Novel Transport Phenomena Near the Putative Quantum Critical Point of an Unconventional Superconductor

The transport properties of unconventional superconductors and other quantum critical metals deviates strongly from the conventional theory of transport in metals. The dramatic T-linear temperature dependence observed in cuprate, iron-pnicitde and heavy fermion superconductors is thought to be a signature of quantum critical physics and is often used as evidence for the proximity to a quantum critical point. We discover that this same physics may be manifest in the magnetotransport properties of these materials. In this talk I focus on a study of the Hall effect in BaFe2As2 near its quantum critical point and reveal a peculiar manifestation of this physics that is reminiscent of the cuprates and the heavy fermions materials.

References:

James Analytis joined the faculty at UC Berkeley in January 2013 as the Charles Kittel Chair in condensed matter physics. He received his B.Sc. in physics from Canterbury University in 2001 and his D. Phil. from the University of Oxford as a Rhodes’ Scholar in 2006. At Oxford, he worked with Stephen Blundell and Arzhang Ardavan on experimental and computational studies of quasi-two dimensional organic superconductors. Following his graduate studies, Analytis was a Lloyd’s Tercentenary Fellow at the University of Bristol, where he worked on understanding the nature of anisotropic scattering in cuprate superconductors. In 2008 he became a post-doctoral fellow at Stanford University where he worked on both pnictide superconductors and topological insulators. In 2010 Analytis became a staff scientist at the Stanford Institute for Materials and Energy Science. The Analytis lab at Berkeley is capable of creating new materials and characterizing their thermodynamic and transport properties, particularly in the presence of high magnetic fields.
A Study of Topology and Quantum Phase Transitions from Monte Carlo Simulations

In this talk I will review recent progress in quantum Monte Carlo simulations of correlated electron systems. This progress allows the study of a variety of phenomena including de-confined phases and phase transitions, instabilities of Dirac metals as well as the competition of classical frustration and Kondo screening.
Magnetic Excitations in SmB$_6$*

A review of neutron scattering work probing the Kondo insulator SmB$_6$ is presented with special emphasis on assessing the topology of the underlying strongly renormalized band structure. A 14 meV exciton dominates the low energy spectrum and is evidence of strong electron correlations. Though the data supports the proposal that SmB$_6$ is a topological Kondo insulator, specific heat, AC conductivity, and the finite width of the exciton peak indicate a continuum of states below the bulk transport gap, the origins of which are presently unknown.

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Collin Leslie Broholm is the Gerhard H. Dieke Professor in the Department of Physics and Astronomy at the Johns Hopkins University. He earned his Ph.D. from the University of Copenhagen in 1988, was a post doc at AT&T Bell Laboratories from 1988-1990, and joined Johns Hopkins in 1990. Dr. Broholm is interested in anomalous forms of magnetism, superconductivity, and their interplay. Of particular interest are crystalline materials where quantum effects are enhanced on account of competing interactions (frustration) or low dimensionality. The main experimental tool is neutron scattering and Dr. Broholm is involved in development of the corresponding instrumentation. He has built two spectrometers at the NIST Center for Neutron Research and has served on committees overseeing instrumentation development at National facilities for Neutron Scattering. Dr. Broholm received the Presidential Faculty Fellowship in 1994, became a fellow of the American Physical Society in 2004, and received the Sustained Research Award of the Neutron Scattering Society of America in 2010. He was selected as a Gordon and Betty Moore Foundation experimentalists in quantum materials in 2014. Dr. Broholm directs the Johns Hopkins Institute for Quantum Matter.
Topology and Quantum Phase Transitions in Heavy Fermion Materials

The excellent tunability of heavy fermion metals by non-thermal control parameters such as magnetic field, pressure, or doping has vastly expanded our understanding of these materials. In particular it has brought to light quantum criticality at the border of different ordered phases, Landau and beyond Landau quantum criticality, as well as “naked” quantum critical points (QCPs) and QCPs covered by domes of new phases [1]. By comparison, the larger energy scales governing Kondo insulators, their (pseudo)gapped sister compounds, has severely limited similar studies in this class of materials [1]. The recent discovery that a new tuning parameter, spin-orbit coupling, can be realized in certain substitution studies and leads to a crossover between a Kondo insulator and semimetal [2] with characteristics of a recently proposed Weyl-Kondo semimetal [3] may bring new impetus to the field.

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References:
Outstanding Issues for the Topological Scenario of SmB$_6$

The mixed valent compound SmB$_6$ was the first candidate example of a new class of strongly correlated topological insulators, with the new TI surface state scenario providing an elegant explanation for a long time mystery of residual conductivity <4K in the insulating phase. Similar to other TI materials, the physical realization of the TI surface properties in surface-sensitive angle resolved photoemission (ARPES) measurements must compete with other possible non-topological materials issues including surface relaxation, surface reconstruction, (001) polar surface termination(s) and surface band bending, and weaker f-d hybridization at the surface (e.g. surface Kondo breakdown). An assessment of these various effects as viewed by ARPES is reviewed for SmB$_6$ in comparison to other non-topological divalent [1] and trivalent hexaborides including both (001) and (110) cleaved and prepared surfaces.

In addition from this renewed interest in SmB$_6$, temperature-dependent ARPES and dynamical mean field theory (DMFT) calculations have provided new insights into the evolution of the bulk mixed-valent 4f electronic structure and hybridization gap formation [2]. In particular, an important role of f-p hybridization is identified in the formation of the insulating gap, which goes beyond the minimal two-band models of f-d hybridization. In addition a dimensional crossover evolution 3D bulk d-band states crossing $E_F$ to 2D helical in-gap surface states is observed to be intimately linked to the bulk gap evolution.

References:

Dr. Jonathan Denlinger works in experimental condensed matter physics, with an emphasis on synchrotron-based angle-resolved photoemission of f-electron and strongly correlated electron systems. Dr. Denlinger obtained his B.S. degree in Physics from Purdue University, and his Ph.D. degree in Physics from the University of California, Berkeley in 1993. He did his postdoctoral works at the Advanced Light Source, commissioning a photoemission beamline in collaboration with U. of Wisconsin-Milwaukee, and at the University of Michigan where he was introduced to f-electron physics. In 1999 he joined the staff at the ALS as a beamline scientist first for a beamline specializing in x-ray absorption and emission and then at a newer high-resolution ARPES beamline.
Unconventional Physics of Conventional Kondo Insulator

The physics of samarium hexaboride — a narrow gap strongly correlated semiconductor discovered almost 50 years ago — continues to inspire experimental and theoretical research. Much of the recent work has been motivated by theoretical proposals that samarium hexaboride provides a prototypical example for the first correlated Z2 topological Kondo insulator. In this talk I will first outline the main ideas, which lead to realization that samarium hexaboride becomes a topological Kondo insulator below a certain temperature. Then, I will discuss recent theoretical works, which address several experiments, which should help to identify the topological nature of the metallic surface states. Finally, I will review recent experimental works which challenge our current understanding of physics of this fascinating material.
Comparison of Kondo Insulating Properties of SmB$_6$ and YbB$_6$

The high pressure studies of Sun\(^1\) provide evidence the YbB$_6$ becomes a topological insulator in the vicinity of 20GPa. We review this evidence and the questions that the data raises concerning the fundamental differences between ordinary divalent hexaborides and SmB$_6$ and YbB$_6$.

Fisk received his PhD from UC San Diego in 1969 as a student in the group of B.T.Matthias. He subsequently held positions at the University of Chicago, UC San Diego, Los Alamos National Laboratory, Florida State University and UC Davis prior to his present position at UC Irvine. His primary interests are in superconductivity and heavy Fermion materials.
Signatures of Topological Weyl Semimetal in Correlated Materials

The Weyl fermions can describe low energy quasiparticles of inversion or time reversal symmetry breaking states in three dimensional materials [1]. They combine seemingly disjoint notions of critical bulk excitations and nontrivial momentum space topology, and support many exotic bulk transport and electrodynamic properties in addition to protected, zero-energy surface states (Fermi arcs). In weakly correlated materials, the angle resolved photoemission spectroscopy provides strong evidence for coherent Weyl fermions in the bulk and Fermi arcs on the surface. However, their spectroscopic detection in a correlated material can be complicated by interaction induced short life time and bandwidth suppression, thus requiring complementary measurements of transport and electrodynamic properties, which are sensitive to the underlying topology. I will discuss such signatures of Weyl fermions, including the large anomalous Hall conductivity [2], the optical activity [3], and the chiral anomaly induced negative longitudinal magnetoresistance [4]. I will argue that combined spectroscopic and transport measurements can unveil elusive Weyl excitations in many correlated materials.

References:

Pallab Goswami is currently a postdoctoral fellow at Condensed Matter Theory Center, University of Maryland. He is interested in developing new theoretical tools for addressing emergent quantum phases and phase transitions in strongly correlated and disordered materials, with an emphasis on topological properties. He received his PhD in 2008 from University of California, Los Angeles. Subsequently, he has carried out postdoctoral research at Rice University, National High Magnetic Field Laboratory at Tallahassee, before moving to University of Maryland in 2014.
High-school physics categorizes matter into solids, liquids and gases, based on its ability to fill up a given container. By the end of an undergraduate course in solid state physics, one learns that matter can also be classified based on its ability to transport charge, as a metal, insulator, semiconductor or a semimetal. Finally, a graduate course in condensed matter physics informs us of the traditional classification of states of matter – the Landau theory – based on which symmetry the ground state breaks that the Hamiltonian does not. However, the last three decades have shown us that even this picture is incomplete – matter can be characterized by topological properties of the ground state wavefunction in addition to its broken symmetries.

This talk will introduce the basic ideas behind how topological labels can be applied to electronic band structures, and focus on a phase that has gained tremendous attention in the last few years, namely, Weyl semimetals. It will be highlighted that doped Weyl semimetals form a natural platform for another topological state of matter, viz., a time-reversal invariant topological superconductor in three dimensions. The latter has no known realizations in electronic systems thus far. Finally, it will be shown, within a fluctuation-exchange approach, that doped Na3Bi with broken inversion symmetry and ferromagnetic interactions has an instability towards such a superconductor.

Prof. Pavan Hosur’s research interests are in theoretical condensed matter physics and quantum statistical mechanics. Within condensed matter theory, he is currently excited about topological phases of matter, especially gapless ones such as Dirac and Weyl semimetals. He is also interested in exploring unusual broken symmetry phases and devising ways to detect them in experiments. Questions in quantum statistical mechanics that he is thinking about revolve around quantum ergodicity, quantum chaos, and generally, how ideas from classical statistical mechanics apply to quantum systems. These questions have received a surge of interest lately via work on Eigenstate Thermalization and Many-Body Localization, but many aspects remain unclear. Hosur hopes to understand and contribute toward resolving them in the coming years.
Emergent Exotic Superconductivity in Artifically Engineered Kondo Superlattices

In the presence of inversion symmetry breaking, strong spin-orbit coupling dramatically affects the superconductivity through the Rashba splitting. It has been proposed that cooperative effect of electron correlations and Rashba splitting provide notable effects on superconductivity, leading to exotic superconducting states such as helical or stripe phases, but such phases have never been reported so far. We have fabricated Kondo superlattices consisting of alternating layers of YbCoIn$_5$, CeCoIn$_5$ and YbRhIn$_5$ with atomic thicknesses, where CeCoIn$_5$ is a $d$-wave superconductor and YbCoIn$_5$ and YbRhIn$_5$ are conventional metals. In these “tricolor” superlattices where the magnitude of the Rashba splitting can be tuned, in-plane upper critical field $H_{c2}$ exhibits an anomalous upturn at low temperatures, indicating a possible emergence of helical or stripe superconducting phase.

We also fabricate CeCoIn$_5$/CeRhIn$_5$ superlattices, where CeRhIn$_5$ is a heavy fermion SDW compound. In these “hybrid” superlattices, $d$-wave superconductivity coexists with SDW at ambient pressure. Under high pressure with approaching SDW QCP of CeRhIn$_5$ layers, $H_{c2}/T_c$ is strikingly enhanced, suggesting an emergence of extremely strong coupling superconductivity.

Yuji Matsuda

Yuji Matsuda received his Ph.D. in Physics from the University of Tokyo (Japan) in 1987 and became a research associate at Department of Pure and Applied Science, the University of Tokyo. He became an associate professor in 1993 at Hokkaido University (Japan) after spending two years at Princeton University (USA) as a postdoctoral fellow. He moved to Institute for Solid State Physics, University of Tokyo, as an associate professor in 1997, and became a full professor at Kyoto University in 2004. He is a condensed matter experimentalist with interests in electronic and magnetic properties of solids. His current research interests include strongly correlated electron systems, in particular exotic superconductivity, heavy fermion systems, high-$T_c$ superconductors, and quantum spin systems.
Topological Nodal Superconductivity, Surface States and the Role of Disorder in UPt₃

The concept of topological states of matter has captured the imagination of physicists in the last decade. Traditionally, such topological phases are predicted to occur in fully gapped insulating or superconducting materials and are characterized by topologically protected gapless excitations on the surface [1]. Here, I will demonstrate a generalization of this concept to metallic materials with gapless bulk excitations, focusing in particular on the B-phase of the heavy fermion superconductor UPt₃. Phase sensitive measurements provide strong evidence for the triplet, chiral pairing symmetry in UPt₃, which endow the Cooper pairs with orbital angular momentum $L_z = \pm 2$ along the c-axis [2]. Such pairing supports both line and point nodes of the superconducting gap, and I show that both types of nodal quasiparticles possess nontrivial topology in the momentum space. In particular, the point nodes located at the intersections of the closed Fermi surfaces with the c-axis act as the double monopoles and the anti-monopoles of the Berry curvature [3]. Consequently, we predict that the B phase should support an anomalous thermal Hall effect, various magneto-electric effects such as the polar Kerr effect, in addition to the topologically protected Majorana arcs on the (1,0,0) and (0,1,0) surfaces [3]. At the transition from the superconducting B-phase to the A-phase of UPt₃, the time reversal symmetry is restored, and the topological Andreev surface states disappear. I will also discuss the role of impurities on the topological properties of double-Weyl superconductors and the corresponding Andreev surface states.

References:

Dr. Andriy Nevidomskyy is a theoretical condensed matter physicist, working in the field of strong electron correlations in quantum materials. The collective behaviour of electrons in such materials often results in the emergence of new exotic quantum phases, such as the unconventional superconductivity and quantum spin orders. Nevidomskyy has explored these phenomena in the heavy fermion materials and in the iron-based superconductor-tors. He is particularly interested in the novel quantum phases emerging in frustrated magnets and their topological properties. Originally from Ukraine, he received his PhD in physics from Cambridge University in the UK, before moving to Université de Sherbrooke in Canada as a postdoctoral fellow to work on high-temperature cuprate superconductors. Prior to joining Rice in 2010, he was a postdoctoral researcher in the Center for Materials Theory at Rutgers University, conducting research into heavy fermion materials. He is the recipient of the NSF CAREER Award and the Cottrell Scholar Award from Research Corporation for Science Advancement.
Surface Ferromagnetism and 1D Edge State Transport in SmB$_6$

The Kondo insulator compound SmB$_6$, with hybridization between itinerant conduction electrons and localized f-electrons driving an insulating gap and metallic surface states at low temperatures, is an ideal candidate for realizing the topological Kondo insulator state. I will present our extensive milliKelvin magnetotransport measurements of SmB$_6$ that provide evidence for the existence of surface ferromagnetism. By exploiting the presence of this time reversal symmetry breaking state, we investigate the topological nature of metallic surface states. We find evidence of one-dimensional surface transport with conductance values approaching the quantized value of e^2/h and originating from the chiral edge channels of ferromagnetic domain walls, providing strong evidence that topologically non-trivial surface states exist in SmB$_6$. 

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Emergence of Superconductivity in the Presence of Two Kinds of Fluctuations

In this talk we compare the emergence of superconductivity, in the presence of two kinds of fluctuations. First, we explore the vicinity of a magnetic quantum critical point where quantum fluctuations are the pairing glue for the formation of Cooper pairs. In contrast, we present a situation where an emergent symmetry controls the fluctuations in a wide region of the phase diagram, leading to d-wave Cooper pairing in competition with d-wave charge order. Application to high temperature superconductors will be discussed.
Identifying Exotic Electronic Ground States Using Quantum Oscillations: The Case of the Kondo Insulator SmB₆

The experimental tool of quantum oscillations have found widespread use in mapping the characteristic electronic structures of strongly correlated materials ranging from heavy fermions to unconventional superconductors. My research focusses on the use of this powerful tool to identify exotic ground states in strongly correlated electron systems. I will present the surprising observation of quantum oscillations from the insulating bulk of the Kondo insulating material samarium hexaboride. An unconventional origin of quantum oscillations is indicated from experimental evidence I will show for novel itinerant low energy excitations. Potential models will be discussed in the context of our findings.

Suchitra Sebastian is Associate Professor in Physics at the University of Cambridge. She searches for exotic quantum phases of matter in new and interesting materials, often by studying them under extreme conditions of high magnetic fields, enormous pressures, and low temperatures. Materials families she studies include unconventional superconductors, and f-electron systems she recently found to display strange dual metal-insulating behaviour.
Strong Correlations and Spin-Orbit Couplings in Kondo Lattice Systems

Strongly correlated electrons represent a vibrant field that continues to expand its horizon. In heavy fermion systems, local moments interact with each other through an RKKY interaction, which contains a variable degree of frustration, and are also coupled to a bath of conduction electrons via the Kondo interaction. Theoretical models of heavy fermion systems consider the interplay between these two types of interactions, which lies at the heart of quantum criticality and a plethora of emergent magnetic and superconducting phases. The underlying physics that goes beyond Landau’s framework is organized by a global phase diagram. There is a rising interest in studying the explicit effect of spin-orbit couplings in such models, and this promises to uncover a new set of phases that are both strongly correlated and topologically non-trivial. An example is the recently predicted Weyl-Kondo semi-metal phase [1], whose key signature has been realized in a new heavy fermion compound [2].

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References:

Prof. Qimiao Si works in theoretical condensed matter physics, with an emphasis on strongly correlated electron systems. One area of Prof. Si’s current interest is quantum criticality. He and his collaborators have advanced a new type of quantum critical point that has considerably shaped the development of the heavy-fermion field. Another focus of Prof. Si’s current research concerns iron-based superconductivity. His work has elucidated the bad-metal behavior in the normal state, and its relationship with magnetism and superconductivity. Prof. Si obtained his B.S. degree in Physics from University of Science and Technology of China in 1986, and his Ph.D. degree in Physics from the University of Chicago in 1991. He did his postdoctoral works at Rutgers University and University of Illinois at Urbana-Champaign. In 1994 he joined the faculty of Rice University, where he is the Harry C. and Olga K. Wiess Professor of Physics. Prof. Si was named a Sloan Research Fellow in 1996, and received a Cottrell Scholar Award from the Research Corporation for Science Advancement in 1998. He was elected a Fellow of the British Institute of Physics in 2004, the American Physical Society in 2005, and the American Association for the Advancement of Science in 2008. He received a Humboldt Prize from the Alexander von Humboldt Foundation in 2012.
Magnetotransport of Surface States in HfNiSn Single Crystals

The large family of half-Heusler compounds hosts a number of topological insulator materials and potential topological superconductors, making these compounds interesting candidates to study physical phenomena on the verge of a topological phase transition. Here we present first magnetotransport measurements on high-quality single crystals of HfNiSn, which according to density functional theory calculations is a nonmagnetic, topologically trivial semiconductor without a bulk band inversion. Our samples show unconventional transport properties already at moderately low temperatures $T < 200$ K. Instead of the thermal carrier freeze-out expected for a bulk semiconductor, electrical conduction in HfNiSn is increasingly dominated by metallic surface states, with a saturation of the longitudinal resistance and highly nonlocal transport. X-ray diffraction shows no structural transitions that could potentially lead to anisotropic conduction in this temperature regime. Magneto-resistance measurements are consistent with weak anti-localization, a signature of low-dimensional transport in a system with strong spin-orbit coupling. The transverse resistance shows an anomalous Hall effect even at zero magnetic field, possibly indicating the presence of chiral edge states. Nonlinearities in $I(V)$ curves at low temperatures suggest a possible role of electronic correlations.

Lucia Steinke received her PhD in physics from the Technical University of Munich, Germany in 2009. After her doctoral research at the Walter Schottky Institute for fundamental research in semiconductor electronics, she worked as a postdoctoral researcher for the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany. She joined Meigan Aronson’s group at Brookhaven National Laboratory in 2014 and in the next year followed Prof. Aronson to her new appointment at Texas A&M University. Lucia’s research interests evolved from novel one-dimensional states along MBE corner-overgrown quantum Hall line junctions to magnetic and multipolar phases in rare-earth intermetallic compounds, as well as magnetism and quantum criticality in transition-metal based compounds. Relating to her PhD work on quantum Hall systems, she recently became interested in topological materials, where she hopes to contribute to the discovery of new topological states and emergent phenomena connected to topological phase transitions.
Pressure-Induced Quantum-Phase Transitions in a Heavy-Fermion Metal

There now are multiple examples of quantum-phase transitions (QPTs) accessed by applying a magnetic field, pressure or both to a heavy-fermion antiferromagnet. In some of these examples, e.g., CeCu$_{6-x}$Au$_x$ and YbRh$_2$Si$_2$, inconsistencies between experimental observations and theoretical expectations of ‘conventional’ criticality motivated new theoretical concepts to account for measured properties. Unlike the convention model that is a quantum extension of the theory of thermally-driven phase transitions, these unconventional models invoke criticality of electronic degrees of freedom that may be coincident with magnetic criticality. Measurements, such as Hall effect, deHaas-vanAlphen and thermoelectric power, that are sensitive to the electronic structure have been instructive for identifying unconventional forms of criticality in which a qualitative reconstruction of the Fermi surface is expected. In this talk, I discuss recent thermopower measurements on a derivative of the unconventional quantum-critical material CeRhIn$_5$, the heavy-fermion antiferromagnet CeRh$_{1.08}$Ir$_{0.42}$In$_5$. As pressure is applied to this material, there is a discontinuous jump in thermopower that signals an abrupt Fermi-surface reconstruction at $p_{c1}$, expected of an unconventional QPT, and this is followed by a conventional QPT at $p_{c2}$ across which the Fermi surface evolves smoothly to a heavy Fermi-liquid state. The variation of thermopower with pressure and temperature around these two QPTs is a particularly clear experimental manifestation of theoretical predictions.

Work was performed in collaboration with Y. K. Luo, X. Lu, P. F. S. Rosa, and Q. Si and under the auspices of the U.S. DOE, Division of Materials Sciences and Engineering.

Thompson is a Fellow of Los Alamos National Laboratory, the APS and AAAS. His research interest has been the discovery and understanding of new physics in new materials, particularly but not exclusively in rare-earth and actinide heavy-fermion systems under applied pressures.