Superfluid response in monolayer high-$T_c$ cuprates

C. Panagopoulos\textsuperscript{1}, T. Xiang\textsuperscript{2}, W. Anakool\textsuperscript{1}, J.R. Cooper\textsuperscript{1}, Y.S. Wang\textsuperscript{3} and C.W. Chu\textsuperscript{3}

\textsuperscript{1} Cavendish Laboratory and IRC in Superconductivity, University of Cambridge, Cambridge CB3 0HE, United Kingdom
\textsuperscript{2} Institute of Theoretical Physics and Interdisciplinary Center of Theoretical Studies, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100080, China
\textsuperscript{3} Department of Physics and Texas Center for Superconductivity, University of Houston, Houston, Texas 77204-5932

(March 22, 2022)

We have studied the doping dependence of the in-plane and out-of-plane superfluid density, $\rho^{s}(0)$, of two monolayer high-$T_c$ superconductors, HgBa$_2$CuO$_{4+\delta}$ and La$_2$-$\delta$Sr$_x$CuO$_4$, using the low frequency ac-susceptibility and the muon spin relaxation techniques. For both superconductors, $\rho^{s}(0)$ increases rapidly with doping in the under- and optimally doped regime and becomes nearly doping independent above a critical doping, $p_c \sim 0.20$.

Measurements of the magnetic penetration depth have been important in probing the order parameter and in testing theories of high-$T_c$ superconductors (HTS) [1–3]. In hole doped HTS, the low temperature dependence of the in-plane penetration depth $\lambda_{ab}(T)$ is linear and doping independent, indicating the presence of nodes in the superconducting energy gap [1,4]. The $c$-axis penetration depth $\lambda_c$ is a key parameter for some theories describing the mechanism of high temperature superconductivity [5–13]. It is sensitive to the electromagnetic anisotropy of the system and has been used to test the pairing symmetry and properties of interlayer dynamics [3,8,9].

In a recent study of the spin and charge response of HTS, it was found that both the superfluid density $\rho^{s}(0) \sim \lambda^{-2}(0)$ and the muon spin relaxation, $\mu$SR, rate show dramatic changes at a critical doping $p_c \sim 0.20$, slightly above optimal doping, in pure and Zn-doped La$_{2-x}$Sr$_x$CuO$_4$ (La-214) and Bi$_2$Sr$_1$Ca$_{1-x}$Y$_x$Cu$_2$O$_{8+y}$ (Bi-2212) at zero temperature [14]. The sharp changes in the superfluid density with the disappearance of a spin glass phase transition near $p_c$ suggested a change in symmetry of the ground state. The existence of such a special doping has been demonstrated in many other physical quantities [15] and the $\rho^{s}(0)$ and $\mu$SR data could be linked to the presence of a quantum phase transition at $p_c$, that is in turn related to the opening of the normal state pseudogap.

To elucidate further the changes in the ground state across the phase diagram of HTS we have studied the doping dependence of the zero-temperature in-plane and out-of-plane superfluid responses, $\rho^{s}_{ab}$ and $\rho^{s}_{c}$, for two monolayer HTS materials: HgBa$_2$CuO$_{4+\delta}$ (Hg-1201) and La-214. This study allows us to determine both the in- and out-of-plane responses as a function of doping and to perform a direct comparison between two simple HTS with different degrees of disorder. We find that in both systems, the superfluid density is strongly doping dependent below $p_c$ and shows abrupt changes around $p_c$. For Hg-1201 the effect is sharper and there is actually a peak in the superfluid density at $p_c$.

The Hg-1201 samples were prepared in Houston using a method similar to that described in ref. [16]. Their doping level can be continuously varied from very under- to heavily over-doped regime by adding or removing oxygen. Unlike La-214, where the doping is varied by Sr substitution for La, which may cause pronounced disorder effects, the variation of oxygen concentration in Hg-1201 is known to induce little lattice disorder [17]. The Hg-1201 samples were characterised using magnetisation and thermoelectric power measurements. The doping level $p$ was determined by both thermopower [18] and the universal relation $T_c=T_{c,max}[1-82.6(p-0.16)^2]$ [19]. The La-124 samples were synthesised in Cambridge using solid-state reaction followed by oxygenation. Effort was taken to ensure high purity and homogeneity. All La-214 powders were dried, reacted, ground, milled, re-pressed and re-sintered at least four times. The phase purity was verified by powder x-ray diffraction as well as extensive transport and thermodynamic measurements. No signal of impurities or inhomogeneity was captured in microanalytical spectroscopic studies [20]. The $T_c$ values as well as lattice parameters of these samples were in good agreement with published data. In La-214 $p$ is taken as equal to the Sr concentration. The heat capacity anomalies and $ac$-susceptibility transitions are sharp.

We have measured the magnetic penetration depth $\lambda$ using the low-field $ac$-susceptibility technique for grain-aligned powders [9,21]. The superfluid density is inversely proportional to the square of the in-plane penetration depth. To determine the in-plane and $c$-axis penetration depths separately, the grains were magnetically aligned in a static field of 12T at room temperature. X-ray powder diffraction scans [22] for both La-214 and Hg-1201 samples showed that more than 90% of the grains had their CuO$_2$ planes aligned. The $ac$-susceptibility measurements were performed down to 1.2K with a home-made susceptometer using miniature coils with $H_{ac}=1$-3G rms at $f=333$Hz. The absence of weak links among grains was confirmed by the linear response of the signal with $H_{ac}$ from 0.3 to 3G rms and $f$ from 33 to 333Hz. We also used a commercial...
susceptometer to confirm some of our findings. Taking the
grains to be approximately spherical, as indicated
by scanning electron microscopy, the data were analysed
using London’s model [2,23]. The ac-susceptibility data
were also confirmed by standard transverse field μSR
experiments performed on unaligned powders at 400G [24].  

Figure 1 shows the data for (a) $T_c$, $\lambda_{ab}^2(0)$ and (b) $\lambda_{c}^2(0)$ for La-214. The $T_c$, and $\lambda_{ab}^2(0)$ data were
published in an earlier paper and are included here for comparison [14]. $\rho_{\text{ab}}^c(0)$ is nearly doping independent in the
overdoped regime, but drops fast below $p_c = 0.19$. This
suppression of the superfluid density for $p < 0.19$ was
previously discussed in terms of a competition between quasi-static magnetic correlations and superconductivity
[14]. It has also been linked to the strong reduction in
entropy as well as condensation energy associated with the
opening of the normal state pseudogap [15,24].

$\rho_{\text{c}}^s(0)$ shows similar behaviour as its in-plane counterpart. However, in contrast to the nearly linear doping
dependence of $\rho_{\text{ab}}^s(0)$ on $p$, $\rho_{\text{c}}^s(0)$ shows a stronger dop-
ing dependence below $p_c$ corresponding to $1/\lambda^2 \propto p^n$
with $n \sim 2.7$. This difference in the doping dependence
between $\rho_{\text{ab}}^s(0)$ and $\rho_{\text{c}}^s(0)$ is probably associated with the
unconventional interlayer coupling of electrons in high-$T_c$
oxides, and is worthy of further theoretical and experi-
mental investigation.

Figure 2(a) shows the doping dependence of $T_c$ and $\rho_{ab}^c(0)$ for Hg-1201. Similar to La-214, $\rho_{ab}^c(0)$ is rela-
tively doping independent in the overdoped regime and
shows a sharp drop below 0.19. A similar $p$ dependence of $\rho_{ab}^c(0)$ has been found for Bi-2212 [25], and recently
also reported for Y$_{0.8}$Ca$_{0.2}$Ba$_2$Cu$_4$O$_{7-\delta}$ (Ca:Y-
123) and $Tl_{0.5-y}Pb_{0.5+y}$Sr$_2$Cu$_{1-x}$Y$_x$Cu$_2$O$_7$ (Pb:TI-
2212) [26]. The maximum of $\rho_{ab}^c(0)$ is located at $p_c$ for all
high-$T_c$ compounds. It suggests that the observed doping
dependence of $\rho_{ab}^c(0)$ below $p_c$ is common to all HTS com-
pounds and is not due to a structural transition or inho-
mogeneity. The relatively doping independent $\rho_{ab}^s(0)$ for $p > p_c$ in La-214 and Hg-1201 is in agreement to Bi-2212
[25] but seems to differ from the data for $Tl_2Ba_2CuO_{6+\delta}$,
Ca:Y-123 and Pb:TI-2212 [26,29]. The mechanism caus-
ing this difference is unknown and is certainly worth fur-
ther investigation. Nevertheless, it is clear that the max-
imum of $\rho_{ab}^c(0)$ is located at $p_c$ for all high-$T_c$ cuprates.

Figure 2(b) shows the doping dependence of the c-axis
superfluid density for Hg-1201. A sharp change from
large to low superfluid response is also observed around $p_c$. This is the sharpest change in $\rho_{c}^s(0)$ ever being reported
and together with the observed peak at $p_c$ could be related to its tetragonal crystal structure and the fact that Hg-1201 is more ordered than La-214. It is worth noting that a significantly weaker glassy response has been observed in Hg-1201 [28]. We may speculate that
this observation suggests that the sharper changes near $p_c$ may be linked to a quantum critical point for which
disorder causes smoothing of the doping dependence of various physical properties and associated phase transi-
tions.

The interlayer distance between the CuO$_2$ planes may be a key parameter for optimal $T_c$. This has been empha-
sised by Uemura recently [29]. Indeed, for the same in-plane superfluid density, $T_c$ is higher if the interlayer
distance is shorter. Therefore, the interlayer coupling
seems to be essential for obtaining higher $T_c$. The ob-
erved variation of $T_c$ cannot be explained by the simple Kosterlitz-Thouless transition where $T_c$ is solely deter-
mined by the 2D superfluid density. The similar dop-
ing dependence of $\rho_{c}^s(0)$ to $\rho_{ab}^s(0)$ observed here supports
this view and indicates the fundamental role of the c-axis
electrodynamics to the overall superconducting conden-
sation. As a matter of fact, $\lambda_c(0)$ for both monolayer
cuprates studied here is small above $p_c$ and agrees, for
example, with the interlayer tunneling model of Anderson
and Chakravarty [5-7]. Large superfluid response above $p_c$ seems to occur in connection with a crossover from two-dimensional to three-dimensional transport, as suggested by the doping dependence of the anisotropy in $\lambda$ (Fig. 3) and the associated behaviour of the anisotropy of the normal state resistivity [30,31].

In summary, for the two monolayer high-$T_c$ cuprates,
La-214 and Hg-1201, both the in-plane and c-axis super-
fluid response remain relatively constant above $p_c$ but
drop rapidly below $p_c$. We have found a peak in $\rho_{c}^s(0)$ at $p_c$ for Hg-1201 indicating the strongest superconduc-
tivity at the point where the spin glass phase transition (the glass transition temperature $T_g$ versus $p$ curve) van-
ishes and the normal state gap extrapolates to zero [14].
The rapid change and peak may be due to a change in the
superconducting ground state. Furthermore, we have observed that the doping dependence of $\rho_{c}^s(0)$ in La-214
follows a power law of approximately 2.7.

C.P. thanks S. Chakravarty and J. W. Loram for enlighten-
ting discussions, D.N. Basov for an earlier collaboration
and discussions on the subject and The Royal So-
ciety for financial support. T.X. acknowledges support from the National Natural Science Foundation of China.

[1] W.N. Hardy, D.A. Bonn, D.C. Morgan, R. Liang, and K.Zhang, Phys. Rev. Lett. 70, 3999 (1993).
[2] A. Porch, J.R. Cooper, D.N. Zheng, J.R. Waldram, A.M. Campbell, and P.A. Freeman, Physica C 214, 350 (1993).
[3] T. Xiang, C. Panagopoulos, and J.R. Cooper, Int. J. Mod. Phys. B 12, 1007 (1998).
[4] C. Panagopoulos and T. Xiang, Phys. Rev. Lett. 81, 2336 (1998).
[5] J.M. Wheatley, T. Hsu, and P.W. Anderson, Nature (London) 33, 121 (1988).
[6] P.W. Anderson, Science 256, 1526 (1992).
[7] S. Chakravarty, A. Sudbo, P.W. Anderson, and S. Strong, Science 261, 337 (1993).
FIG. 1. (a) Doping dependence of the superconducting transition temperature $T_c$ and inverse square of the zero temperature in-plane penetration depth for La$_{2-x}$Sr$_x$CuO$_4$ (La-214) measured by the ac-susceptibility technique. (b) Doping dependence of the inverse square of the zero temperature out-of-plane penetration depth.

FIG. 2. (a) Doping dependence of the critical temperature $T_c$ and inverse square of the zero temperature in-plane penetration depth for HgBa$_2$CuO$_{4+\delta}$ (Hg-1201). (b) Doping dependence of the inverse square of the zero temperature out-of-plane penetration depth.

FIG. 3. Doping dependence of the anisotropic ratio $\lambda_c(0)/\lambda_{ab}(0)$ for La$_{2-x}$Sr$_x$CuO$_4$ (La-214) and HgBa$_2$CuO$_{4+\delta}$ (Hg-1201).
Panagopoulos et al., Fig. 1a

Graph showing the relationship between $T_c$ (K) and holes/planar Cu for La-214.
Panagopoulos et al. Fig. 1b

The figure shows a graph with the x-axis labeled as "holes/planar Cu" and the y-axis labeled as "$1/\lambda_c^2 (0) [\mu m^2]". The graph plots the data points for La-214, with a steep increase in the y-values as the x-values approach 0.2.
Panagopoulos et al. Fig. 2a

![Graph showing $T_c$ versus holes/planar Cu for Hg-1201.](image)

- $T_c (K)$ on the y-axis.
- Holes/planar Cu on the x-axis.
- Two distinct lines indicating different trends.
- $1/\lambda^2$ and $\mu ab (0) [\mu m^{-2}]$ on the right y-axis.
Panagopoulos et al. Fig. 2b

![Graph](image.png)

$\frac{1}{\lambda^2 c(0)} \left[ \mu \text{m}^2 \right]$ vs. holes/planar Cu
Panagopoulos et al_Fig. 3

\[ \gamma = \left[ \frac{\lambda_c(0)}{\lambda_{ab}(0)} \right] \]

![Graph showing the relationship between holes/planar Cu and \( \gamma \) for Hg-1201 and La-214.](image)