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Normal state diamagnetism of charged bosons in cuprate superconductors

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Abstract

Normal state orbital diamagnetism of charged bosons quantitatively accounts for recent high-resolution magnetometry results near and above the resistive critical temperature $T_c$ of superconducting cuprates. Our parameter-free descriptions of normal state diamagnetism, $T_c$, upper critical fields and specific heat anomalies unambiguously support the 3D Bose-Einstein condensation of preformed real-space pairs with zero off-diagonal order parameter above $T_c$ at variance with phase fluctuation scenarios of cuprates.

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A possibility of real-space pairing, as opposed to the Cooper pairing, has been the subject of many discussions, particularly heated over the last 20 years after the discovery of high temperature superconductivity in cuprates \[1\]. The first proposal for high temperature superconductivity, made by Ogg Jr in 1946 \[2\], already involved real-space pairing of individual electrons into bosonic molecules with zero total spin. This idea was further developed as a natural explanation of conventional superconductivity by Schafroth and Butler and Blatt \[3\]. However, with one or two exceptions, the Ogg-Schafroth picture was condemned and practically forgotten because it neither accounted quantitatively for the critical behavior of conventional (i.e. low \(T_c\)) superconductors, nor did it explain the microscopic nature of attractive forces which could overcome the Coulomb repulsion between two electrons constituting a pair. The failure of the ‘bosonic’ picture of individual electron pairs became fully transparent when Bardeen, Cooper and Schrieffer \[4\] proposed that two electrons in a superconductor were indeed correlated, but on a very large distance of about \(10^3\) times of the average inter-electron spacing.

Highly successful for low-\(T_c\) metals and alloys the BCS theory has led many researchers to believe that novel high-temperature superconductors should also be “BCS-like”. However, the Ogg-Schafroth and the BCS descriptions are actually two opposite extremes of the same electron-phonon interaction. Indeed by extending the BCS theory towards the strong interaction between electrons and ion vibrations, a charged Bose gas (CBG) of tightly bound electron pairs surrounded by lattice deformations (i.e. of small bipolarons) was predicted by us \[5\] with a further prediction that high \(T_c\) should exist in the crossover region of the electron-lattice interaction strength from the BCS-like to bipolaronic superconductivity \[6\]. Experimental evidence for an exceptionally strong electron-phonon interaction in novel superconductors \[7, 8, 9, 10\] is so overwhelming that bipolaronic CBG \[11\] could be a feasible alternative to BCS-like scenarios of cuprates. Nevertheless, some authors \[12\] have dismissed any real-space pairing, advocating a collective pairing (i.e. Cooper pairs in the momentum space) at some high temperature \(T^*\) which are phase coherent below a lower temperature \(T_c < T^*\). Ref.\[12\] has argued that the superconducting transition in cuprates is an almost two-dimensional Kosterlitz-Thouless (KT) transition, where a vortex liquid exists above \(T_c\) different from the BCS theory and its strong-coupling bipolaronic extension with a perfectly "normal" state without any off-diagonal order.

So far there has been no decisive conclusion on the origin of anomalous normal state
of cuprates. Some normal state properties have been satisfactorily interpreted within the Fermi-liquid approach, while many others have been understood with preformed real-space or Cooper pairs, in particular on the underdoped side of the phase diagram. Moreover preformed real-space pairs could coexist with the Fermi-liquid, which effectively hides them in the normal state kinetics. Any direct evidence in favor of either scenario is highly desirable. If real-space pairs indeed exist in superconducting cuprates, then their superconducting state should be a three-dimensional (3D) Bose-Einstein condensate (BEC) of CBG. Its critical behavior is rather different from any "universal" criticality like mean-field BCS, 3D "XY" or KT transitions.

Here I show that high-resolution magnetometry in the critical and normal regions provides unambiguous evidence for real-space pairing in cuprates.

A number of experiments (see, for example, 13, 14, 15, 16, 17, 18, and references therein), including torque magnetometry, showed enhanced diamagnetism above \( T_c \). Originally it was explained as the conventional fluctuation diamagnetism in quasi-2D BCS superconductors (see, for example Ref. 16). The data taken at relatively low magnetic fields (typically below 5 Tesla) revealed a crossing point in the magnetization \( M(T, B) \) of most anisotropic cuprates (e.g. Bi-2212), or in \( M(T, B)/B^{1/2} \) of less anisotropic YBa\(_2\)Cu\(_3\)O\(_{7−δ}\) 14. The dependence of magnetization (or \( M/B^{1/2} \)) on the magnetic field was shown to vanish at some characteristic temperature below \( T_c \). Importantly more recent data taken in high magnetic fields (up to 30 Tesla) show that the crossing point, anticipated for low-dimensional superconductors and associated with conventional superconducting fluctuations, does not explicitly exist in magnetic fields above 5 Tesla 15, 18.

Ref. 18 has linked the enhanced normal state diamagnetism with mobile vortexes well above \( T_c \) where conventional fluctuations should be negligible. Surprisingly the same torque magnetometry 13, 15, 18 uncovered that the diamagnetic signal above \( T_c \) increases in magnitude with applied magnetic field, \( B \). Such magnetic field dependence of magnetization \( M(T, B) \) is entirely inconsistent with what one expects from vortex liquid. While \(-M(B)\) decreases logarithmically at temperatures well below \( T_c \), the experimental curves clearly show that \(-M(B)\) increases with the field at and above \( T_c \), just opposite to what one could expect in a conventional vortex liquid. These significant departures from the London liquid behavior indicates that vortex liquid does not appear above the resistive phase transition (see also Ref. 13). Also accepting the vortex scenario and fitting the magnetization data in Bi-2212
FIG. 1: Bipolaron picture of high temperature superconductors. A corresponds to a singlet oxygen intersite bipolaron, B is a triplet intersite bipolaron.

with the conventional logarithmic field dependence \[ H_{c2} > 120 \text{ Tesla} \] and a very large Ginzburg-Landau parameter, \( \kappa = \lambda_H / \xi > 450 \) even at temperatures close to \( T_c \). The in-plane low-temperature magnetic field penetration depth is \( \lambda_H \approx 220 \text{ nm} \) in optimally doped Bi-2212 (see, for example \[ 23 \]). Hence the zero temperature coherence length \( \xi \) turns out to be about the lattice constant, \( \xi \lesssim 0.5 \text{nm} \). Such a small coherence length is perfectly compatible with direct STM measurements of the individual vortex cores in Bi-2212 \[ 19 \] and with the size of the vortex core in CBG \[ 11 \]. However it rules out the "preformed Cooper pairs" \[ 12 \], since the pairs are virtually not overlapped at any size of the Fermi surface.

Here I calculate the magnetization, \( M(T, B) \), of anisotropic CBG on a lattice, and compare the result with diamagnetism of cuprates recently measured in Ref. \[ 18 \]. A low-energy structure of cuprates in the bipolaron model is shown in Fig.1, where oxygen holes are bound into real-space intersite singlets (A) and triplets (B) separated by an exchange energy \( J \) \[ 20 \], which is estimated as a few tens or hundreds Kelvin depending on doping in agreement with experimental charge and spin pseudogaps in cuprates \[ 21 \]. Bipolarons are almost ideal charged bosons, because their Coulomb repulsion is strongly suppressed by a large lattice dielectric constant. When the magnetic field is applied perpendicular to
copper-oxygen plains the quasi-2D bipolaron energy spectrum is quantized as

\[ E_\alpha = \omega(n + 1/2) + 2t_c[1 - \cos(K_zd)] , \]  

where \( \alpha \) comprises \( n = 0, 1, 2, ... \) and in-plane \( K_x \) and out-of-plane \( K_z \) center-of-mass quasi-momenta, \( \omega = 2\hbar eB/\sqrt{m_xm_y} \), \( t_c \) and \( d \) are the hopping integral and the lattice period perpendicular to the planes. The spectrum consists of two degenerate branches, the so-called ”\( x \)” and ”\( y \)” bipolarons [11], with anisotropic in-plane bipolaron masses \( m_x \equiv m \) and \( m_y \approx 4m \). Expanding the Bose-Einstein distribution function in powers of \( \exp[(\mu - E)/k_BT] \) with the negative chemical potential \( \mu \) one can after summation over \( n \) readily obtain the boson density

\[ n_b = \frac{2eB}{\pi \hbar d} \sum_{r=1}^{\infty} I_0(2t_c r/k_BT) \exp[(\tilde{\mu} - 2t_c r/k_BT)] \frac{\exp(-\omega r/k_BT)}{1 - \exp(-\omega r/k_BT)} , \]  

and the magnetization, \( M(T, B) = -k_BT \partial/\partial B \sum_{\alpha} \ln[1 - \exp(\mu - E_\alpha)/k_BT] \),

\[ M(T, B) = -n_b \mu_b + \frac{2eB}{\pi \hbar d} \sum_{r=1}^{\infty} I_0(2t_c r/k_BT) \times \]

\[ \exp[(\tilde{\mu} - 2t_c r/k_BT)] \left( \frac{1}{r} - \frac{\omega \exp(-\omega r/k_BT)}{k_BT[1 - \exp(-\omega r/k_BT)]} \right) , \]

where \( \mu_b = \hbar e/\sqrt{m_xm_y} \), \( \tilde{\mu} = \mu - \omega/2 \) and \( I_0(x) \) is the modified Bessel function. At low temperatures \( T \rightarrow 0 \) Schafroth’s result [2] is recovered, \( M(0, B) = -n_b \mu_b \). The magnetization of charged bosons is field-independent at low temperatures. At high temperatures, \( T \gg T_c \) the chemical potential has a large magnitude, and we can keep only the terms with \( r = 1 \) in Eqs.(2,3) to obtain \( M(T, B) = -n_b \mu_b \omega/(6k_BT) \) at \( k_BT \gg k_BT_c \gg \omega \), which is the familiar Landau orbital diamagnetism of nondegenerate carriers.

The critical region \( \tau = T/T_c - 1 \ll 1 \) requires numerical calculations, which have been done [22] for an anisotropic 3D CBG with \( t_c \gtrsim k_BT_c/2 \) and \( I_0(x) \approx e^x/\sqrt{2\pi x} \) in Eqs.(2,3). Notwithstanding, one can nicely map the exact results, Fig.2, with a simple analytical expression by replacing summation over all but the first Landau level for integration,

\[ \frac{M(T, B)}{n_b \mu_b} = -0.22\omega \frac{0.37\omega}{k_BT_c} \left( \tau + \sqrt{0.37\omega/k_BT_c + \tau^2} \right)^{-1} . \]  

Remarkably Eq.(4) predicts almost field-independent diamagnetism well below \( T_c, |\tau| \gg \omega/k_BT_c \), a linear field dependence \( M(T_c, B) \sim B \) well above \( T_c, \tau \gg \omega/k_BT_c \), and an unusual square root behavior at \( T = T_c, M(T_c, B) \sim B^{3/2} \). Here \( T_c \) is the familiar Bose-Einstein condensation temperature \( k_BT_c = 3.31\hbar^2(n_b/2)^{2/3}/(m_xm_ym_c)^{1/3} \), with \( m_c = \hbar^2/|t_c|d^2 \).
FIG. 2: Exact numerical magnetization (symbols) compared with the analytical approximation, Eq.(4) (lines).

FIG. 3: Diamagnetism of optimally doped Bi-2212 (symbols) compared with magnetization of CBG, Eq.(6), near and above $T_c$ (lines).

Comparing with experimental data one has to take into account a temperature and field depletion of singlets due to their thermal excitations into spin-split triplets and single polaron states, Fig.1B. If the spin gap is small compared with the charge pseudogap, $J < \Delta/2$, triplets mainly contribute to temperature and field dependencies of the singlet bipolaron.
density near $T_c$,
\[ n_b(T, B) = n_b(T_c, 0)[1 - \alpha \tau - (B/B^*)^2] \tag{5} \]
where \( \alpha = 3(2n_c t)^{-1}[J(e^{-J/k_BT_c} - 1)^{-1} - k_BT_c \ln(1 - e^{-J/k_BT_c})] \), \( \mu_B B^* = (2k_BT_c n_c t)^{1/2} \sinh(J/2k_BT_c) \), \( \mu_B \approx 0.93 \times 10^{-23} \text{ Am}^2 \) is the Bohr magneton, \( n_c \) is the atomic density of singlets at \( T = T_c \) in zero field (\( n_c \lesssim 0.1 \) in optimally doped cuprates), and \( 2t \) is the triplet bandwidth, which is taken much larger than \( k_BT_c \). A triplet contribution to diamagnetism remains negligible compared with the singlet diamagnetism if \( \tau \ll J/k_BT_c \). Then Eq.(4) mapping numerical magnetization in the critical region is modified as
\[ M(T, B) = -\frac{0.22n_b(T_c, 0)\mu_B B}{B_0(1+2\alpha/3)} \times \left[ \tau + (B/B^*)^2 \left( \frac{B/B_0}{1+2\alpha/3} + \sqrt{\frac{0.37B/B_0}{(1+2\alpha/3)^2} + \left( \tau + (B/B^*)^2 \right)^2} \right) ^{-1} \right], \tag{6} \]
where \( B_0 = k_BT_c/2\mu_b \). Using the magnetic field in-plane penetration depth, \( \lambda_H^{-2} \approx 21 \, (\mu m)^{-2} \) of optimally doped Bi-2212 \cite{23} and of CBG \cite{11}, \( \lambda_H^{-2} = 2n_b e^2(m_x + m_y)/(\mu_0 m_x m_y) \), we estimate the bipolaron mass as \( m \approx 7.5m_e \) in agreement with the analytical and numerical QMC results \cite{11}, and \( n_b(T_c, 0)\mu_b = \hbar \mu_0 (m_x + m_y)^{1/2}/2e\lambda_H^2(m_x + m_y) \approx 2100 \text{A/m} \). The BEC temperature corresponds to the temperature were the in-plane resistivity starts to drop with temperature lowering, which is about \( T_c = 90K \) in optimally doped Bi-2212, so that \( B_0 = 524 \text{ Tesla} \). This choice of \( T_c = 90K \) is also justified by low-field magnetization \cite{18}, which has an exponent close to \( 1/2 \), \( M(90K, B) \sim B^{1/2} \) just for this temperature. The remaining two parameters in Eq.(6) are found using the experimental field dependence of \( M(T, B) \) at any fixed temperature near \( T_c \). Fitting \( M(T, B) \) at \( T = 89 \text{ K} \), Fig.3, yields \( \alpha = 0.62 \) and \( B^* = 56 \text{ Tesla} \), which according to Eq.(5) corresponds to the singlet-triplet exchange energy \( J \approx 20K \). Quite remarkably all other experimental curves in the critical region are well described by Eq.(6) without any fitting parameters, Fig.3.

I conclude that the normal state diamagnetism observed in many cuprates \cite{13, 14, 15, 16, 17, 18} provides unambiguous evidence for charged real-space bosons. The experimental data, Fig.3, clearly contradict BCS (with or without conventional fluctuations) and KT scenarios of the phase transition in cuprates. If we define a critical exponent as \( \delta = \ln B/\ln |M(T, B)| \) for \( B \to 0 \), the \( T \) dependence of \( \delta(T) \) in CBG is dramatically different
from KT and other “universal” critical exponents, but it is very close to the experimental [18] δ(T), Fig.4.

Another strong argument in favor of 3D BEC in cuprates has been drawn using parameter-free fitting of experimental $T_c$ with BEC $T_c$ in more than 30 underdoped, optimally and overdoped samples [24]. Whereas the KT critical temperature expressed through the in-plane penetration depth $k_BT_{KT} \approx 0.9d\hbar^2/(16\pi e^2\lambda_H^2)$ appears several times higher than the experimental values in many cases. There are also quite a few samples with about the same $\lambda_H$ and the same $d$, but with very different values of $T_c$, in disagreement with the KT transition. The large Nernst signal, allegedly supporting vortex liquid in the normal state of cuprates [26], has been explained as perfectly normal state phenomenon owing to a partial localization of charge carriers in a random potential inevitable in cuprates [27]. CBG upper critical field and the specific heat in the magnetic field have been found in striking consensus with experimental data [28] following our prediction [29]. More recently the d-wave symmetry and real-space modulations of the order parameter have been also explained with CBG in underdoped [11] and overdoped [30] cuprates.

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