Strange metals

Afiq Hatta

December 3, 2019

The structure of the talk. - Theory of metals - Theory of superconductors - Something goes wrong - high temperature superconductors come about how do we understand this? - A hint of what's going on - linear resistance above the critical temperature - this is a hint of some deeper structure.

1 Introduction

Now initially when I started making this talk, I knew I wanted to do something on the topic of strange metals. Initially, I started by you know, taking a paper, trying to reproduce and explain the derivations and so on. But a lot of people in this room know me, and I'm sure that everyone agrees that I'm a political guy. I'm a big fan of how mathematics can be used for the betterment of society, how people should use it, and I care about wider applications. So I'm going to use that as a starting point from this talk. I'm a big believer in using the human cause for motivating mathematics, so this is how I'll approach this.

As I'm sure everyone in this room is aware, the Earth is basically frying out. We're in a climate crisis. And, in a world in which we're trying to make technology more efficient, superconductors are a type of material which everyone should care about. What are superconductors? Basically, they're materials that allow electricity to pass through them with zero resistance when they're cold enough. Now, does anyone know the useful things we can do with? Well since superconductors allow electricity to flow through them very effectively, we can create very powerful magnetic fields.

1.1 Why are superconductors useful?

First and foremost, being able to transmit electricity with zero resistance is less wasteful, so it's better for the environment. Well, if we have zero resistance, the powerful electric current can generate a really, really strong magnetic field. We call this temperature the 'critical temperature'. Now, why exactly this occurs is still quite magical and mysterious.

1.2 The problem with superconductors

This sounds great, and you might ask for example, why doesn't everyone use superconductors? But the issue with this is that superconductors have to be very cold to work. Cooling these objects is often very expensive and difficult, and the expense and energy consumption of cooling Now, we don't understand superconductors very well - and recently we've discovered some superconductors which behave in that way at higher temperatures than expected.

So know, everyone's like 'Oh shit' how do we solve this problem, and what's really going on? So, I'll be taking us on a journey through what we know about metals, all the way up to how black hole physics can help us understand what's going on.

High temperature superconductors are materials which can behave like superconductors above $-200°C$. Currently, we can cool some superconductors we know with liquid helium and liquid nitrogen, but not dry ice! Cooling is expensive and inefficient, and currently this is the main reason why we don't use it.

2 What we thought we knew!

2.1 Fermi liquid Theory

Our current and most ubiquitous model for metals is something called Fermi liquid theory, which was put forward by the eminent Soviet physicist Lev Landau. And up until the 1950's, this theory has actually worked out really well for us in modelling the phases of matter we can find metals in.

Metals are weird and hard to understand. Roughly speaking, some available tools we know about to model metals are a kind of particle called electrons. Electrons are a kind of particle called fermions, and one of the things that make fermions special is that they obey a rule called the Pauli-exclusion principle. Those familiar with quantum mechanics might recognise the term 'Fermi-Dirac statistics'.

Now, what does the Pauli-exclusion principle say? It says that we can't have two electrons in the same place at the same time. This is a condition in which rules out a lot of models which we can have on metals.

This predicts the emergence of something called quasi-particles, which are blob like objects which run through the material and behave like particles in their own right. Now, why do we use the term 'quasi'? Well this is a way of using the English language which I don't like, but since every one does it I'll talk about it. 'Quasi' is used to describe this because the mechanism is somewhat describing 'emergent behaviour'.

This is important because Fermi liquid theory predicts that these quasi-particles, in a rather surprising way, don't really interact at all with each other. Now, even though there's repulsion from the original electrons, since these quasi-particles emerge, it's shown that it conducts electricity.

This is good - so we've come up with a model, it predicts the existence of quasi-particles in metals, and then it says well, these quasi-particles don't cause many problems for us in terms of information.

How does this work?

In particular, we understand the story of how 'conventional superconductors' work. I'll describe this phenomena here.

2.2 The theory of superconductors up until (relatively recently)

The theory of superconductivity up until now relied on a fairly simple mechanism. It relies on a concept called 'Cooper pairs', where when an electron moves forward, it drags with it other surrounding positively charged atoms. Then, what happens is that this creates a small pocket of positive charge which attracts an electron behind it. This allows the two electrons to shoot basically shoot past the metal at high speeds.

3 What goes wrong?

So, we've got this very nice model of metals, which worked quite well for until the 1980's. In 1986 however, George Bednorz and Alex Muller discovered a new kind of material. These materials are metals which exhibit superconductivity at slightly higher temperatures.

3.1 The weird phenomena which puts everything into question

'Strange metals' come into the picture because they are a phase of matter where resistance varies with temperature in ways which we do not expect. At temperatures slightly higher than the super-conducting phase for example, we see that resistance varies linearly with temperature.

In particular, we have that resistance increases linearly in temperature, which is weird - usually it increases quadratically, something predicted by Fermi liquid theory. We have that

$$\rho \sim T$$

This article will cover some of the modelling that has been done with these kinds of materials. Currently, materials we know which exhibit this kind of behaviour are high temperature cuprates, ruthenium oxides and iron pnictides.

(Insert graph here)

3.2 What is AdS / CFT?

Explanations for this behaviour. To go any further, I'm going to relate this problem to how physicists have been trying to unify the theory of gravity and quantum mechanics. Basically, we have theories of how things work on a small scale, and this roughly speaking concerns quantum mechanics.

And, we also have a really good theory of how things work on a large scale. In particular, the theory of general relativity, which is our current best theory of gravity.

Now, since this is a mixed audience, I'm going to try and sum this up by saying that this is an insanely hard problem to solve - the problem of 'quantum gravity'. It's a problem that physicists have been trying to tackle since the theories of gravity and quantum mechanics have been developed.

Imagine trying to watch a movie with 3d glasses. What you might see, that if you don't wear the glasses, is a weird looking image. It's in 2d, and obviously is on the screen. But, when we put on our 3d goggles, we see that the image 'pops' out from the screen. Now, this is interesting.

This is

https://arxiv.org/pdf/1310.4319.pdf

3.3 The SYK Model

What are the links between the SYK model and the correlation functions, for example? https://arxiv.org/pdf/1807

3.4 The status quo - Fermi liquid theory for metals

Crucially, we predict that resistance varies with the square of temperature. However, this is not something we observe in real life.

3.5 The Phase diagram of strange metals

3.6 What has failed before

Other theories fail to not make quasi-particles. Quasi-particles act like small particles through the metal, which gives resistance.

3.7 The SYK model

Random pairwise movements. - Further work by Xue-Yang Song on strongly correlated metal built from SYK models.

3.8 Quantum entanglement from inside and outside a black hole horizon

Links since we have similar equilibration time.

4 AdS / CFT

d spacetime quantum system with no quasi-particles dual with d + 1 dimensions. Quantum entanglement leads to an emergent spatial direction.

5 References

https://arxiv.org/pdf/1807.03334.pdf