Fluctuating superconductivity in organic molecular metals close to the Mott transition

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Nature **449**, 4 (2007).

Recommended with a Commentary by Steven A. Kivelson, Stanford University.

There is such a vast literature dealing with the properties of the cuprate high temperature superconductors that the benefits of comparative studies relating them to the properties of other materials are sometimes neglected. In particular, there is a set of phenomena that occur in a broad range of temperatures above the superconducting T_c in underdoped cuprates that, collectively, are known as "pseudogap" behaviors, whose microscopic origins have been the subject of intensive study and debate. At least three distinct perspectives have been proposed to account for some or all of these phenomena: 1) Due to the small superfluid stiffness of underdoped cuprates, the onset of global phase coherence is anomalously suppressed below the temperature at which significant local superconducting (pairing) correlations develop, and consequently there is a broad range of temperatures above T_c in which superconducting fluctuations play a significant role. The figure of merit, in this context, is T_θ/T_c, where $T_\theta = n_s \xi /4m^*$, is a temperature scale that characterizes the energy scale of phase fluctuations of the superconducting order parameter, $n_s/4m^*$ is the zero temperature superfluid stiffness, and ξ is a microscopic length scale which, in the case of a quasi-2D superconductor, is simply the distance between layers; when T_θ/T_c,>> 1 (the case in most conventional superconductors), the superfluid stiffness is large, but when $T_\theta/T_c \sim 1$, phase fluctuations are expected to make an order 1 contribution to the physics in the neighborhood of T_c. 2) Magnetic correlations reflecting the proximity of a "Mott insulating state" (i.e. an insulating state with one electron per unit cell and no long-range magnetic order), lead to a regime in which there is a "spin-gap" (which evolves into the superconducting gap in the superconducting state) but which has, at most, indirect effect on the charge degrees of freedom. 3) There is a second significant type of "competing order" whose ordering (in the case of "hidden order") or whose fluctuations are responsible for the opening of a pseudogap. It is important to note that, despite much rhetoric to the contrary, these perspectives are certainly not mutually exclusive.

An important paper that makes a welcomed comparative study is Nam *et al*, Nature **449**, 4 (2007). Nam *et al* have measured the Nernst coefficient in two organic superconductors in the κ-(BEDT-TTF)$_2$X family. The Nernst coefficient has been identified in the cuprates as the transport coefficient that is most sensitive to local superconductivity. Specifically, a "vortex Nernst signal" is observed in a significant portion of the pseudo-gap regime in the cuprates (where $T_\theta/T_c \sim 1$). The vortex Nernst signal is an anomalously large, positive Nernst coefficient, with strong and readily characterized temperature and magnetic field dependences, and which evolves smoothly into the well known flux flow Nernst response at temperatures below the zero-field T_c. As the name proclaims, this Nernst signal has been identified, at least intuitively, as arising from the drift of vortices down the thermal gradient. In crystals with X= Cu[N(CN)$_2$]Br (hereafter κ-Br), Nam *et al* report the observation of a large Nernst signal, qualitatively similar to that observed in the underdoped cuprates, which extends from T_c=11.8K up to approximately T_{Nernst} ~ 18K. This result is an important confirmation of the identification of the effect with superconducting fluctuations.

The κ-(BEDT-TTF)$_2$X family of materials is, a priori, a good choice for a comparative study because, in common with the cuprates, it has a quasi-two dimensional electronic structure and has low superfluid densities (in the sense defined above). Moreover, as a function of pressure (or chemical pressure), the superconducting phase is proximate to an antiferromagnetically ordered insulating phase. Indeed, the phase diagram in the (generalized) pressure - temperature plane looks similar to that of the cuprates in the doping – temperature plane, with the difference that the antiferromagnetic insulating phase has expanded to "swallow" the underdoped regime, so that in the superconducting phase, both T_c and the superfluid stiffness, n_s/m^*, decrease monotonically with distance from the insulating phase, rather than rising and then falling as they do in the cuprates. Moreover, the antiferromagnet to superconductor transition in the organics is direct and first order whereas (at least in p-type materials) there generally seems to be an intermediate spin-glass phase in the cuprates.

While the observation of a vortex Nernst signal in κ-Br is highly analogous to what is seen in the cuprates, there is a significant complication when it comes to the second material studied by Nam *et al.*, with X= Cu(NCS)$_2$ (hereafter κ-NCS). κ-NCS has a slightly lower T_c = 9.8 than in κ-Br. In κ-NCS, Nam *et al.* found no identifiable vortex Nernst signal above T_c. Both κ-NCS and κ-Br have values of T_θ/T_c ~ 1; while T_c is slightly lower for κ-NCS, seemingly so is T_θ, so that in fact the ratio of T_θ/T_c is thought to be nearly the same for the two materials. Thus, on the one hand, the vortex Nernst signal seen in the κ-Br crystals is consistent with the notion that a small superfluid density is a necessary condition for the existence of an anomalously large fluctuation regime. Conversely, the fact that a similar regime is not seen for κ-NCS crystals, implies that this, by itself, may not be sufficient. Since κ-NCS is, in a sense, more "overdoped" than κ-Br (in the sense of being farther from the insulating phase), the difference between the two materials is not entirely unexpected, in comparison with the cuprates. However, what specific physical parameter is responsible for the enormous (qualitative) difference in the normal state Nernst response of κ-Br and κ-NCS is, to me at least, currently unclear.