Emergent electronic phases in cuprate strange metals

Smit, S.

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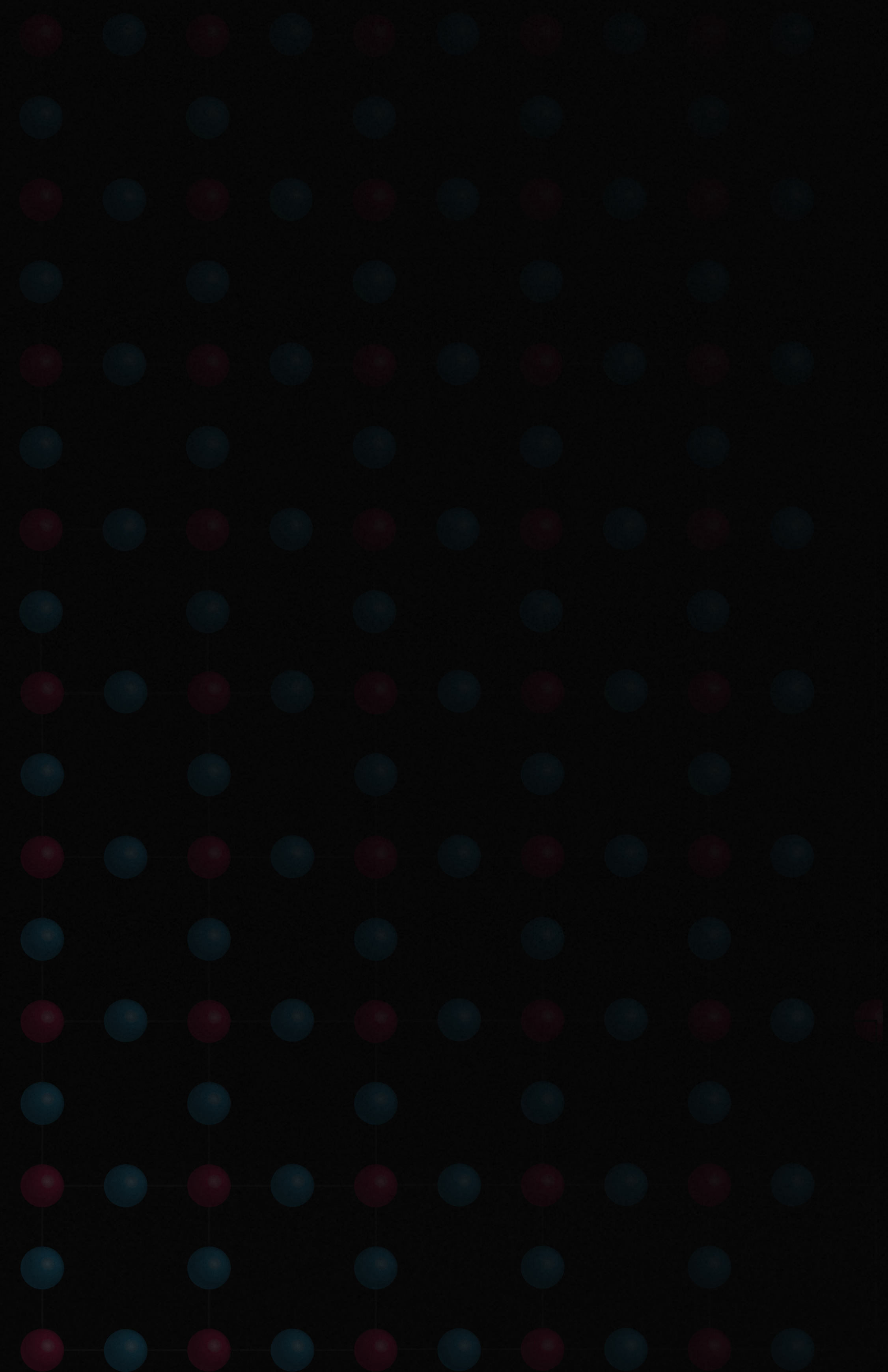

Emergent electronic phases in a cuprate strange metal Steef Smit

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Faculteit der Natuurwetenschappen, Wiskunde en Informatica

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INTRODUCTION

The study of condensed matter concerns some of the most fundamental topics in physics. Ranging from the macroscopic behavior of flowing liquids, to the microscopic laws of quantum mechanics that rule the behavior of electrons in solids, the common goal is to capture the physical laws governing the world around us, as well as finding ways to use their properties in real world applications.

Among the most fascinating subjects in condensed matter is that of strongly correlated electrons. Quantum matter containing strongly correlated electrons can display surprising properties that go well beyond our classical understanding. These properties require descriptions that do not treat only single electrons, but rather the emergent behavior caused by the collective behavior of many, many electrons together. These are the 'emergent electronic phases' in the title of this thesis. The most famous examples of such emergent electronic phenomena are magnetism and high temperature superconductivity, with the latter one still not completely understood, more than 35 years after its discovery.

The research in this thesis is focused on a material that has remarkable properties due to its strongly correlated electrons. It is a layered ceramic compound containing copper and oxygen (a 'cuprate', contributing the second part of the title) and up to four other elements in varying concentrations: $(Pb,Bi)_2Sr_{2-x}La_xCuO_{6+\delta}$, or Bi2201 for short. Bi2201 and related compounds are some of the most heavily-researched materials in the world, since it was found that they can show superconducting behavior at higher temperatures then was ever thought possible (with 'high' here meaning up to half of room temperature in Kelvin, or -150 degrees Celsius). Despite this, the scientific community has recently been coming to regard the superconductivity itself as not even their weirdest attribute. The so-called normal state out of which the superconductivity is born currently defies all conventional theories of metals, driving the search for microscopic descriptions of this state. This electronic phase is dubbed the 'strange metal', and explains the final piece of the thesis title.

The work presented here is part of the Dutch strange metal consortium, funded by the Nederlandse Wetenschaps Organisatie (NWO). This program brought together both experimental and theoretical researchers in the Netherlands to study the enigma of the strange metal. This proved to be a fruitful collaboration, as the work described in this thesis contains results obtained together with the (magneto)transport group from the Radboud University (Nigel Hussey's group), with the Scanning Probe group from Leiden University (Milan Allan's group), and contains theoretical input from both the condensed matter and holography side of the collaboration (the groups of Henk Stoof from Utrecht University and Koenraad Schalm & Alexander Krikun from Leiden University).

Outline

In **Chapter 1** of this thesis, a background sketch is provided of the cuprate field, with a focus on ARPES-related work. Some important results from the literature are highlighted, and relevant theoretical and practical concepts are introduced that will return later, in the research-oriented chapters.

Chapter 2 describes the experimental technique used (Angle Resolved Photo Emission Spectroscopy, or ARPES) as well as the nuts and bolts of the experimental setup in the Amsterdam lab, that has been upgraded specifically for this project and is now called the Amsterdam Momentum Space Telescope, or AMSTEL.

The phase diagram of Bi2201 as a function of doping and temperature is investigated in **Chapter 3**, using a combination of ARPES and magnetotransport, in collaboration with the transport group from Radboud University. Here we attempt to resolve some controversies in the literature, by bringing the dependence of the electronic phases on the hole doping level in Bi2201 in line with other cuprate families. This includes results on the endpoint of the pseudogap phase, which is found to coincide with that of two other important cuprates, and the location of the Lifshitz transition of the Fermi surface, due to states near the antinode. This transition is found to coincide with the disappearance of superconductivity at very high hole doping.

Chapter 4 describes the energy, temperature and doping dependent behavior of the nodal electronic dispersions in Bi2201. From an ARPES point of view, the interesting properties of the correlated electrons can be described by the self-energy, which is a measure of the interactions that the electrons undergo, both with each other and with their environment. This self-energy can be extracted from such nodal dispersions with extremely high precision, and we find that the low energy and temperature dependent behavior can be very well captured by a power law containing a momentum dependent exponent. This is the first time such a momentum dependence of the self-energy has been demonstrated using ARPES, and we show that this can be surprisingly well modelled using tools from an unexpected corner of physics, namely that of the holographic duality. These results followed from a close collaboration with our theory colleagues from Utrecht and Leiden.

In **Chapter 5** the Fermi surface of Bi2201 is inspected more carefully, and we find that it deviates from having four-fold rotational symmetry, a fact that, to the best of our knowledge, has as yet gone unreported in previous studies. We combine these observations with Density Functional Theory calculations provided by Jorge Facio (IFW Dresden), that use the crystal parameters extracted from X-ray diffraction experiments performed by Mariia Roslova (IFW Dresden) and Anna Isaeva (UvA). The results of this combined study show that the reduced symmetry of the Fermi surface originates from the orthorhombic structure of the CuO_2 planes in the crystal. We discuss the implications of this, as anisotropic velocities and lifetimes of the quasiparticles can impose strong constraints on their theoretical description.

Finally, in **Chapter 6** we turn the attention to the behavior of the spectral function around the Fermi surface of overdoped Bi2201. We look for trends as a function of doping that indicate a transition from coherent to incoherent charge carriers as hole doping is decreased, which are then linked to the results of electrical transport-based studies. In these studies major changes are seen in the number of transport-active charge carriers, all in the same overdoped region of the phase diagram, as well as in the linear-in-T behavior of the resistivity and the superfluid density.

The research presented here illustrates that, even after more than 35 years of intense research, the field of high T_c superconductors is still evolving, and solving one problem almost inevitably leads to many new unanswered questions. Many exciting avenues of research in this field continue to open up and remain to be explored, and some important ones that have fallen outside the scope of this thesis are indicated in the discussion section of the research chapters. We hope that the results presented in the following help the field move forwards, opening up possible pathways out of phenomenology and into a microscopic understanding of the strange metals.