Diamagnetism of real-space pairs above $T_c$ in hole doped cuprates

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Received 19 July 2010, in final form 15 September 2010
Published 7 October 2010
Online at stacks.iop.org/JPhysCM/22/426004

Abstract

The nonlinear normal state diamagnetism reported by Li et al (2010 Phys. Rev. B 81 054510) is shown to be incompatible with a claimed Cooper pairing and vortex liquid above the resistive critical temperature. However, it is perfectly compatible with the normal state Landau diamagnetism of real-space composed bosons, which provides a description of the nonlinear magnetization curves of the less anisotropic cuprates La–Sr–Cu–O (LSCO) and Y–Ba–Cu–O (YBCO) as well as for strongly anisotropic bismuth-based cuprates over the whole range of available magnetic fields.

(Some figures in this article are in colour only in the electronic version)

A growing number of experiments ([1–7] and references therein) reveal a large diamagnetic response that is both nonlinear in the magnetic field and strongly $T$-dependent well above the resistive critical temperature $T_c$ of cuprate superconductors. The authors of [1, 7] suggest that a long-range phase coherence is destroyed by mobile vortices, however the off-diagonal order parameter amplitude remains finite and the Cooper pairing (with a large binding energy) survives up to some temperature well above $T_c$ supporting a so-called ‘preformed Cooper-pair’ scenario [8].

Here I show that the anomalous normal state diamagnetism above resistive $T_c$ reported recently [1] in crystals of La$_{2-x}$Sr$_x$CuO$_4$ (LSCO), Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ (B2201), Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ (B2212), and YBa$_2$Cu$_3$O$_7$ (YBCO) is actually incompatible with the acclamed Cooper pairing and vortex liquid, but it is fully congruent with the normal state Landau diamagnetism of real-space composed bosons [9, 10].

The magnetization of less anisotropic cuprates LSCO and YBCO is described with the simple charged-boson magnetization as well as the magnetization of quasi-two-dimensional bismuth-based cuprates, described by us earlier [10].

(i) The extremely sharp resistive transitions measured in high quality samples at $T_c$ make it impossible to reconcile with the vortex (or phase-fluctuation) scenario as the resistivity looks perfectly normal showing only moderate magnetoresistance above $T_c$. Both in-plane [11] and out-of-plane (see, for example [12]) resistive transitions remain sharp in the magnetic field in overdoped, optimally doped and underdoped high quality samples, providing a reliable determination of the genuine upper critical field, $H_{c2}$. The sharpness of the transition and little magnetoresistance argues against the existence of any residual superconducting order well above $T_c$ (see also [2]).

(ii) In disagreement with resistive determinations of the upper critical field [1] claims that $H_{c2}$ is a much higher field which fully suppresses the diamagnetism. In many cuprates, the full suppression requires fields as high as 150 T. Such a field corresponds to a very short zero temperature in-plane coherence length, $\xi = \sqrt{\phi_0/(2\pi H_{c2})} \lesssim 1.5$ nm, which is less or about the distance between carriers, $r = \sqrt{2\pi/k_F}$, in underdoped and overdoped cuprates, respectively ($k_F$ is the Fermi wavevector measured, for example, in quantum magnetic oscillation experiments [13]). The extremely short in-plane coherence length rules out the ‘preformed Cooper-pair’ scenario, which requires $\xi \gg r$. In cuprates the pairs do not overlap in underdoped compounds, and they barely touch at overdoping, so they are not Cooper pairs.

(iii) The authors of [1, 7] claim that the profile of the magnetization $M(B)$ is consistent with what one would expect from a vortex liquid in which long-range coherence is destroyed. This claim is untrue. While the magnitude $|M(B)|$ decreases logarithmically below $T_c$ as in the conventional vortex liquid, the set of experimental curves [1, 7] show that $|M(B)|$ first increases with increasing field $B$ above $T_c$. This is the opposite of what is expected in the vortex scenario. This significant departure from the London liquid behaviour is incompatible with the vortex liquid above the resistive phase transition.

(iv) In the phase-fluctuation scenario [8] $T_c$ is determined by the superfluid density ($\lambda$) rather than by the density of...
normal carriers $1 + x$. Obviously this scenario is at odds with a great number of thermodynamic, kinetic and magnetic measurements, including recent magneto-oscillations [13], which show that only carriers (density $x$) doped into a parent insulator conduct both in the normal and superconducting state of underdoped cuprates. On theoretical grounds, the preformed Cooper-pair scenario contradicts the theorem [14] that proves that the number of supercarriers at zero temperature is the same as the total number of carriers in any clean superfluid. The periodic crystal-field potential and electron–electron correlations could not change this conclusion. The experimental data [1] clearly contradict the Kosterlitz–Thouless (KT) scenario of the phase transition in cuprates, invoked as an origin of the ‘normal state’ vortex liquid [1, 7, 8]. Real-space correlation is included, the superconducting condensation energy is significantly enhanced [18] and mobile small bipolarons are stabilized [19, 20] as anticipated for strongly correlated cuprate conductors in [27]. High resolution ARPES [32–34] provides another piece of evidence for a strong electron–phonon effect on the carrier mass [26] predicted for (bi)polaronic conductors in [27].

Each inconsistency ((i)–(iv)) is individually sufficient to refute the vortex scenario [1, 7] of the normal state diamagnetism. Surprisingly Li et al [1] claimed that ‘Cooper pairing is (to their knowledge) the only established electronic state capable of generating the current response consistent with the nonlinear, strongly $T$ dependent diamagnetism’. These authors overlooked or neglected our theory of the normal state diamagnetism [9, 10], which quantitatively accounted for the nonlinear magnetization curves in Bi2212 [10], and in LSCO, YBCO and Bi2201 as well, as shown here.

Recent quantum Monte Carlo and some other numerical simulations show that the simplest repulsive Hubbard model does not explain high-$T_c$ superconductivity [17]. On the other hand, when a weak to moderate electron–phonon coupling is included, the superconducting condensation energy is significantly enhanced [18] and mobile small bipolarons are stabilized [19, 20] as anticipated for strongly correlated electrons in highly polarizable ionic lattices [21]. Real-space tightly bound pairs, whatever the pairing interaction is, are described as a charged Bose liquid on a lattice [22]. The superfluid state of such a liquid is the true Bose–Einstein condensate (BEC), rather than a coherent state of overlapping Cooper pairs, while the state above $T_c$ is perfectly normal with no local or global off-diagonal order.

The magnetization of the charged Bose liquid is given by the simple expression [10]:

$$M(T, B) = -A\frac{B}{\tau + (B/B_2)^2 + \sqrt{B/B_1 + \left[\tau + (B/B_2)^2\right]^2}},$$

(1)

which extends the original Schafroth result [23] to the temperature region just above $T_c$, for $|\tau| = |T/T_c - 1| \ll 1$ and $B \ll B_2$. It takes into account the temperature and field depletion of singlet pairs due to their thermal excitation into spin triplet and single polaron states split by the magnetic field. The amplitude $A$ and two characteristic fields, $B_1$ and $B_2$, are expressed through the zero temperature London penetration depth, $\lambda H$, and the same inter-plane distance $d$, but with very different values of $T_c$ [16], in disagreement with the KT scenario.

Figure 1. Diamagnetism of underdoped LSCO (symbols, figure 2 in [1]) and optimally doped YBCO (symbols, figure 8 in [1]) described with equation (1) above $T_c$ (lines, $T_c = 25$ K, $A = 2.75$ A T m$^{-1}$, $B_1 = 140$ T, $B_2 = 33$ T for LSCO and $T_c = 92$ K, $A = 0.45$ A T$^{-1}$, $B_1 = 2300$ T, $B_2 = 90$ T for YBCO).
A parameter-free estimate of the Fermi energy using the magnetic field penetration depth [36] and the magnetic quantum oscillations [13] found its very low value, \( \epsilon_F \lesssim 50 \text{ meV} \) supporting the real-space pairing in underdoped cuprate superconductors. There is strong experimental evidence for a gap in the normal state electron density of states of cuprates, which is known as the pseudogap. Experimentally measured pseudogaps, \( \Delta_p \), of many cuprates are about 50 meV or larger [37]. If one accepts that the pseudogap is about half of the pair binding energy then the condition for real-space pairing, \( \epsilon_F \lesssim \pi \Delta_p \) is well satisfied [36, 38]. There is also a parameter-free fit of experimental critical temperature \( T_c \) with the 3D BEC \( T_c \) in a vast number of cuprates [16].

Magnetotransport and thermal magnetotransport data strongly support preformed bosons in cuprates. In particular, many high-magnetic-field studies revealed a non-BCS upward curvature of the upper critical field \( H_{c2}(T) \) (see [39] for a review of experimental data), predicted for the Bose–Einstein condensation of charged bosons in the magnetic field [40]. The Lorenz number, \( L = \kappa_e / T \sigma \) differs significantly from the Sommerfeld value \( L_s \) of the standard Fermi-liquid theory, if carriers are double-charged bosons [41]. Here \( \kappa_e \), and \( \sigma \) are electron thermal and electrical conductivities, respectively. Reference [41] predicted a rather low Lorenz number for bipolarons, \( L \approx 0.15 L_s \), due to the double elementary charge of bipolarons, and also due to their nearly classical distribution function above \( T_c \). Direct measurements of the Lorenz number using the thermal Hall effect [42] produced the value of \( L \) just above \( T_c \) about the same as predicted by the bipolaron model, and its strong temperature dependence. This breakdown of the Wiedemann–Franz law is apparently caused by thermally excited single polarons coexisting with mobile bipolarons in the thermal equilibrium [43]. Such a strong departure from the conventional BCS–Fermi-liquid behaviour is most likely due to a strong EPI in highly polarizable cuprate layered structures. In accordance with our extension of the BCS theory [22] carriers are real-space Bosonic pairs (bipolarons) in the strong-coupling regime.

Single polarons, localized within an impurity band-tail, coexist with bipolarons in the charge-transfer doped Mott–Hubbard insulator. They account for sharp ‘quasi-particle’ peaks near \( (\pi/2, \pi/2) \) of the Brillouin zone and high-energy ‘waterfall’ effects observed with ARPES in cuprate superconductors [44]. This ‘band-tail’ model also accounts for two energy scales in ARPES and in the extrinsic and intrinsic tunnelling, their temperature and doping dependence, and for the asymmetry and inhomogeneity of extrinsic tunnelling spectra of cuprates [45]. Essentially, different doping and magnetic field dependence of the superconducting gap compared with the pseudogap and their different real-space profiles have prompted an opinion that the pseudogap is not connected to preformed Cooper pairs [46].

The fluctuating phase (preformed Cooper-pair) scenario has been also questioned by other authors, for instance by Tan and Levin [47]. The latter approach implies that the short coherence length of cuprate superconductors suggests they lie somewhere between the BCS limit of large momentum–space pairs and the opposite case of small real-space pairs undergoing the Bose–Einstein condensation. The BCS–BEC crossover has been studied in detail by many authors, for example in [48] a superfluid state is approached in a system of localized bosons (tightly bound electron pairs) in contact with a reservoir of itinerant fermions (electrons), it is assumed the spontaneous decay and recombination between the two species causes superconductivity and the PG is a consequence of this, opening up in the fermionic density of states. Along with composed bosons these approaches acknowledge coexisting fermionic excitations, which different from [44, 45] are itinerant rather than localized by disorder. Overall the real-space pairing seems to be a remarkable feature of cuprates no matter what the microscopic pairing mechanism is. The detailed microscopic physics of the Bosonic many body state seems to be irrelevant for fitting their electrodynamic properties.

To conclude I have shown that the nonlinear magnetization curves of quite a few hole doped cuprates have a profile
characteristic of normal state real-space composed bosons, rather than ‘preformed’ Cooper pairs, vortex liquid and the KT phase transition hypothesized in [1, 7, 8]. Importantly, the large Nernst signal, allegedly supporting vortex liquid in the normal state of cuprates [1, 7], has been explained as the normal state phenomenon owing to a broken electron–hole symmetry in the random potential [49], and/or as a result of the Fermi-surface reconstruction [50].

Acknowledgments

I greatly appreciate helpful comments from Joanne Beanland and Viktor Kabanov.

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