**Professional Accomplishments**

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## High temperature superconductivity

The advent of high temperature superconductivity in the layered copper oxide materials opened many new directions for superconductivity, from anisotropy in the normal and superconducting properties to enhanced thermodynamic fluctuations to the role of hole and electron doping on properties. Notable achievements include

- the first and still definitive measurement of the upper critical field in $YBa_2Cu_3O_7$, separating the effects of vortex motion from the formation of the superconducting state.
- definitive measurements of fluctuation behavior at the onset of superconductivity in zero and applied field, correlating fluctuations in magnetization, resistivity, heat capacity, and Ettingshausen effect in a single picture.
- first and still definitive study of the anisotropic effect of uniaxial stress on the transition temperature of $YBa_2Cu_3O_7$, showing surprisingly large and opposite effects of pressure along the a- and b- axes that average to zero in a hydrostatic environment.

## Vortex matter

The cuprate superconductors bring four basic vortex energies into competition: the vortex-vortex repulsion energy favoring lattice formation, the thermal energy favoring liquid formation, the pinning energy favoring glass formation, and the Josephson tunneling energy between cuprate layers favoring the formation of conventional Abrikosov vortices from pancake vortices. The interplay of these four energies produces a rich phase diagram of lattice, liquid, and glassy vortex states, now referred to as "vortex matter" in recognition of its analogs with ordinary atomic matter. My research in vortex matter was recognized with the Kamerlingh Onnes Prize in Experimental Superconductivity for 2003. Notable accomplishments include

- definitive observation of the first order vortex melting transition in thermodynamic magnetization and heat capacity and in steady state transport measurements. These papers are now the standard references in the field and established the vortex liquid state as new phase of vortex matter.
- definitive measurements and interpretation of upper and lower critical points on the vortex melting line, where the phase transition shifts from first to second or higher order. Increasing line disorder is shown to drive the lower critical point to higher field leaving a Bose glass state in its wake and allowing the first quantitative measurement of the minimum disorder needed to destroy the lattice.
- an unusual phase transition in the vortex liquid revealed in the equilibrium heat capacity separating a liquid of vortex lines with line tension from a liquid of vortex line segments with reduced or vanishing line tension.
- the first identification of twin boundaries as strong pinning defects, a major factor in creating disordered glassy states and high critical currents in $YBa_2Cu_3O_7$.
- systematic studies of the effects of point and line pinning defects on the glassy states of $YBa_2Cu_3O_7$ through controlled irradiation and transport measurements.
- pioneering studies of dynamic correlation of moving vortex states using the Corbino disk geometry where driving forces overcome pinning forces at the onset of motion and vortex-vortex interactions restore lattice-like spatial order to the moving vortex array.

**Two-band superconductivity**

The discovery of superconductivity at approximately 40K in $MgB_2$ revealed two distinct bands of superconducting electrons with distinct order parameters, dimensionalities, critical fields, coherence lengths and penetration depths. The implications of this fascinating set of circumstances are yet to be fully understood. My notable accomplishments include

- scanning tunneling microscopy studies as a function of temperature and magnetic field that resolve the two energy gaps and map their evolution.
- observation of zero resistance above the thermodynamic superconducting transition temperature in magnetic fields parallel to the c-axis, possibly related to surface superconductivity.

**Mesoscopic superconductivity and magnetism**

Structure in superconductors on the scale of the superconducting coherence length or the magnetic penetration depth and in magnets on the scale of the domain wall thickness or the magnetic coherence length induces fundamentally new behavior with potentially profound scientific and technological implications. My work explores the challenge of fabricating complex structures with the required length scales and the response of such structures to magnetic and electric fields. Notable accomplishments include

- fabrication of periodic nanoporous arrays allowing the deposition of perforated superconducting or magnetic films
- fabrication of nanowires and nanoribbons of the charge density wave material $NbSe_3$ and its subsequent conversion to the superconductor $NbSe_2$
- fabrication of 3D regular geometric solids (icosahedra, dodecahedra, cubes, hexagons), nanowires, brushes, snowflakes, and tripods by kinetic electrodeposition on graphite substrates
- commensurate pinning and matching effects in superconductors with nanoscale periodic pinning arrays

**Organic superconductors**

The large highly layered unit cells of the organic superconductors admit a wide range of structural and compositional variation. My research reveals the structure of their low dimensional Fermi surfaces and the variation in their effective masses, their upper critical fields, and the competition of weak ferromagnetism with superconductivity. Notable accomplishments include

- definitive studies of the Fermi surfaces and effective masses of layered organic superconductors through quantum oscillations.
- the discovery of a weakly ferromagnetic phase adjacent to the high pressure superconducting phase of kappa-$(ET)_2Cu[N(CN)_2Cl)$ where Coulomb correlation creates localized magnetic states through a Mott-Hubbard transition. The magnetic structure is complex, exhibiting a sequence of "devil's staircase" canted antiferromagnetic states with temperature and field. The close proximity of superconductivity and magnetism in this compound demonstrates the strong role of Coulomb correlation in mediating between the two competing ground states.

**Magnetic superconductors**

The magnetic superconductors display simultaneous magnetism and superconductivity, violating the conventional wisdom that these two forms of order are mutually exclusive. One of the most interesting cases is the re-entrant compound $ErRh_4B_4$, where superconducting order at 8.6 K is quenched by ferromagnetic order near 1K. The presence of large paramagnetic local moments above the ferromagnetic transition dramatically affects the anisotropy and stability of the superconducting state, while the onset and growth of an internal magnetic field at the ferromagnetic transition opens the possibility of coexisting superconducting and magnetic states with spontaneous vortex formation. Notable accomplishments include

- the definitive study of the effect of local moments on the magnetic phase diagram of $ErRh_4B_4$, including a novel first order transition from the Meissner to the vortex state and crystal field-induced magnetic anisotropy in the upper critical field.
- the definitive study of the coexistence of magnetism and superconductivity at the re-entrant transition, showing that superconductivity induces a long-range incommensurate oscillating magnetic order before finally being quenched by the more stable ferromagnetic order.

**Electronic structure of correlated electron metals**

Correlated electron metals display two fundamental limits at low temperature: localization to magnetic or insulating ground states due to Coulomb repulsion, and condensation to superconducting ground states due to attractive pairing by the electron-phonon interaction or other exotic mechanisms. Among the transition elements, Pd and Pt are “nearly ferromagnetic” (they are easily localized by the addition of a few magnetic atoms), and Nb is the highest transition temperature superconductor among the naturally occurring elements. My studies of these two limits of correlated electrons are among the first definitive experiments revealing the **k**-dependence of electron correlation in superconducting or localized magnetic ground states. Notable accomplishments include

- definitive studies of the **k**-dependence of the Fermi radii, Fermi velocities, and effective masses of Pd, Pt, and Nb.
- the first measurement of the **k**-dependence of the superconducting energy gap in a superconductor (Nb), showing that **k**-dependence of gap anisotropy correlates with the **k**-dependence of the strength of the electron-phonon pairing interaction.
- definitive measurements of the **k**-dependence of transition metal (Au, Pt, Pd) itinerant electron Zeeman splitting.

4f and 5f electron systems allow tuning electronic correlation by the degree of hybridization between local f-electrons and itinerant s-, p-, and d-electrons. My studies show that hybridized f-electrons have explicit itinerant character described by Bloch’s theorem and the conserved momentum **k**, and that they can be treated and understood using the principles of correlated electronic structure calculations. My studies run the gamut of f-electron behavior, including mixed valent compounds such as $CeSn_3$, systematic f-electron itinerancy in $UGe_3$, $USn_3$, $UPb_3$, localized f-electron magnets such as $U_3As_4$, $U_3P_4$, and CeSb, and Kondo lattices such as $CeB_6$. Notable achievements include

- the first observation of coherent Bloch states in a mixed-valent metal ($CeSn_3$) directly demonstrating that **k** is a good quantum number for these systems. This work established that highly correlated metals can be probed experimentally by quantum oscillations and described theoretically by band structure and Fermi surface concepts. This result inspired a wave of quantum oscillation experiments in other highly correlated and heavy fermion metals such as $UPt_3$ and $CeB_6$.

- the first observation of a field dependent effective mass in an f-electron system ($CeB_6$), showing directly the tendency to saturation of Kondo compensation of a local moment by a specific set of conduction electrons.
- the definitive study of the role of conduction electrons in mediating the “devil’s staircase” magnetic order in CeSb.