Systematic behaviour of the in-plane penetration depth in d-wave cuprates

C. Panagopoulos, J.R. Cooper* and T. Xiang

Research Center in Superconductivity, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom

We report the temperature T and oxygen concentration dependences of the penetration depth of high-Tc cuprates. In a recent study of the c-axis coupling of d-wave high-Tc cuprates we reported the values and temperature (T) dependences of the in-plane (λab) and out-of-plane (λc) penetration depths for slightly overdoped samples. However, recent angle-resolved photoemission spectroscopy (ARPES) data strongly suggest that for underdoped samples the MF theory might be expected. We have therefore extended our investigation to deoxygenated (underdoped) pure YBa2Cu3O7−δ using the same ac susceptibility technique to measure the penetration depth. We report experimental results for the values and temperature dependences of λab and λc of high quality c-axis grain-aligned orthohombic YBa2Cu3O7−δ (which has two CuO2 planes per unit cell as well as Cu-O chains) with δ = 0.0, 0.3 and 0.43, and compare them with tetragonal Hg-1201 with one CuO2 plane per unit cell and tetragonal Hg-1223 with three CuO2 planes per unit cell. We find that the presence of the linear term in λab(T) is independent of the number of CuO2 planes per unit cell, carrier concentration, crystal structure, anisotropy and the presence of chains. Surprisingly our data show good agreement with weak coupling d-wave theory, and the linear term in |λab(T) / λab(0)| appears to scale with T/Tc. This result highlights the need for detailed consideration of the relationship between superconducting and normal state energy gaps in underdoped cuprates.

Sample preparation was carried out by the standard solid state reaction process using high purity (99.999%) Y2O3, BaCO3 and CuO oxides. Electron probe microanalysis and x-ray diffraction showed that all samples were single phase within an accuracy of ±1%. The fully oxygenated, δ = 0.0 (YBCO7, Tc = 92 K), samples were prepared by annealing bulk pieces in pure oxygen atmosphere at 380 °C for 24 hours and then slowly cooling to room temperature. The δ = 0.0 bulk piece was lightly ground and sieved through a 20 µm sieve in an argon glove box to obtain a well-defined grain size distribution. The sedimented powders were then heat treated to repair any structural damages to the surface of the grains. For δ = 0.3 and 0.43 on the other hand a bulk piece for each δ was lightly ground and sieved through a 20 µm sieve in an argon glove box to obtain a well-defined grain size distribution and to avoid surface degradation of the crystallites. The collected powders were then kept in argon atmosphere for 30 min before being aligned. All powders, δ = 0.0, 0.3 and 0.43, were magnetically aligned in epoxy as described earlier. The average grain diameters corresponding to the 50% cumulative volume point were 5 and 10 µm for the fully oxygenated and the oxygen deficient samples, respectively. The fraction of the unoriented powder in all grain aligned samples was estimated to be < 5 %. Rocking curve analysis of the δ = 0.0 and δ > 0.0 samples gave a full width at half maximum of ±1.4 and 1 °, respectively. Low field susceptibility, χ, measurements were performed using commercial equipment (down to 0.2 K) for samples with δ = 0.0, 0.3 and 0.43. The sample with δ = 0.43 was also measured down to 1.2 K using a home built susceptometer. Details of the experimental technique and the application of London’s model for deriving λ from the measured χ in cuprate superconductors can be found in earlier publications.

The values of λab(0) derived from our data are 0.14, 0.21 and 0.28 µm and the corresponding values for λc(0) are 1.26, 4.53 and 7.17 µm for δ = 0.0, 0.3 and 0.43, respectively. The errors in λab(0) arising from a possible uncertainty of ±5% in the alignment can be as high as ±25%, whereas those in λc(0) are ±8%. How-
ever, the corresponding uncertainty in the linear term in 
$[\lambda_{ab}(T)/\lambda_{ab}(0)]$ is much less, at most $\pm 10\%$. The present results differ from previous work$^{17}$ in which the surfaces of the particles were probably not as clean and the degree of grain alignment was probably lower. As $T_c$ is reduced by lowering the carrier concentration (for $\delta = 0.3$ and 0.43), $[1 / \lambda_{ab}^2(0)]$ falls, a behaviour which has been extensively discussed in terms of the Uemura relation.$^{18,19}$ The ratio $\gamma = [\lambda_c(0) / \lambda_{ab}(0)]$ i.e. the anisotropy, increases with oxygen deficiency.

Figures 1(a) and 1(b), show characteristic low temperature plots of $[\lambda(T) / \lambda(0)]$ for the $ab$-plane (measured with the applied field $H \parallel c$) and $c$-axis (measured with $H \parallel ab$), respectively, for the three oxygen concentrations studied. The low temperature ($T / T_c < 0.25$) linear term in $\lambda_{ab}(T)$ is 4.8 $A/K$ for YBCO$_7$ in good agreement with that found from microwave measurements on YBCO$_{6.95}$ single crystals.$^{20}$ As oxygen is removed from the lattice (the chains) the linear term increases to 12 and 20 $A/K$ for $\delta = 0.3$ and 0.43, respectively. For YBCO$_2$ we also observe a linear $T$ dependence in $\lambda_c$ at low temperatures but the relative change is about a factor of two smaller than in $[\lambda_{ab}(T) / \lambda_{ab}(0)]$, while $\lambda_c(T)$ of YBCO$_{6.7}$ and YBCO$_{6.57}$ obeys a $T^2$ behaviour at low $T$. Details of the systematics of $\lambda_c(T)$ of cuprate superconductors can be found in Refs [1,6,21,22].

In Fig. 2 we present normalised plots of $[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ and $[\lambda_c(0) / \lambda_c(T)]^2$ versus $T / T_c$ for $T / T_c < 0.25$. There is excellent agreement between the $[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ curves for the three oxygen concentrations. The data in Fig. 2(a) are compared with the weak coupling theory for a d-wave superconductor (solid line).$^{23}$ It can be seen that the d-wave curve fits the data very well. On the other hand the $[\lambda_c(0) / \lambda_c(T)]^2$ curves do not fit the d-wave curve and also differ from each other slightly, because of the effect of the interplane coupling on $\lambda_c(T)$.$^{1,6,10,21,22}$

We also find that $[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ of YBa$_2$Cu$_3$O$_{7-\delta}$ agrees with that of Hg$_{1201}$ and Hg$_{1223}$.$^{1,10}$ The behaviour of $[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ is generally similar to that of YBa$_2$(Cu$_{1-x}$Zn$_x$)$_2$O$_7$ ($x = 0.02$ and 0.03),$^{5}$ except at very low temperatures where a $T^4$ term developed in the Zn doped samples due to impurity scattering.

The full temperature dependences of $[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ for YBa$_2$Cu$_3$O$_{7-\delta}$ ($\delta = 0.0, 0.3$ and 0.43), YBa$_2$(Cu$_{1-x}$Zn$_x$)$_3$O$_7$ ($x = 0.02$ and 0.03), Hg$_{1201}$ and Hg$_{1223}$ are also in agreement with recent data of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi-2212)$^{24}$ and Tl$_2$Ba$_2$CuO$_{6+\delta}$ (Tl-2201)$^{25}$ single crystals measured by a microwave technique with $H \parallel c$, but they only agree with another set of microwave data ($H \parallel c$) for Bi-2212 single crystals$^{36}$ at $T / T_c < 0.3$. At higher temperatures the data in Ref. [26] deviate from the weak-coupling d-wave calculation. Independent evidence for the scaling behaviour of $[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ with $T / T_c$ can also be found in a recent publication by Bonn et al.$^{27}$ who measured the relative changes in $\lambda$ with temperature for underdoped, optimally doped and slightly overdoped untwinned YBa$_2$Cu$_3$O$_{7-\delta}$ crystals using a microwave technique and $H \perp c$. However, in Ref. [27] the changes of $[\lambda_{a,b}(0) / \lambda_{a,b}(T)]^2$ for YBCO$_{6.95}$, at high temperatures, and YBCO$_{6.6}$, over the whole temperature range, were smaller than ours and closer, at high temperatures, to the Bi-2212 data in Ref. [26]. We do not know the precise origin of this difference but we believe that for weakly coupled layers, data taken with $H \parallel c$ give the best measure of the superfluid density.

Figure 3 shows plots of $1-[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ vs $T$ which is equivalent to $[n_s(0) - n_s(T)] / n_s(0)$, i.e. the normalised density of quasiparticle excitations, where $n_s(T)$ is the density of condensed electrons at a temperature $T$, for all the samples studied. It is clear that the linear term in $1-[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ increases as $T_c$ decreases. If we use the standard BCS result for $\lambda(T)$ of a d-wave superconductor,$^{28}$

$$
\left(\frac{\lambda(0)}{\lambda(T)}\right)^2 \approx 1 - \frac{(2 \ln 2)T}{\Delta_0},
$$

(1)
to fit the experimental data shown in Fig. 3 (at $T / T_c < 0.25$) we find that $\Delta_0$ scales approximately with $T_c$ [Fig. 3 (inset)], giving $\Delta_0 \approx 2T_c$, a value close to that expected for weak-coupling superconductivity.$^{28}$ For comparison we also include data for the s-wave perovskite Ba$_2$K$_4$CuO$_4$ (BKBO).$^{10}$ The compounds Bi-2212$^{24,26}$ and Tl-2201$^{25}$ would also give $\Delta_0 \approx 2T_c$ on this plot. The maximum error in the linear terms i.e. the values of $\Delta_0$ in Fig. 3 (inset), is $\pm 20\%$.

The scaling of $\Delta_0$ with $T_c$, Fig. 3 (inset), is in agreement with early tunneling spectroscopy data$^{29}$ for several cuprates as a function of carrier concentration, ranging from the underdoped to the optimally doped regimes. It is not consistent however, with more recent tunneling$^{6}$ and ARPES$^7$ results for underdoped cuprates where $\Delta_0$ was actually found to increase slightly while $T_c$ falls. There seems to be two possible ways of accounting this discrepancy. One is that the recent spectroscopic experiments$^7,8$ actually measure the normal state gap. In this scenario the effect of the normal state gap would be to leave small pockets of holes whose superconducting properties are still described reasonably well by MF theory. The other is similar to a recent phenomenological approach.$^{30}$ As shown in Fig. 4, it is probable, that within experimental error, the unnormalised plots of $[1/\lambda_{ab}(T)]^2$, i.e. $n_s(T)$, versus $T$ at low temperatures are parallel for samples with different $T_c$ values. This would correspond to the same number of excited quasiparticles, $[n_s(0) - n_s(T)]$, at a given temperature for all $T_c$ values, as implied by specific heat work on underdoped YBCO.$^{31}$ Such parallel shifts give $[n_s(0) - n_s(T)] = aT$, where $a$ is independent of doping level ($T_c$). In combination with the well-known Uemura relation $n_s(0) \propto T_c^{18}$ this gives $1 - n_s(0) / n_s(T) = b T / T_c$, where $b$ is independent of $T_c$. So at low $T$, $[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ versus $T / T_c$ would still scale on to a single curve even when the MF relation $\Delta_0 / T_c \approx 2$, is strongly violated.

In conclusion, we have studied $\lambda_{ab}(T)$ and $\lambda_c(T)$ of high quality grain-aligned YBa$_2$Cu$_3$O$_{7-\delta}$ with $\delta = 0.0, 0.3$ and 0.43. The values of $\lambda_{ab}(0)$, $\lambda_c(0)$ and $\gamma$ were found to increase with oxygen deficiency. We find that the existence of the linear term in $\lambda_{ab}(T)$ is independent
of the number of CuO$_2$ planes per unit cell, carrier concentration, crystal structure, anisotropy and the presence of chains. If viewed in isolation, all the penetration depth data presented here and most of the microwave measurements for $H \parallel c$ appear to be in excellent agreement with mean field theory for a weak coupling d-wave superconductor for which $\Delta_0 / T_c \approx 2$. However, recent spectroscopic data are more consistent with a different approach in which there is a strong interplay between the superconducting and normal state gaps. Clearly the relationship between these two gaps is of crucial importance for understanding superconductivity in the cuprates.

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* On leave from the Institute of Physics, The University of Zagreb, P.O. Box 304, Zagreb, Croatia.

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FIGURE CAPTIONS

FIG. 1. Low temperature plots of (a) $[\lambda_{ab}(T) / \lambda_{ab}(0)]$ and (b) $[\lambda_c(T) / \lambda_c(0)]$ for YBCO$_7$ (closed circles), YBCO$_{6.7}$ (open circles) and YBCO$_{6.57}$ (open squares). The $T_c$, $\lambda_{ab}(0)$ and $\lambda_c(0)$ values are given in the text.
FIG. 2. Plots of (a) $[\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ and (b) $[\lambda_c(0) / \lambda_c(T)]^2$ as functions of $T / T_c$ for YBCO$_7$ (closed circles), YBCO$_6.7$ (open circles) and YBCO$_6.57$ (open squares). The solid line in (a) is the theoretical prediction for the normalised superfluid density from the weak coupling BCS theory for a $d$-wave superconductor.$^{23}$

FIG. 3. Low temperature plot of $1 - [\lambda_{ab}(0) / \lambda_{ab}(T)]^2$ for Hg-1223 [$\lambda_{ab}(0) = 1770 \pm 300 \, \text{Å}$] (closed triangles),$^1$ Hg-1201 [$\lambda_{ab}(0) = 1710 \pm 250 \, \text{Å}$] (open triangles),$^1$ YBCO$_7$ (closed circles), YBCO$_6.7$ (open circles) and YBCO$_6.57$ (open squares). Inset: $T_c$ versus $2\Delta_0$ as derived from the plot in the main panel (see text for details). BKBO is included for comparison. The solid line is drawn as a guide to the eye.

FIG. 4. Low temperature plot of $[1/\lambda_{ab}^2(T)]$ (i.e., $n_s$) for YBCO$_6.57$ (open squares) and Hg-1201 (open triangles) showing the approximate parallel shift of $n_s$ with $T_c$ as discussed in the text. The dashed lines, immediately above and below each data set, indicate the maximum possible error in $1/\lambda_{ab}^2(T)$ arising from ±5% uncertainty in the alignment (see text).