Does T^* – the temperature that defines the onset of the pseudogap regime in underdoped cuprates – correspond to a phase transition or a crossover?

Nature of the enigmatic pseudogap state: novel magnetic order in superconducting $HgBa_2CuO_{4+d}$

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Thermodynamic signature of a phase transition to the pseudogap phase of $YBa_2Cu_3O_x$ high-T_c superconductor

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A consensus on the microscopic origin of superconductivity in metals has been achieved whenever superconductivity can be shown to emerge, upon decreasing temperature, from a Fermi-liquid phase of matter. In contrast, for a large range of doping in hole-doped cuprates, the state from which superconductivity originates upon decreasing temperature appears not to be a genuine Fermi liquid. In the underdoped regime, the phenomenology of the pseudogap characterizes an intermediate range of temperature bounded from below by the onset of d-wave superconductivity at the critical temperature T_c and from above by the temperature T^*. The pseudogap regime is characterized by a loss in the number of charge and spin degrees of freedom with decreasing temperature as measured by transport, thermodynamic, and spectroscopic probes. Moreover, the doping dependence of T_c and T^* are opposite (T_c decreases with underdoping whereas T^* increases) in the underdoped regime while they appear to merge around optimal doping. The fact that, more than twenty years after its discovery, the origin of superconductivity in the cuprates remains an outstanding open problem in physics has often been attributed to the mystery represented by the origin of the pseudogap. Is it a crossover phenomenon or is it a genuine new phase of matter characterized by an order parameter that has remained hidden until now?

There were early reports of time-reversal symmetry breaking in the pseudogap regime using spectroscopic probes: muon spin rotation [3], angle resolved photoemission spectroscopy dichroism [4], and neutron scattering [5]. However, these observations are controversial (see Refs. [6], [7], and [8]). More recently, two papers reported the observation of time-reversal symmetry breaking using polarized neutron scattering on the YBCO family [9, 10]. The lack of change of translational symmetry makes the experiment very hard to do because the magnetically induced spin-flip scattering of neutron occurs on top of some of the Bragg peaks due to the nuclear scattering. The nuclear Bragg scattering intensity is typically two orders of magnitude larger than magnetic scattering from an ordered magnetic array of $\mathcal{O}(10^{-1})\mu_B$. Extraordinary care has to be taken with high neutron polarization (flipping ratio as high as 95) and making sure that it does not change with temperature.

The associated breaking of time-reversal invariance was supported by a polar Kerr-effect measurement on the YBCO family [11]. Here, we comment on two complementary papers reporting spectroscopic as well as thermodynamic evidences for a new state of matter in the pseudogap phase.

Using polarized neutron scattering, a novel magnetic signal has been observed in underdoped mercury based cuprate superconductors in Ref. [1]. As in Refs. [9, 10], the effect occurs at positions in reciprocal space that had been overlooked in older neutron experiments. In addition, through progress in the growth of sizable high-quality Hg1201 single crystals, such measurements could be performed on a hole-doped family of cuprates that has a simple tetragonal crystal structure with only one CuO_2 layer in the unit cell, the highest T_c among single-layer compounds, a wide accessible doping range, and minimal effects from disorder.

Remarkably, the signal appears well above T_c for all samples and correlates well with T^* as determined from resistivity measurements. The signal is observed at the reciprocal point $\boldsymbol{Q} = (1, 0, 1)$ and its equivalents (tetragonal symmetry notation), which indicates that, unlike the ordering wave vector $\boldsymbol{Q} = (1/2, 1/2, 0)$ that characterizes a d-density wave order parameter for spontaneously circulating currents [12], the novel order preserves translation symmetry. Another important observation is the "dramatic" decrease of the intensity with increasing $|\boldsymbol{Q}|$ that indicates a rather delocalized nature of the magnetic moment. Finally and maybe the most astonishing result, is the observation that the magnetic moment possesses a large in-plane component. These results are crucial since on a different family of cuprates, they confirm those reported earlier in Refs. [9, 10] on YBCO.

That T^* corresponds to a phase transition rather than a crossover is also inferred from a second recent report by Leridon, Monod, and Colson in Ref. [2]. In this work a detailed analysis of the uniform static magnetic susceptibility taken on the YBCO family over a wide range of doping indicates a subtle anomaly of the temperature derivative at temperatures corresponding to the pseudogap temperatures determined by the polarized neutron scattering experiments in Refs. [9, 10]. What is remarkable about this experiment is the sensitivity level for magnetization of $10^{-7}\mu_B$ per unit-cell and a temperature resolution of 1 K.

The appearance of circulating currents as a defining property of the pseudogap phase that are consistent with the breaking of time-reversal symmetry without the breaking of translation invariance seen in the polarized neutron results of Ref. [1] (as well as Refs. [9, 10]) had been predicted in Ref. 13. In this scenario, the circulating currents are restricted to the CuO_2 planes and thus imply a magnetic moment aligned along the c-axis in contradiction with the observation in Ref. [1]. Evidently, a modification of this idea (involving apical oxygen as suggested by the authors of Refs. [14] and [1]) or perhaps an entirely new idea will be needed for a satisfactory explanation of these exciting data. A theoretical challenge will be to reconciliate the smooth dependence on temperature of the specific heat with the nonanalytic dependence of the uniform static magnetic susceptibility as a function of temperature claimed in Ref. [2].

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[2] B. Leridon, P. Monod, and D. Colson, *Thermodynamic signature of a phase transition to the pseudogap phase of $YBa_2Cu_3O_x$ high-T_c superconductor*, arXiv:0806.****.

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