Possibility of Room Temperature Superconductivity using the Resonating Valence Bond Mechanism

Based on theoretical considerations we suggest that solid state and quantum chemical constraints do not limit superconducting Tc in real materials to the presently observed maximum value of Tc ~ 163 K. Under favorable conditions Tc could reach room temperature scales. Major hurdles on the path to achieving room temperature superconductivity are competing orders involving spatial localization of charges and spins. We discuss some synthetic routes to overcome this hurdle by taking clue from existing systems such as organic, cuprate and Fe base superconductors. According to our theory optimally doped graphene might achieve the goal.
Dmitri N. Basov

University of California, San Diego (http://infrared.ucsd.edu/)

Shedding infrared light on high-Tc superconductivity

The mechanism of high-Tc superconductivity is one of the most challenging unresolved problems in contemporary physics. The recent discovery of high Tc superconductivity in the iron pnictides, while interesting in itself, offers a new perspective on several aspects of cuprate high-Tc superconductors. In this talk, I will overview common patterns as well as contrasting trends between the two classes of high-Tc materials (cuprates and pnictides), focusing on the information generated through infrared/optical probes. Infrared methods [Rev. Mod. Phys. 83, 471 (2011)] enable experimental access to energy gaps in a superconductor, strong coupling effects responsible for pairing, the collective response of the superfluid and allow one to quantify the strength of electronic correlations [Nat. Phys. 5, 647 (2009), Phys. Rev. Lett. 108, 147001 (2012) & Phys. Rev. Lett. 109, 027006 (2012)]. With this panoramic view of effects central for our understanding of superconductivity I will attempt to identify factors favoring higher Tc in exotic superconductors [Nat. Phys. 7, 271 (2011)].
High Temperature vs Room Temperature Superconductivity: Lessons from the world of heavy fermion superconductors.

Heavy fermion superconductivity is the oldest area of electronically mediated superconductors. The various families of superconductivity found in these materials have Tc's ranging over three orders of magnitude in temperature up to a current maximum of 18.5K. Many of these systems, including the discovery compound, CeCu2Si2 are "high temperature superconductors", in the sense that the Tc is a large fraction of the Fermi energy and the condensation entropy is a large fraction of Rln2. Moreover, in some families, such as the 115 superconductors, the entropy of condensation is fixed, and Tc simply scales with the characteristic hybridization energy, which goes up by a factor of ten in going from rare earth to actinide atoms.

I shall discuss the various families of superconductivity in these materials, asking, can we scale them up by moving to transition metals? One of the ideas to emerge, is that it may be possible to engineer atomic clusters to have properties reminiscent of the strongly correlated rare earth or actinide atoms. This could even be what is happening in the iron based superconductors, where the the Fe-As tetrahedra behave as a single renormalized atom that somehow favors pairing.
Paul C. W. Chu

Texas Center for Superconductivity at the University of Houston

The Holistic Multidisciplinary Empirical Approach to Higher Tc with Possible Evidence for Interfacial Mechanism

Advancing the superconducting transition temperature (Tc) has been one of the major driving forces in superconductivity research ever since its discovery 100 years ago. The holistic multidisciplinary empirical approach to higher Tc may be proven most fruitful and depends on imagination, insight, experience and knowledge from different fields plus courage and luck. Two general steps have been adopted: to discover new compounds guided by experience and insight empirically and to realize novel mechanisms inspired by models theoretically. Until now, successes have come almost exclusively from the former. Of the many theoretical mechanisms proposed, few have led to the discovery of a superconductor with a clear enhanced-Tc. Interfacial mechanism has been one such most explored theoretically and experimentally but without clear evidence for an enhanced Tc. Our recent detection \cite{1} of non-bulk superconductivity with an unexpectedly high onset-Tc up to 49 K in rare-earth-doped CaFe2As2 (Ca122) single crystals), that is higher than that in known compounds consisting of any combinations of the constituent elements, affords an opportunity for the study. Through systematic structural and magnetic investigations, we have shown \cite{2} the existence of nano-2D structures in the chemically homogeneous rare-earth doped Ca122 single crystals and thus provided evidence for the possible interface-enhanced Tc in Fe-based superconductors.

References
\cite{1} B. Lv et al., PNAS 108, 15705 (2011).
\cite{2} F. Y. Wei et al., preprint.
Steve Conradson

Los Alamos National Laboratory

Tutorial: Structure Determination and Functionality in Inhomogeneous and Heterogeneous Ordered Solids

Whether one is in the phonon camp that believes that the charge and spin defects and stripes are the origin of superconductivity in cuprates, or favor spin-based mechanisms that are intrinsic to the ordered lattice so that the defects are just interferences, the importance of inhomogeneities in the structure if not the function of high temperature superconductors is beyond cavil. Inhomogeneities result from substitution or doping that causes the unit cells’ stoichiometry to differ from the bulk composition. Understanding the effects of these aperiodic structure, charge, and spin loci is probably best accomplished by a “chemistry” approach that dictates that the speciation of individual sites is retained locally and is the determinant of behavior. The associated lattice distortions usually elude detection by conventional crystallographic methods and are therefore best probed by local structure methods – notably pair distribution function (pdf) analysis and X-ray Absorption Fine Structure (XAFS) – that are sensitive to local order on length scales below the diffraction limit. Actually determining the arrangements of a sufficient number of atoms to describe systems with inhomogeneities ultimately requires a combination of experiment and modeling.

It the inhomogeneities interact weakly then the defects will be dispersed to form a boring random solid solution. In complex materials the inhomogeneities interact strongly to self organize and cluster so that the local composition will exhibit large fluctuations on the nanometer scale and larger. If this composition crosses a phase boundary there will be a tendency within that domain for the atoms to rearrange into this native structure. However, because of the epitaxial constraints or equivalently because of the inverse correlation between length scale and fluctuation region for martensitic transformations, the transition will be frustrated so that entirely novel structures may result. This coexistence of a second ordered structure that is typically at or below the diffraction limit in size embedded within the lattice of a host can be called nanoscale heterogeneity. Although there are some examples where the coupling between the nanophase separation and bulk properties is apparent, notably manganites, there are many more complex materials where this relationship is unknown. One important aspect of the phase separation and heterogeneity that is often overlooked is the interfaces between domains.
Prof. Dr. Claudia Felser

Max Planck Institute for Chemical Physics of Solids

Tutorial: Routes to Room temperature Superconductivity from a Chemist’s Perspective

Nobody knows the route to high temperature superconductors, but there are ideas about the direction. It is established that superconductors with higher transition temperatures are found at the borderline to semiconductors or Mott insulators and the borderline to magnetism. Learning from the elements and their properties under pressure, we know that the highest transition temperature are achieved for elements on the right side of the periodic table (semiconductors or insulators) and on the left side (alkali or alkaline earth metals). In general, certain structure types show higher transition temperatures such as perovskites and ThCr$_2$Si$_2$ structure type, which are good for phonon driven superconductors (Ba$_{1-x}$K$_x$BiO$_3$ or LuNi$_2$B$_2$C) as well as for unconventional superconductors (YBa$_2$Cu$_3$O$_{7-x}$, Ba$_{1-x}$K$_x$Fe$_2$As$_2$). These structure types allow band gaps between correlated states or hybridization gaps. Valence instabilities and electronic instabilities are sensors for Fermi surface nesting and higher critical temperatures.
Superconductivity at Crossover from Localized to Itinerant Electrons

Superconductivity is nature's last resort to stabilize occupied electronic states at the expense of unoccupied states by opening an energy gap between the two. Electron localization allows single-valent compounds to open a Mott-Hubbard U gap. Formation of small polarons opens a gap in strongly correlated mixed-valent compounds. BCS superconductivity is found with Pauli paramagnetic metals having a large density of one-electron states $N(\varepsilon)$ at the Fermi energy. High-temperature superconductivity is a phenomenon that is found where there is a crossover from localized to itinerant electrons, but at this crossover, superconductivity must compete with the formation of a charge-density wave (CDW) and/or a spin-density wave (SDW). Therefore, high-temperature superconductivity is restricted to mixed-valent transition-metal compounds with an electron redox couple pinned at the top of anion-p bands and an electron/decation ratio that stabilizes mobile, diamagnetic bipolarons having an energy gap competitive with any CDW/SDW; long-range ordering of the bipolarons by electrostatic and elastic forces is needed for superconductivity. The Cu(III)/Cu(II) redox couple of the high-$T_c$ copper-oxide superconductors is pinned at the top of the 0-2p bands; the properties of these oxides are consistent with large, diamagnetic bipolarons that are coupled to optical phonons propagating along Cu-0-Cu bond axes within the CuO$_2$ planes. What needs to be clarified by calculation is the morphology of the bipolarons and how they are long-range ordered. The model should accommodate diamagnetic bipolarons with an optimum hole concentration $p \sim 1/6$ for the p-type copper-oxide superconductors. One such model was proposed a decade ago; recent experiments by Kohsaka et.al. [2] and Ghiringhelli et.al. [3] support such an approach.

Gernot Guntherodt

Physics Institute (IIA), RWTH Aachen University

Superconductor $T_C$: Extrapolating from basic facts and concepts?

Superconductivity is one of the most challenging phenomena of condensed matter physics. The discovery of high temperature superconductors (HTSC) in 1986 and of the iron-pnictide based superconductors in 2008 has spurred intense research worldwide, but has also raised the question as to limiting factors of the superconductor transition temperature $T_C$. Starting from conventional superconductors, their basic phenomenology, model concepts and characteristic electronic energies for pairing and $T_C$ will be described and contrasted with those of the HTSC, such as electron-phonon coupling vs spin fluctuations and antiferromagnetic exchange energy. Based on the present understanding of HTSC the goal is to discuss the characteristic parameters in the light of feasible extrapolations toward higher values of $T_C$. From an experimental point of view the methodology for the search for new superconducting materials will be addressed, such as highly inhomogeneous “phase spread alloys” and fast screening methods using microwave spectroscopy.
Superconductors based on transition metal with large magnetic moment

It’s a widely accepted belief that transition metal with a large magnetic moment represented by iron, cobalt and nickel is antagonistic superconductivity. In 2006-2008, we reported iron and nickel based oxypnictide superconductors but no Co-based oxypnicid/pnictides remain itinerant ferromagnet. Co-based superconductors (Tc=-4K) were obtained in LaCo2B2:Fe with a layered structure in 2011. In this talk, I will show recent data on this subject.
Hao Tjeng

Max Planck Institute for Chemical Physics of Solids

**Novel states using high oxidation state materials**

Many interesting and important oxides, such as the high-$T_c$ cuprates and the colossal magnetoresistance manganites, belong to the class of correlated systems called charge transfer (CT) insulators within the Zaanen-Sawatzky-Allen frame work. In these systems the lowest excited states are not those with electron transitions between the d-shells $d^n + d^n \rightarrow d^{n+1} + d^{n+1}$, as in usual Mott insulators, but rather transitions between the d-levels of the transition metal and the p-levels of the oxygen, $d^n p^6 \rightarrow d^{n+1} p^5$. The energy of such excitation is called the charge-transfer energy. One can show that for transition metal compounds with a high oxidation state this charge transfer energy can become negative, with the result that a spontaneous electron redistribution could occur in which oxygen holes are formed. Important is that one then can arrive at states that are no longer of the Hund’s rule high spin type. This is for instance the case for the doped cuprates, where one encounters the presence of Zhang-Rice/Eskes-Sawatzky singlets, which are non-magnetic and thus can help for the superconductivity to occur. In this talk we would like to discuss the occurrence and properties of spin-compensated states in high oxidation cobaltate materials which we have investigated recently.
Control of correlated electrons in metal-oxide superlattices

This talk will begin with a brief overview of recent experimental results on spin-fluctuation-mediated Cooper pairing [1,2,3] and competing order [4] in high-temperature superconducting cuprates. Guided by these and other results, we are pursuing a research program on artificially designed metal-oxide superlattices. We outline recent progress of this program, including the control of the electronic dimensionality [5], electron-phonon interactions [6], and spin, charge, and orbital order [7,8] in cuprate- and nickelate-based superlattices.

Steve Kivelson

Stanford University

High Temperature Superconductivity is a Crossover Phenomenon

Firstly, by way of an elaborate set of excuses, we will discuss the reasons that it is so difficult to develop the theoretical precision necessary for a search for “high temperature superconductivity by design.” However, some general features which determine the superconducting Tc in certain simple, “solvable,” paradigmatic models will be explored with the hope of providing some general strategies for such a search. In particular, it is shown that optimal Tc occurs as a crossover between regimes with different dominant low-energy degrees of freedom, an observation which at once exhibits why controlled theory is nearly impossible, but which at the same time may give useful insight into the problem.
Gabriel Kotliar
Rutgers

Strong Correlations and High Temperature Superconductivity

We will give an overview of the different classes of electronic correlations and how they can be used to organize the various correlation maps that can aid in the search for higher temperature superconductors.
M. Brian Maple

University of California, San Diego

Tutorial: Survey of Superconducting Materials

We give a brief survey of different classes of superconducting materials that have been discovered during the remarkable history of this subject. These classes of materials include conventional (BCS) superconductors, conventional superconductors containing ions with magnetic moments, A15 superconductors, organic superconductors, heavy fermion superconductors, layered superconductors, high temperature cuprate and Fe-based pnictide and chalcogenide superconductors, and other novel superconductors. Relevant topics and issues will be discussed such as magnetic interactions in superconductors, unconventional types of superconductivity, superconducting order parameter symmetry, magnetic pairing mechanisms, the role of electronic correlations, emergence of superconductivity from magnetically ordered phases and other ordered phases, empirical rules for superconductivity, etc.
Michael Norman
Argonne National Lab

Stay Away from Theorists

Despite Bernd Matthias’ somewhat apocryphal suggestion, theory has played an important role (misguided or otherwise) for those searching for new classes of superconductors. In this talk, I will review some crazy, and not so crazy, ideas for new superconductors: heavy holes playing the role of ions, filling up the Brillouin zone with Fermi surfaces, searching for materials with large superexchange, hybrid systems that play off the pairing scale against the phase stiffness scale, and attempts at large scale data mining. I will end with a thought offered by Mac Beasley – even if we had a high temperature superconductor, would it really make a difference?
David Pines

UC Davis, ICAM, and UIUC

Finding New Superconductors: Looking under the Magnetic Lamp Post

I will review the arguments for a common origin of the unconventional superconductivity discovered in the cuprates and heavy electron materials—it's magnetic, stupid!--with particular attention to lessons learned from magnetic measurements of their normal state properties and model calculations of the role played by spin fluctuations, dimensionality, and band structure. These suggest that for optimally doped materials the superconducting transition temperature scales with a characteristic magnetic energy, that in all these materials one likely has a quantum critical point denoting the emergence of local moment behavior with the highest superconducting transition occurring in the vicinity of that qcp, and offer a strategy for searching for room temperature superconductivity.
Matt J. Rosseinsky

Department of Chemistry, University of Liverpool

Magnetism and superconductivity in metal fullerides

Recent advances in the understanding of superconductivity in the $A_3C_{60}$ fullerides are presented, which reveal that the superconducting state is in direct competition with localised electron magnetic ground states.\textsuperscript{1-4} This competition is revealed by the synthesis of two polymorphs of $Cs_3C_{60}$. The molecular electronic structure of the $C_{60}^{3-}$ anion determines the nature of the parent magnetic insulator.\textsuperscript{5}

2. Y. Takabayashi et al. Science 2009, 323, 1585
George Sawatzky

Physics Department, UBC Vancouver

Utilizing the proximity of highly polarizable atoms or molecules to mediate an attractive nearest neighbor interaction

I will present arguments that the close proximity of strongly polarizable species such as heavy large anions or molecules can mediate strong nearest neighbor attractive coulomb interactions perhaps even large enough to result in nearest neighbor bipolarons or Cooper pairing. These interactions depend strongly on the local geometry and the angle subtended by the polarizable atom and the two neighboring atomic sites of interest. For example in the Fe pnictides the an attractive contribution to the interaction (screening) results between electrons on nearest neighbors while a strong repulsive interaction results for electrons on next nearest neighbors. I will discuss the details of these kinds of mechanisms which are a result of the more general problem of local field corrections in non uniformly polarizable media. Estimates of potentially possible net attractive interactions indicate that high temperature superconductivity may be reachable.
Darrell Schlom & Kyle Shen
Cornell University

A Modern Spectroscopic Search for New High Temperature Superconductors

We will describe our investigation of candidate materials for new high-temperature superconductors using a combination of oxide molecular beam epitaxy (MBE) synthesis and angle-resolved photoemission spectroscopy (ARPES) to investigate the electronic structure. Using the atomic layer-by-layer growth possible by MBE, we aim to epitaxially stabilize compounds which are difficult to achieve in bulk, or synthesize entirely new artificial structures. Instead of searching through columns of the periodic table, our modern alchemists' approach is to identify materials which may be quasi-two-dimensional antiferromagnetic materials with strong electron correlations and that can be doped with carriers. Due to their strong correlations, ARPES plays an essential role in determining their true electronic structure, which we can use to close the loop between materials synthesis, theory, and experiment in search for higher $T_c$ superconductors. We are also using epitaxial strain and interfacial effects to try to enhance the properties of known superconducting materials. We will describe some of our recent work on the infinite layer cuprate SrCuO$_2$, layered titanates, nickelates, and ruthenates.
Chandra Varma

Chancellor's Professor, University of California, Riverside

Tutorial: Unusual Metallic States and Anisotropic Superconductivity

In these lectures I will summarize the principal properties of the normal and superconducting states of metals discovered in the last thirty years, with special emphasis on the cuprates, in which superconductivity appears to be promoted by quantum-critical fluctuations of the fermions. These properties have raised fundamental questions about the nature of the excitation spectra in interacting fermions. The quantum critical fluctuations lead to unusual normal state properties of the materials, which in the case of the cuprates at least take the form of marginal fermi-liquid rather than Landau's fermi-liquid. Bordering the marginal Fermi-liquid in the phase diagram of the cuprates is the region of pseudo gap in the normal state, which is contrary to the Bloch paradigm about excitations in periodic systems.

I will cover the following topics in these lectures:
(1) Basic experimental and theoretical properties of Landau Fermi-liquids.
(2) Survey of the normal state properties of the novel superconductors.
(3) Phenomenology of marginal Fermi-liquids.
(4) Properties of normal state fluctuations necessary to get Anisotropic p-wave or d-wave superconductivity.
(5) Microscopic Model for the Cuprates and the theory of Loop-Current order.
(6) Experimental Observations of Loop Current order.
(7) Pseudo-gap in the Loop Current order state.
(8) Derivation of the Quantum-critical fluctuations and marginal Fermi-liquid from fluctuations of loop current order.
(9) d-wave superconductivity from Loop current fluctuations and alternate possibilities.
(10) Analysis of high resolution ARPES data to decipher nature of spectra responsible for pairing in Cuprates.
Panel Discussion: Questions!

(1) Why is it hard to dope Mott insulators?
(2) Basic physics of anisotropic superconductivity.
(3) Deciphering the mechanism of superconductivity in cuprates through extensions of Rowell-McMillan methods using ARPES.
(4) Is it possible to have electronic fluctuation induced s-wave superconductivity?
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Harold Weinstock

Panel Discussion
Qi-Kun Xue

Department of Physics, Tsinghua University, Beijing 100084, China

Interface induced high temperature superconductivity in single unit-cell FeSe films on SrTiO$_3$

We report high transition temperature superconductivity in one unit-cell (UC) thick FeSe films grown on the Se-etched SrTiO$_3$(001) substrate by molecular beam epitaxy (MBE). A superconductive gap as large as 20 meV and the magnetic field induced vortex state revealed by in situ scanning tunneling microscopy (STM) suggest that the superconductivity of the 1 UC FeSe films could occur around 77 K. The control transport measurement shows that the onset superconductivity temperature is well above 50 K. Our work not only demonstrates a powerful way for finding new superconductors and for raising $T_C$, but also provides a well-defined platform for systematic study of the mechanism of unconventional superconductivity by using different superconducting materials and substrates.

The work was carried out in collaboration with Xucun Ma, Lili Wang, Xi Chen, Ke He, Shuahua Ji, Yayu Wang, Xingjiang Zhou and Jinfeng Jia.