# Chapter 1. Physics of Single-Electron Transistors and Doped Mott Insulators

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## 1.1 Quantum Magnetism

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The transition-metal oxide Interdisciplinary Research group of the MRSEC at MIT has the goal of understanding the interplay of magnetism and electron motion in materials related to those which display high temperature superconductivity. The group focuses on Cu oxides which contain spin-1/2 ions in unusual geometries. In particular, all the high-temperature superconductors have $CuO_2$ layers in which the spin-1/2 ions are arranged on a square lattice and the nearest neighbors interact in a way that is well-described by the Heisenberg model: $JS_i \bullet S_j$. These are quantum magnets because the small spin results in large quantum mechanical fluctuations in magnetic moment. Other quantum magnets that have received attention recently are those containing chains of Cu ions or pairs of chains (ladders) weakly coupled to each other. We have studied $Sr_2Cu_3O_4Cl_2$, a variant of the lamellar copper oxides containing an extra $Cu^{2+}$ ion in the center of every second plaquette. The two types of Cu form interpenetrating Heisenberg antiferromagnets, which order at 380 K and 40 K. Magnetization measurements yield a small spontaneous ferromagnetic moment below 380 K and two spin rotation transitions. The results have been explained in detail by a pseudo-dipolar coupling between the two Cu lattices. A quantitative analysis of the data has yielded several previously unknown microscopic coupling constants, relevant to other lamellar, chain and ladder copper oxides. Neutron measurements have provided a complete description of the spin waves in this new system.

## 1.2 Electrochemistry and Staging in $La_2CuO_{4+\delta}$

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Measurements are reported of the time dependence of the current during electrochemical oxidation and reduction at a fixed voltage of single crystals and ceramic samples of $La_2CuO_{4+\delta}$. Staging peaks in neutron measurements of the single crystals together with the electrochemical measurements and magnetization measurements confirm that stage n = 6 corresponds to $\delta = 0.055 \pm 0.05$, the high-delta-side of the oxygen-rich-oxygen-poor miscibility gap. Furthermore, stage n = 4 occurs at a value of $\delta$ consistent with delta proportional to $n^{-1}$. For ceramic samples it is shown that two different superconducting compounds are formed depending on the oxidation voltage used.

## 1.3 Midinfrared Optical Excitations in Undoped Lamellar Copper Oxides

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The weakly electric-dipole-allowed midinfrared excitations are studied in insulating single crystals of $La_2CuO_4$, $Sr_2CuO_2Cl_2$, and $Nd_2CuO_4$. These intrinsic excitations of the undoped $CuO_2$ layers are lower in energy than the charge-transfer excitation. Temperature-dependent optical-absorption measurements are presented from 10 to 450 K. Photoinduced absorption measurements on single-crystal $La_2CuO_4$ are also presented. Recent theoretical work and optical-absorption experiments on $La_2NiO_4$, as well as the copper oxides, provide strong evidence that a sharp absorption peak seen in all the copper oxides at photon energy similar to 0.4 eV and a related peak near 0.25 eV in $La_2NiO_4$ arise from phonon-assisted creation of a quasibound two-magnon state. A comparison between the intrinsic absorption in $La_2NiO_4$ and that in the copper oxides suggests that the broad midinfrared absorption bands observed between 0.4 and 1.2 eV in the undoped copper oxides have a different electronic origin. We discuss our measurements in regards to two proposed origins (phonon-multimagnon and exciton sidebands) for these broad higher-energy bands. We find that multimagnon and phonon sidebands associated with a Cu $d_{(x^2-y^2)} \rightarrow d_{(3z^2-r^2)}$ crystal-field exciton at ~0.5 eV plausibly explain the structure, strength, and polarization dependence of these broad bands.

## 1.4 Systematics of the Photoemission Spectral Function of Cuprates: Insulators and Hole- and Electron-Doped Superconductor

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Angle-resolved photoemission studies on $Sr_2CuO_2Cl_2$ at a temperature below its Neel temperature reveal detailed momentum dependent line shape changes as a function of wave vector. While a sharp quasiparticle-like peak is observed near ($\pi/2$, $\pi/2$), broad peaks are observed near ($\pi$, 0). Additional second and third neighbor hopping terms must be added to the t-J Hamiltonian to account for both the dispersion and the line shape. It is found that this Hamiltonian can be used to explain the measured momentum dependent spectral function for hole-doped materials, both underdoped and overdoped, as well as electron-doped materials.

## 1.5 Doping Dependence of the Spatially Modulated Dynamical Spin Correlations and the Superconducting-Transition Temperature in $La_{2-x}Sr_xCuO_4$

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Systematic low-energy neutron-scattering studies have been performed on float-zone-grown single crystals of $La_{2-x}Sr_xCuO_4$ with x extending from zero doping, x = 0, to the overdoped, weakly superconducting regime, x = 0.25. For x beyond a critical doping value of x(c) approximate to 0.05, the low-energy spin-fluctuation peak position shifts from (1/2,1/2) to ($1/2 \pm \delta$,1/2), and ($1/2,1/2 \pm \delta$); x(c) also represents the onset concentration for superconductivity. For $0.06 \leq x \leq 0.12$ the incommensurability $\delta$ follows approximately the quantitative relation $\delta = x$. However, beyond $x \approx 0.12$ the incommensurability tends to saturate around delta approximate to 1/8. The superconducting-transition temperature $T_c(x)$ for stoichiometric samples at a given doping scales linearly with delta up to the optimal doping value of x. The peak momentum width of the spin fluctuations at low energies is small throughout the superconducting concentration region except in the strongly overdoped region. An anomalously small width is observed for x = 1/8. The incommensurate spatial modulation is found to be robust with respect to pair-breaking effects that lower $T_c$, such as deoxygenation of the sample or replacement of Cu by Zn.

## 1.6 Kondo Effect in a Single-Electron Transistor

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**Project Staff**

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How localized electrons interact with delocalized electrons is a central question to many problems in solid-state physics. The simplest manifestation of this situation is the Kondo effect, which occurs when an impurity atom with an unpaired electron is placed in a metal. At low temperatures a spin-singlet state is formed between the unpaired localized electron and delocalized electrons at the Fermi energy. Theories predict that a Kondo singlet should form in a single-electron transistor (SET), which contains a confined 'droplet' of electrons coupled by quantum-mechanical tunnelling to the delocalized electrons in the transistor's leads. If this is so, a SET could provide a means of investigating aspects of the Kondo effect under controlled circumstances that are not accessible in conventional systems: The number of electrons can be changed from odd to even, the difference in energy between the localized state and the Fermi level can be tuned, the coupling to the leads can be adjusted, voltage differences can be applied to reveal non-equilibrium Kondo phenomena, and a single localized state can be studied rather than a statistical distribution. But for SETs fabricated previously, the binding energy of the spin singlet has been too small to observe Kondo phenomena. We report measurements on SETs smaller than those made previously, which exhibit all of the predicted aspects of the Kondo effect in such a system.

## 1.7 Insulator to Quantum Hall Liquid Transition in an Antidot Lattice

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Magnetic-field-induced transition from insulator to quantum Hall liquid is observed in a two-dimensional electron gas system with a triangular lattice of small circular depletion regions (antidots). In the insulating regime the localization length is close to the antidot lattice constant at zero magnetic field and oscillates with a period of h/2e as a function of magnetic flux threading through the unit cell of the antidot lattice. A sample shows resistivity oscillations with a period of h/e at high magnetic field where the filling factor for Landau levels is less than unity. The high-held oscillations may result from the quantization of composite fermion orbits around an antidot.

## 1.8 From the Kondo Regime to the Mixed-Valence Regime in a Single-Electron Transistor

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We demonstrate that the conductance through a single-electron transistor at low temperature is in quantitative agreement with predictions of the equilibrium Anderson model. The Kondo effect is observed when an unpaired electron is localized within the transistor. Tuning the unpaired electron's energy toward the Fermi level in nearby leads produces a crossover between the Kondo and mixed-valence regimes of the Anderson model.

## 1.9 Publications

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