Title and abstracts of keynote lectures

Monday 27 February

1. **J.C. Davis** – “Connection of Symmetry-breaking in Metallic Spin Liquids to High Temperature Copper/Iron-based Superconductivity”

   After quickly reviewing the present status of research into copper-based HTS, I will discuss the commonalities of fundamental physics in the copper-based and iron-based HTS materials. Then, by focusing on the emergent broken symmetry phases and critical points in these metallic spin liquids, I hope to stimulate discussion of the essential elements required to generate high (and higher) temperature superconductivity in this class of materials.

2. **Hai-Hu Wen** – “To explore the unified picture for pairing mechanism in iron based superconductors”

   About 8 years have elapsed since the first discovery of iron based superconductors, while there is no consensus yet about the pairing mechanism of the system. It was widely accepted that superconductivity is spin-fluctuation driven and intimately related with their specific fermiology. Most FeAs based superconductors have both the hole and electron pockets, and the wave vector which measures the distance in momentum between the hole and electron pocket is equal to that of the static antiferromagnetic order. This has gained experimental support in the FeAs based systems. This picture was questioned after the discovery of some new families, based on the FeSe layers, either intercalated KxFe2-ySe2, Li1-xFexOHFeSe, or in monolayer thin film form. Apart of yet unresolved considerable Tc enhancement at an interface with the SrTiO3– substrate, these intercalated materials show critical temperature reaching ~40K, the same as in optimally doped bulk FeSe – despite the fact that the hole pockets are absent! Taking Li1-xFexOHFeSe as the model system, we have done the scanning tunneling spectroscopy measurements. Elegant quasiparticle interference analysis shows that the so-called electron pockets seen earlier by ARPES are actually two composed ones¹, formed with either folding or hybridization effect. Furthermore, using two independent methodologies (including the recently proposed phase-sensitive quasiparticle interference technique), we show that in Li1-xFexOHFeSe compound the OP does change sign, albeit within the electronic pockets, and not between the hole and electron ones². This result unifies the pairing mechanism of iron based superconductors with or without the hole Fermi pockets, concluding that the spin fluctuation is the key factor to pair the electrons.

References

¹ Zengyi Du, Xiong Yang, Hai Lin, Delong Fang, Guan Du, Jie Xing, Huan Yang, Xiyu Zhu & Hai-Hu Wen, Nature Communications 7, 10565 (2016).
² Zengyi Du et al., to be published

3. **M. Brian Maple** – “Current status of research on heavy fermion superconductors”

   An overview of research on heavy fermion f-electron superconductors with emphasis on experiment will be presented in this talk. Topics covered will include: (1) basic normal and superconducting state properties of heavy fermion superconductors (mostly Ce- and U-based compounds) and underlying
physical concepts; (2) emergence of superconductivity and non-Fermi liquid behavior in the vicinity of the critical composition or pressure where an ordered phase (usually magnetic) is suppressed to 0 K (quantum criticality); (3) evidence for a magnetic pairing mechanism; (4) heavy fermion superconductivity, quadrupolar order, and possible quadrupolar Kondo phenomena in Pr-based “cage” compounds; (5) heavy fermion superconductivity in Yb-based compounds; and (6) relation to cuprate and Fe-pnictide and chalcogenide high temperature superconductors.

Tuesday 28 February

4. **D-H Lee** – “Approximation-free studies of models for cuprates and iron chalcogenides”

I review our sign-problem-free Monte-Carlo studies of models for electron doped cuprates and FeSe-based high temperature superconductors. Phase diagrams, Cooper pairing and pairing enhancement mechanisms as well as competing electronic orders will be discussed.

5. **R. Thomale** – “Beyond s-wave: theoretical frontiers of superconductivity in the pnictides”

While several open quests are still pending, a significant amount of theoretical questions on superconductivity in iron pnictides has appeared to be successfully answered over the past decade. One milestone of understanding has been given by the concept of extended s-wave to naturally allow for a homogeneous s-wave gap generated by electronic interactions in a multi-pocket Fermi surface scenario. In my talk, I will shortly review contemporary directions of theoretical research on superconductivity in iron pnictides, and then specifically focus on the possibility and implications of d-wave superconductivity in the pnictide materials class.

6. **P. Coleman** – “Hidden, Composite and Emergent Order in heavy fermion materials”

The low transition temperature and high tunability of heavy electron materials make them an ideal test bed for exploring new forms of order and superconductivity. I will discuss the challenges posed by various heavy electron materials, in their normal, quantum critical and superconducting configurations, not only questions they pose, but the lessons they might impart for other higher temperature superconductors.

In particular, we'll examine the case of the 115 superconductors, with Tc's ranging from 0.2 to 20K, which in their most extreme form undergo a direct transition from Curie paramagnet to Superconductor, indicating that the local moments directly entangle with the condensate to form "composite pairs". I'll present a simple mean-field theory of this kind of behavior[1].

Another challenge is posed by the heavy fermion superconductors URu2Si2 and UBe13. These materials exhibit some kind of "hidden order", either preceeding or coinciding with the superconducting transition. I will discuss the possibility of order parameter that lie beyond the Hartree-Fock paradigm [2].

Finally, I'll talk about the "spin dilemma", and our most recent efforts to understand the bosonic and fermionic manifestations of spin order in terms of supersymmetry[3].
Wednesday 1 March

10. Peter Abbamonte – “Signatures of exciton condensation in a transition metal dichalcogenide”

Bose condensation has shaped our understanding of macroscopic quantum phenomena, having been realized in superconductors, atomic gases, and liquid helium. Excitons are bosons that have been predicted to condense into either a superfluid or an insulating electronic crystal. But definitive evidence for a thermodynamically stable exciton condensate has never been achieved. In this talk I will describe our use of momentum-resolved electron energy-loss spectroscopy (M-EELS) to study the valence plasmon in the transition metal dichalcogenide semimetal, 1T-TiSe2. Near the phase transition temperature, TC = 190 K, the plasmon energy falls to zero at nonzero momentum, indicating dynamical slowing down of plasma fluctuations and crystallization of the valence electrons into an exciton condensate. At low temperature, the plasmon evolves into an amplitude mode of this electronic crystal. Our study represents the first observation of a soft plasmon in any material, the first definitive evidence for exciton condensation in a three-dimensional solid, and the discovery of a new form of matter, “excitonium.”

11. Simon Gerber

Resonant inelastic X-ray scattering (RIXS) is a powerful bulk-sensitive photon-in / photon-out spectroscopic probe of the electronic structure of condensed matter with atomic and orbital sensitivity. It is a unique tool for studying excitations from the electronic ground state in correlated materials, being directly sensitive to lattice-, charge-, orbital- and spin-degrees of freedom. In particular, the developments of the high-resolution RIXS technique during the last decade have enabled investigations of magnetic excitations in parent and superconducting cuprates.

In this presentation we demonstrate that RIXS at the Fe L3 edge can be used to measure collective magnetic excitations in iron-based superconductors and their parent compounds despite their much stronger itinerancy compared to cuprates. Our experiments on hole doped Ba1-xKxFe2As2 and electron doped Ba(Fe1-xCox)2As2 single crystals with under-, nearly optimal- and over-doping show well-defined spin-excitations dispersing up to 200 meV and persisting into the superconducting phase, thereby demonstrating the existence of an universal correlated spin state responsible for the
spin fluctuations in these materials. High-energy spin-excitations in Ba(Fe1-xCox)2As2 are in agreement with NaFe1-xCoxAs independent on electron doping, in contrast to hole doped Ba1-xKxFe2As2 for which the spin excitations are clearly softening relative to parent BaFe2As2 highlighting an electron-hole asymmetry of the spin excitations.

The situation is different in the BaFe2(As1-xPx)2 series for which superconductivity appears with isovalent doping without changing the number of carriers. Remarkably, the energy of the persistent broad dispersive magnetic excitations in BaFe2(As1-xPx)2 are strongly hardened by doping. This hardening trend of the spin excitations arises from a gradual decrease of electronic correlations. However, Fe-Kβ X-rays emission spectroscopy shows a gradual quenching of the local magnetic moment, which is intriguing if compared to the behavior of the spin correlations. We link this unconventional evolution of the magnetism to the shift from 2- to 3-dimensional electronic structure of the system, hand in hand with the warping of the Fermi surface.

13. L. Taillefer – “The quantum critical point of cuprate superconductors”

By suppressing superconductivity with a large magnetic field, we have investigated the metallic ground state of cuprate superconductors in the T = 0 limit, using various transport properties. We observe a sharp transition at a critical doping p*, into the enigmatic pseudogap phase. The key signature is a drop in carrier density n from n = 1 + p above p* to n = p below p* [1,2,3], signalling a major transformation of the Fermi surface. Understanding the mechanism for this transformation would elucidate the nature of the pseudogap phase.

I will compare the cuprates to organic, iron-based and heavy-fermion superconductors, materials in which the key organizing principle is a quantum critical point where a phase of antiferromagnetic order ends, responsible for Fermi-surface reconstruction, non-Fermi liquid behaviour and the superconducting dome itself [4].


Although the mechanism of superconductivity in the cuprates remains elusive, it is generally agreed that at the heart of the problem is the physics of doped Mott insulators. A crucial step for solving the high temperature superconductivity puzzle is to elucidate the electronic structure of the parent compound and the behaviour of doped charge carriers. In this talk we report recent scanning tunnelling microscopy studies of the atomic-scale electronic structure and electronic order in the parent and lightly doped cuprates in the antiferromagnetic insulating regime. In the parent compound, the full electronic spectrum across the Mott–Hubbard gap, or more precisely the charge transfer gap, is uncovered by scanning tunnelling spectroscopy. The size of the charge transfer gap shows strong variations for different cuprate families, and may have important implications to the maximum transition temperature that can be achieved at optimal doping. Defect-induced charge
carriers are found to create broad in-gap electronic states that are strongly localized in space. In lightly doped insulating Bi-2201 compound, we find that the main effect of charge doping is to induce a spectral weight transfer from the high energy Hubbard band to the low energy in-gap states. At sufficiently high doping, a sharp energy gap reminiscent of the pseudogap starts to form near the Fermi level, and is accompanied by the emergence of a checkerboard-like charge order. Our results demonstrate that the first ordered phase in the doped Mott insulator is a charge ordered insulator, which will gradually evolve into the superconducting state upon further doping.

15. B. Buchner – “Orbitals and short range order in Fe-based superconductors”

While there is broad consensus that superconductivity in Fe based superconductors is due to an unconventional, most likely purely electronic pairing, many important aspects of both, normal and superconducting state are still unexplored. For example, the role of orbital degrees of freedom for the normal state electronic properties, nematicity, and pairing is discussed very controversial. It is not clear whether nesting or the proximity to Lifshitz points are crucial for superconductivity. Moreover, the broad variety of properties found for different systems raises the question about the generic phase diagram of these systems. In my talk I will focus on anomalous normal state properties of Fe-based superconductors. Based on new NMR data I will discuss the origin of nematic order addressing again the apparent differences in FeSe and BaFe2As2. The role of orbitals will be emphasized including the possibility of formation of `orbital polarons'. Moreover, highly unusual temperature dependencies of the electronic structure as revealed from our recent ARPES measurements will be presented. A possible connection to well-known anomalous T dependencies of both, magnetic and structural properties will be discussed.
Numerous experiments have reported discrete symmetry breaking in the high temperature pseudogap of the cuprates, including breaking of one or more of lattice rotation, inversion, or time-reversal symmetries. However, none of these order parameters is sufficient to explain the gap in the fermion excitation spectrum in the anti-nodal region. I describe a theory of the pseudogap metal in which topological order combines naturally with the breaking of these conventional discrete symmetries, including cases which realize Varma’s current loops. The optimal doping criticality is then primarily associated with the loss of topological order, which is proposed to control the strange metal. I will also discuss an extended SYK model of a disordered strange metal, and note its close connection to certain holographic metals.

"String theorists need Eddington" - the advent of the holographic duality in condensed matter physics [1] may be misunderstood as the so-manieth theoretical contender claiming an answer to why Tc is high in cuprate superconductors. Instead it is about a main mathematical edifice - the AdS/CFT correspondence - that dropped out of string theory, having intriguing things to say about for instance quantum gravity, being at the same time however highly mysterious. It can be unleashed in a condensed matter context: so much seems clear that it describes a phenomenology of strongly entangled states of compressible quantum matter that cannot be computed in other ways because it is invested by the fermion signs. This phenomenology is governed by emergence principles of a new kind: are these pathologies of the weird "large N" UV degrees of freedom or are these truly general? I will discuss a program aimed at nailing this down employing experimental condensed matter physics. The main questions to be answered by experiment are: (1) are strange metals quantum critical phases? (2) Is there even deep in the superconducting state quantum critical "dark matter" present? (3) Is transport governed by Planckian dissipation, which is in turn rooted in the many body entanglement?


The understanding of iron-based superconductors (FeSCs) is still in flux, in large part due to the entwining of various degrees of freedom (spin, orbital and nematic) and the question about the degree of electron correlations. In this talk, I will start by discussing some perspectives on these general issues [1]. The observed bad-metal properties directly imply the importance of electron correlations, thereby linking the FeSCs with other systems such as the cuprates and heavy fermion superconductors. The electron correlations in turn motivate the considerations of frustrated magnetism and amplified orbital selectivity in the FeSCs. In the remainder of the talk, I will turn to several topics of particular current interest, including quantum criticality; nematic order especially in the puzzling case of FeSe [2,3]; and superconductivity with an emphasis on a new type of pairing
state, which is enabled by orbital selectivity and can reconcile the seemingly contradictory properties observed in the iron-selenide superconductors.


Friday 3 March


Comparable energy of the Cu 3d and O 2p orbitals in copper oxides provides a platform for high-Tc superconductivity, known as a charge transfer insulator. Even in iron-based superconductors, the Fe 3d and As 4p orbitals are energetically close, which produces various chemical bonds of arsenic depending on the filling of the Fe 3d band. The 122-type CaFe2As2 represents a typical example, where the disappearance/appearance of superconductivity results from the making/breaking of As-As bonds between the adjacent FeAs layers. In the 10-4-8-type compounds, in-plane As-As dimers are formed, resulting in superconductivity at 38 K. Infinite As chains are created in the 112-type CaFeAs2, which exhibits superconductivity at 47 K. We discuss strategy for new superconductors with the abovementioned compounds as examples.

22. Ivan Bozovic – “Cracking the enigma of HTS in cuprates — atomic layer-by-layer”

We use atomic-layer-by-layer molecular beam epitaxy to synthesize atomically perfect thin films and multilayers of cuprates and other complex oxides. By atomic-layer engineering, we optimize the samples for the particular experiment. Using a continuous spread in composition we tune the doping level in steps of 0.01%. We use high-throughput measurements on combinatorial libraries to study magneto-resistance and Hall effect in fields up to 90 T and measure accurately the coherence length. We measure the absolute value of penetration depth to accuracy better than 1%.

We have shown that HTS films can be quite homogeneous, having a very uniform SC gap. Charge density waves and charge glass are observed in underdoped LSCO samples, but none at optimal doping. Phase fluctuations are seen up to 10-20 K above Tc. In-plane charge excitations are strongly coupled to out-of-plane lattice vibrations. Superfluid can be confined to a single CuO2 layer, with Tc equal to that in bulk samples. A large enhancement of Tc is seen in certain heterostructures. Pairs exist on both sides of the superconducting transition, be it induced thermally or by doping. [1]

I will present the results of a comprehensive study that took twelve years and encompassed thousands of cuprate samples, perhaps without precedence in Condensed Matter Physics. The large statistics reveals clear trends and intrinsic properties; this is essential when dealing with complex materials such as cuprates. We have measured accurately the key physical parameters in the normal and the superconducting states (resistivity, Hall effect, magnetoresistance, Tc, and others) and established their precise dependence on doping, temperature, and external fields. The findings bring in some great surprises. The standard Bardeen-Cooper-Schrieffer description of the superconducting state fails dramatically everywhere in the phase diagram, including the heavily overdoped side. The normal state also shows a dramatic departure from the standard Landau Fermi Liquid theory. Cuprates are indeed unusual, not just because of the exceptionally high Tc.
References


On the overdoped side, the standard Bardeen-Cooper-Schrieffer description fails dramatically, challenging the idea that the normal state is a simple Fermi liquid.

23. Mike Norman – “Are there new cuprates out there? The Electronic Structure of Herbertsmithite, Pr4Ni3O8, and CuTeO4”

No new analogues of superconducting cuprates have been found in a long time. In this talk, I will discuss three layered materials that have the potential to exhibit superconductivity: (1) a doped version of herbertsmithite - a copper hydroxychloride mineral with kagome planes whose stoichiometric phase is a Mott insulator with a spin liquid ground state, (2) Pr4Ni3O8, a self-doped trilayer square lattice metal whose Ni valence corresponds to 1/3 hole doping of a cuprate, and thus with electron doping could move into a desired doping range, and (3) CuTeO4, an unstudied copper tellurium oxide where copper ions sit on a square lattice, and which could potentially be hole doped by replacing Te6+ by Sb5+. In all cases, the known (or predicted) electronic properties of these materials will be presented, and the prospect for doping them discussed.