COLLÈGE
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Supraconductivité à haute température dans les cuprates et les organiques: Où en est-on?

High temperature superconductivity in cuprates and in organics: Where do we stand?

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Salle 5, Collège de France, 11 place Marcelin Berthelot, 75005 Paris

Refinement of materials and of experimental tools over the last two decades has led to broad agreement on many aspects of the phase diagram of cuprate high-temperature superconductors. Similarly, theoretical tools have been improving steadily. In this series of four talks, I give an overview of experimental results and focus on state of the art for two classes of theoretical methods and what they teach us on the physics of high-temperature superconductors and of related strongly correlated materials, such as the layered organic superconductors of the BEDT family. I hope to convey that we are beginning to see some convergence between theory and experiment.

Lectures will be one and half-hour long but will generally be divided in two parts, with a short break in between. The first part of each talk should be broadly accessible while the second part, especially in the last two talks, will be a bit more formal, expanding on some aspects of the first part.

I. Challenges and some answers: a (biased) overview of the field (March, 9)

The most towering successes of Solid State Physics rest on two pillars: Band Theory and the phonon-mediated BCS theory of superconductivity. Yet, these theories have been helpless to explain normal and superconducting phases of cuprate and layered organic superconductors. In this talk I first indicate the theoretical difficulties suggested by the structure of the materials and by their phase diagrams. I present evidence that an interaction-induced metal-insulator (Mott) transition controls the physics of these materials. I then introduce the one-band Hubbard model and show that it explains the antiferromagnetism observed in these compounds as well spectral weight transfer. This allows to more sharply define what is a phase of matter and why there are differences between strong and weak correlations in both antiferromagnetic and superconducting phases. After a brief overview of theoretical methods, I move on to a more detailed discussion of the phase diagrams. Why are there two domes in hole-doped cuprates? What are the three broad classes of mechanisms for the pseudogap? What can theoretical methods explain at least qualitatively? I also make a few brief comments on heavy-fermions and the role of quantum-critical points for superconductivity.

II. Doped Mott Insulators: Strongly Correlated Superconductivity and its normal phase (March, 16)

Here I focus on what we have learned on the Hubbard model for cuprates and for layered superconductors, focusing mostly on approaches based on generalizations of Dynamical Mean-Field Theory. I begin with the normal state and the pseudogap, showing that there can be a low-temperature first-order transition between a pseudogap phase and a normal metal. Crossovers at high temperature can be related to this first order transition and the associated Widom line. In the second part I move on to superconductivity. I discuss what is special about strongly-correlated superconductivity by contrast with BCS theory. I talk about c-axis superfluid density, scanning-tunneling spectroscopy. I end with a discussion of mechanism, the role of retardation and opened questions.

III. Spin-fluctuation induced superconductivity: Electron-Doped High-Temperature Superconductors and Two-Particle Self-Consistent Approach (March, 23)

Some of the first ideas on d-wave superconductivity mediated by antiferromagnetic fluctuations came from an Orsay-Sherbrooke collaboration in the 80's. In this talk I explain the Two-Particle Self-Consistent Approach to the Hubbard model, developed in the 90's, that is non-perturbative, yet controlled through sum-rules and consistency requirements. I first show how it works and some benchmarks for the normal state. I discuss how several experiments in the normal state of electron-doped cuprates, including the pseudogap, can be explained with this approach. I then move on to antiferromagnetically-mediated superconductivity, explaining optimal conditions for pairing. In the second part, I follow a more formal approach and discuss opened questions.

IV. Generalizations of Dynamical-Mean Field Theory and Improved Solvers (March, 30)

Dynamical Mean-Field Theory (DMFT), developed in good part in Paris, is the basis for many of the successes presented in this series of lectures. Here I first recall physical intuitions and concepts that are behind DMFT and generalizations that are necessary to work in low dimensions. I present advantages and disadvantages of various versions of the approach, from Cluster Perturbation Theory to Variational Cluster Approximation, Cellular Dynamical Mean Field Theory and Dynamical Cluster Approximation. I briefly discuss various versions of so-called "impurity solvers", from exact diagonalization to Continuous-Time Quantum Monte Carlo. In the second part of the talk, I proceed more formally, introducing the Luttinger-Ward Functional and showing how various schemes follow from this. I expand on a few details of solvers, briefly discuss the problem of analytical continuation and end with open questions.