Physics of Single Electron Transistors and Doped Mott Insulators

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Statistics of the Coulomb-blockade peak spacings of a silicon quantum dot

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We have made a study of the fluctuations of Coulomb-blockade peak positions of a quantum dot. The dot is defined by patterning the two-dimensional electron gas of a silicon metal-oxide-semiconductor field-effect transistor structure using stacked gates. This permits variation of the number of electrons on the quantum dot without significant shape distortion. The ratio of charging energy to single-particle energy is considerably larger than in comparable $GaAs/Al_xGa_{1-x}As$ quantum dots. The statistical distribution of the conductance peak spacings in the Coulomb-blockade regime was found to be unimodal and does not follow the Wigner surmise. The fluctuations of the spacings are much larger than the typical single-particle level spacing and thus clearly contradict the expectation of constant interaction-random matrix theory.

Kondo effect 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.

Quantum Magnetism

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The transition-metal oxide IRG 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, the high temperature superconductors all 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-dexcribed 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.

The Cu_3O_4 layer in $Sr_2Cu_3O_4Cl_2$ is a variant of the square CuO_2 lattice of the high-temperature superconductors, in which the center of every second plaquette contains an extra Cu^{2+} ion. The ions that make up the conventional CuO_2 network, called CuI, have CuI-CuI exchange energy ~130 meV, and order antiferromagnetically at about 380 K; the CuII-CuII exchange is only ~ 10 meV, and the CuII's order at ~ 40 K. We have studied the dependence of the magnetization on field, temperature, and crystallographic orientation for this interesting system. We show that the small permanent ferromagnetic moment, that appears when the CuI spins order, and the unusual spin rotation transitions seen most clearly for one particular direction of the magnetic field, are the result of several small bond-dependent anisotropic terms in the spin Hamiltonian that are revealed because of the frustration of the isotropic Heisenberg interaction between CuI and CuII spins. These include a term which favors collinearity of the CuI and CuII spins, which originates from quantum fluctuations, and also a pseudodipolar interaction. Some of these small interactions also come into play in other lamellar cuprates, connected with the high-T_c superconductivity materials, and in many spin-chain and spin-ladder compounds.

The classical ground state of this system is degenerate, due to frustration of the intersubsystem interactions. Magnetic neutron scattering experiments show that quantum fluctuations cause a two dimensional Ising ordering of the Cu-II's, lifting the degeneracy, and a dramatic increase of the Cu-I out-of-plane spin-wave gap, unique for order out of disorder. The spin-wave energies are quantitatively predicted by calculations which include quantum fluctuations.

We have carried out a quantum Monte Carlo study of the thermodynamic properties of arrays of spin ladders with various widths (n), coupled via a weak interladder exchange coupling αJ, where J is the intraladder coupling both along and between the chains. This coupled ladder system serves as a simplified model for the magnetism of presumed ordered spin and charge stripes in the two-dimensional CuO_2 planes of hole-doped copper oxides. Our results for n = 3 with weak interladder coupling α = 0.05, estimated from the t-t'-t''-J model, show good agreement with the ordering temperature of the recently observed spin-density-wave condensation in La_2CuO_{4+y}. We show that there exists a quantum critical point at $\alpha_c \sim 0.07$ for n = 4, and determine the phase diagram. Our data at this quantum critical point agree quantitatively with the universal scaling predicted by the quantum nonlinear a model. We also report results on random mixtures of n = 2 and n = 3 ladders, which correspond to the doping region near but above 1/8. Our study of the magnetic static structure factor reveals a saturation of the incommensurability of the spin correlations around 1/8, while the incommensurability of the charge stripes grows linearly with hole concentration.

We have carried out a neutron-scattering study of the instantaneous spin-spin correlations in La_2CuO_4 (T_N = 325 K) over the temperature range 337-824 K. Incident neutron energies varying from 14.7-115 meV have been employed in order to guarantee that the energy integration is carried out properly. The results so obtained for the spin-correlation length as a function of temperature when expressed in reduced units agree quantitatively both with previous results for the two-dimensional (2D) tetragonal material $Sr_2CuO_2Cl_2$, and with quantum Monte Carlo results for the nearest-neighbor square lattice S = 1/2 Heisenberg model. All of the experimental and numerical results for the correlation length are well described without any adjustable parameters by the behavior predicted for the quantum nonlinear sigma model in the low-temperature renormalized classical regime. The amplitude, on the other hand, deviates subtly from the predicted low-temperature behavior.

Neutron-scattering study of spin-density wave order in the superconducting state of excess-oxygen-doped La_2CuO_{4+y}

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Personnel: Lee YS, Birgeneau RJ, Kastner MA, Endoh Y, Wakimoto S, Yamada K, Erwin RW, Lee SH, Shirane G

We have made neutron-scattering measurements of spin-density wave order within the superconducting state of a single crystal of predominately stage-4 La_2CuO_{4+y} with a T_c (onset) of 42 K. The low-temperature elastic magnetic scattering is incommensurate with the lattice and is characterized by long-range order in the copper-oxide plane with the spin direction identical to that in the insulator. Between neighboring planes, the spins exhibit short-range correlations with a stacking arrangement reminiscent of that in the undoped antiferromagnetic insulator. The elastic magnetic peak intensity appears at the same temperature within the errors as the superconductivity, suggesting that the two phenomena are strongly correlated. These observations directly reveal the persistent influence of the antiferromagnetic order as the doping level increases from the insulator to the superconductor. In addition, our results confirm that spin-density wave order for incommensurabilities near 1/8 is a robust feature of the La_2CuO_4-based superconductors.

Observation of incommensurate magnetic correlations at the lower critical concentration for superconductivity in $La_{2-x}Sr_xCuO_4$ (x=0.05)

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Personnel: Wakimoto S, Shirane G, Endoh Y, Hirota K, Ueki S, Yamada K, Birgeneau RJ, Kastner MA, Lee YS, Gehring PM, Lee SH

Neutron-scattering experiments have been performed on lightly doped $La_{2-x}Sr_xCuO_4$ single crystals in both the insulating (x = 0.03,0.04,0.05) and superconducting (x = 0.06) regions. Elastic magnetic peaks are observed at low temperatures in all samples with the maximum peak linewidth occurring at the critical concentration x = 0.05. Incommensurate peaks are observed only at x = 0.05, the positions of which are rotated by 45 degrees in reciprocal space about (π,π) from those observed for x ≥ 0.06 in the superconducting phase.

Neutron-scattering study of static antiferromagnetic correlations in $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$

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Neutron-scattering measurements have been performed to search for possible elastic incommensurate magnetic peaks in superconducting $La_{2-x}Sr_xCuO_4$ with x=0.10, 0.12, and 0.15. The most dramatic effects are found for x=0.12; in this case, the peak intensity first appears at the onset of superconductivity Tc (=31 K). The resolution-limited peak width indicates that the static magnetic correlation length exceeds 200 Angstrom isotropically in the CuO_2 planes. Weak elastic peaks are also observed at low temperatures for x=0.10 while for x = 0.15 any incommensurate elastic scattering is below the limit of detectability. Elastic peaks are observed in Zn-substituted nonsuperconducting $La_{1.88}Sr_{0.12}Cu_{0.97}Zn_{0.03}O_4$ However, in this case, the Zn substitution degrades the magnetic order; the peak appears at lower temperature (17 K) and the correlation length is shorter (80 Angstrom) than that in the Zn-free x = 0.12 sample.

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