.

After several years of hard work, ironing out all bugs and problems in the code, we were able to use this setup to great effect. Chapter 4 for example shows that the effect of the crystal lattice can lead to very similar behaviour as is found in photoemission experiments. However, the duality is only a phenomenological tool: we show that we can reproduce a similar looking effect, but we have gained no greater insight into what might cause these effects in the real materials in the lab.

The heart of this thesis is formed by Chapter 6. In this chapter, we take a different approach to the duality. Here we treat our supercomputer codes truly like an experiment, and we try to see if we can, in the language of the duality, find explanations or suggestions for the observed mysteries in the strange metal. We are able to see and explain many of the phenomena of the strange metal in our framework. Above all, what we find is that holography appears to argue for there to be a fundamentally different physical principle to be on the foreground when it comes to the strange metal. Rather than electrons zooming around in metals, we should think instead in a truly quantum (supreme) manner: all intuition we have from our everyday life should go out of the window, and instead we should be concerned with the most exotic quantum physics.

While the data is extremely suggestive of this, the jury is still out on this one. The viewpoints of holography are highly unconventional in the condensed matter physics community, and often dismissed out of hand. We propose certain measurements that could potentially be done that can shed more light on the veracity of our statements, but these experiments may be many years away still. On the other hand, with a recent uptake in attention from the community at large, perhaps the time is ripe for the holographic duality to become another common tool in the toolbox of theoretical physics.