The coexistence of superconductivity and ferromagnetism in nanoscale metallic grains

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A nano-scale metallic grain in which the single-particle dynamics are chaotic is a zero-dimensional system described by the so-called universal Hamiltonian. This Hamiltonian includes a superconducting pairing term and a ferromagnetic exchange term that compete with each other: pairing correlations favor minimal ground-state spin while the exchange interaction favors maximal spin polarization. Of particular interest is the fluctuation-dominated regime where the bulk pairing gap is comparable or smaller that the single-particle mean level spacing and the BCS theory of superconductivity breaks down. We find that superconductivity and ferromagnetism can coexist in this regime. Signatures of the competition between superconductivity and ferromagnetism are identified in a number of quantities:

Ground-state spin [1]. The coexistence regime is characterized by a ground state in which a number of electrons in the vicinity of the Fermi energy are polarized while all other electrons are paired. The coexistence region is characterized by jumps of more than one unit in the ground-state spin.

Conductance fluctuations [2]. The tunneling conductance through an almost-isolated grain that is connected to leads exhibits Coulomb blockade peaks as a function of a gate voltage. Pairing correlations leads to bimodality in the peak spacing distribution while exchange correlations suppress the conductance peak height fluctuations.

Thermodynamic properties and their mesoscopic fluctuations [3,4]. Pairing correlations lead to number-parity effects in the thermodynamic properties of the grain such as the heat capacity and spin susceptibility. The effects of spin exchange correlations differ qualitatively between the BCS and fluctuation-dominated regimes.

We have used two methods to calculate thermodynamic properties: (i) a quantum Monte Carlo method [3] and (ii) an approach in which exchange correlations are treated exactly using spin projection methods, while pairing correlations are treated in the static path approximation plus small amplitude time-dependent fluctuations around each static value of the pairing field [4]. Odd-even effects in the number of electrons are captured by a number-parity projection.

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[3] K. Van Houcke, Y. Alhassid, S. Schmidt, and S. Rombouts, arXiv: 1011.5421 (2010).

[4] K. Nesterov and Y. Alhassid, in preparation (2011).