New Surprises in the Nernst Effect of Cuprate Superconductors

"Broken rotational symmetry in the pseudogap phase of a high-Tc superconductor"

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arXiv:0909.4430 (in press, Nature)

Recommended with a commentary by Catherine Kallin, McMaster University

The mysterious pseudogap phase is widely thought to hold the key to understanding high temperature superconductivity in the cuprates. This phase extends up to temperatures well above the superconducting transition temperature, T_c , in underdoped cuprates and exhibits a partial suppression of the density of states around the Fermi energy, a feature which shows up in the temperature dependence of most thermodynamic and transport properties. The onset temperature for the pseudogap, T*, appears to be a crossover, although some experiments point to broken time reversal symmetry and a true (albeit subtle) phase transition at T*.[1] In addition, charge and/or spin stripe-like order has been observed in some materials in some parts of the pseudogap region and other data has been interpreted as evidence for Fermi surface reconstruction in part of the pseudogap region, which implies broken translational symmetry. Still, it remains an important open question as to whether any symmetry breaking is *universally* associated with the pseudogap phase. Therefore, it is of considerable interest that new studies, by Taillefer and coworkers, of the Nernst effect in YBCO suggest that the pseudogap phase is an electronic state which breaks four-fold rotational symmetry.

The Nernst effect, in which a temperature gradient, $\nabla_y T$, induces a transverse electric field, E_x, in the presence of a perpendicular magnetic field, B, has been a powerful probe of superconducting fluctuations and vorticity above T_c in the cuprates.[2] The sign of the Nernst coefficient, $\nu_{xy}=-E_x/B\nabla_y T$, is defined so that the contribution due to superconducting fluctuations is positive, while the contribution due to charged quasiparticles can be of either sign. Daou *et al.* measured the Nernst coefficient in untwinned $YBa_2Cu_3O_y$ crystals over a range of dopings from underdoped to overdoped (p=0.08 to p=0.18). Their data are consistent with other published data where they overlap in doping and temperature. However, while previous studies have focused on the contribution from superconducting fluctuations [2], Daou *et al.* focus on the quasiparticle contribution in a temperature range sufficiently above T_c that the superconducting contribution is negligible. Furthermore, they focus on the anisotropy between ν_{ab} and ν_{ba}, where b is the direction along the CuO chains.

In the normal state at temperatures above T*, the Nernst coefficients are small, positive, mostly independent of temperature, and exhibit a small ab anisotropy. At each doping, Daou *et al.* observe an onset temperature, T_ν, where the Nernst coefficients develop temperature dependence and an enhanced anisotropy that grows with decreasing temperature. This onset temperature coincides with the pseudogap temperature, T*, measured by NMR and other probes, for underdoped YBCO.[3] Below T_ν the Nernst coefficients become negative and remain negative and independent of magnetic field down to about 1.3 T_c. This implies that the contribution from vortices or superconducting fluctuations (which must be positive and field dependent) is negligible outside of a rather narrow region just above T_c. This is consistent with recent measurements of torque magnetization in YBCO, which detect the onset of diamagnetism only below 1.3 T_c or so.[4]

Above such a superconducting fluctuation regime, the Nernst effect is dominated by the quasiparticle contribution, which can have a large and temperature dependent value if the density of states is rapidly varying. We know this to be the case in the pseudogap regime from a
variety of other experiments, including ARPES, specific heat, and magnetic susceptibility. The quasiparticle contribution to the Nernst effect was obscured in earlier measurements done on LSCO, because in LSCO this contribution has the same sign as the vortex contribution. By doping LSCO with Eu, so that its T_c is reduced, a recent study was able to separate the two contributions.[5]

The experiments reported by Daou *et al.* were done on untwinned YBCO crystals, which allowed another remarkable discovery. The quasiparticle contribution has an ab anisotropy that grows with decreasing temperature below T*, and develops into a very substantial anisotropy, with ν_{ab}/ν_{ba} as large as 7. Four-fold rotational symmetry is already broken in YBCO by the presence of chains, and Daou *et al.* make several measurements to determine whether the chains are responsible for the Nernst anisotropy. The most important of these is that they are able to observe directly the effect of chain conductivity on the Nernst anisotropy by maximizing the chain conductivity with a very small change in doping (near y=7.0). When the chain conductivity is maximized, the anisotropy of the conductivity is also maximized and the effect on the Nernst coefficients is clearly observable, but in the direction opposite to the effect which sets in at T* for all dopings. The difference in Nernst coefficients, $D(T)= \nu_{ba}/T-\nu_{ab}/T$, which grows up below T* at all dopings, is reduced when the chain conductivity is maximized.

The above observation, as well as others described in the paper, rule out the chains being responsible in any simple way for the Nernst anisotropy and led Daou *et al.* to suggest that the pseudogap phase strongly breaks four-fold rotational symmetry. (Since this symmetry is already weakly broken by the orthorhombic distortion produced by the chains, domain formation would be suppressed and T* would be a crossover analogous to that of a ferromagnet in a weak magnetic field.) One possibility is that the pseudogap phase has nematic order.[6] In fact, Hackl and Vojta argue that the data are consistent with nematic order developing at T*, if the Fermi surface is in proximity to a van Hove singularity over the doping range studied.[7]

Another possibility discussed by Daou *et al.* is fluctuating stripes.[8] It has recently been shown that stripe order does cause a major enhancement of the quasiparticle Nernst signal, with the sign of the resulting Nernst coefficient depending on the details of the stripe order and band structure.[5,9] However, a question which remains to be addressed is how static the stripes need to be in order to so substantially affect the transport.

In summary, these experiments find a surprisingly large anisotropy below T* and highlight the fact that the Nernst effect can be effectively used to probe quasiparticles and pseudogap physics beyond superconducting fluctuations. Further experiments on compounds without chains or where the anisotropy can be controlled with uniaxial stress, would be of great interest.

[1] See Y. Li, et al., Nature 455, 372 (2008) and references therein. Note that this unusual magnetic order breaks four-fold rotational symmetry.
[2] See, for example, N.P. Ong, Yayu Wang, S. Ono, Yoichi Ando, and S. Uchida, Ann. Phys. (Leipzig) **13**, 9 (2004).
[3] At p=0.18 (slightly overdoped), T_v remains above T_c, whereas other measurements appear to give a T* which intersects the superconducting dome closer to optimal doping in YBCO. This may be due to the difficulty in separating the effects of the pseudogap and superconducting fluctuations near optimal doping.
[4] L. Li, Y. Wang, S. Komiya, S. Ono, Y.Ando, G. D. Gu, N. P. Ong, arXiv:0906:1823.
[5] O. Cyr-Choinière *et al.*, Nature **458**, 743 (2009).
[6] E. Fradkin, S.A. Kivelson, M.J. Lawler, J.P. Eisenstein, A.P. Mackenzie, arXiv:0910.4166.
[7] Andreas Hackl and Matthias Vojta, arXiv:0909.4534.
[8] S.A. Kivelson *et al.*, Rev. Mod. Phys. **75**, 1201 (2003).
[9] A. Hackl, M. Vojta and S. Sachdev, arXiv:0908.1088.