59001-00-105

Simple Model of the Anisotropic Penetration Depth in High T_c Superconductors

ANL/MSD/CP-- 89996
CONF-960849--4

RECEIVED
JUL 18 1996
OSTI

Richard A. Klemm[1] and Samuel H. Liu[2]

Materials Science Division
Argonne National Laboratory
Argonne, IL 60439

Department of Physics
University of California at San Diego
La Jolla, CA 92093

April, 1996

Submitted to Physica C

/sm

Distribution:

1-2. M. J. Masek
3. B. D. Dunlap
4. G. W. Crabtree
5. A. A. Abrikosov
6. Editorial Office
7. Authors

Invited Paper submitted to the XXI International Conference on Low Temperature Physics, Prague, Czech Republic, August 8-14, 1996

This work is supported by the Division of Materials Sciences, Office of Basic Energy Sciences of DOE, under contract No. W-31-109-ENG-38.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

DISCLAIMER

59001-00-105

Simple Model of the Anisotropic Penetration Depth in High T_c Superconductors

Richard A. Klemm[1] and Samuel H. Liu[2]

Materials Science Division
Argonne National Laboratory
Argonne, IL 60439

Department of Physics
University of California at San Diego
La Jolla, CA 92093

April, 1996

Submitted to Physica C

/sm

Invited Paper submitted to the XXI International Conference on Low Temperature Physics, Prague, Czech Republic, August 8-14, 1996

This work is supported by the Division of Materials Sciences, Office of Basic Energy Sciences of DOE, under contract No. W-31-109-ENG-38.

Simple model of the anisotropic penetration depth in high T_c superconductors*

Richard A. Klemm[a] and Samuel H. Liu[b]

[a] Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439 USA

[b] Department of Physics, University of California at San Diego, La Jolla, California 92093 USA

We present a simple model of some high T_c cuprates based upon superconducting (S) and normal (N) layers, which quantitatively fits the data of Bonn *et al.* for the low temperature T dependence of the penetration depths $\lambda_{a,b,c}$ in untwinned $YBa_2Cu_3O_{7-\delta}$, assuming s-wave intralayer pairing. This SN model also leads to anisotropic surface states, which complicate the analysis of photoemission and tunneling measurements.

1. INTRODUCTION

Recently, there has been a controversy regarding the source of the low energy states in the superconducting gap observed in measurements sensitive to the quasiparticle density of states (DOS). Most of this controversy has centered on the orthorhombic material $YBa_2Cu_3O_{7-\delta}$ (YBCO), which consists of two conducting CuO_2 planes in which the superconductivity is thought by most to arise, plus one CuO chain layer per unit cell. Measurements of the in-plane penetration depth $\lambda_{ab}(T)$ in twinned YBCO by microwave[2] and neutron scattering[3] were shown[1] to be in agreement with each other, exhibiting a quasilinear low-T behavior. While these data were interpreted[2] as being evidence for superconductivity with an order parameter exhibiting line nodes, such as for $d_{x^2-y^2}$ symmetry, we showed[1] that an SN model of superconducting (S) and normal (N) layers could fit the low-T data[2, 3] just as well. In addition, we predicted that $\lambda_c(T)$ might be a useful tool in discriminating between these models. Our SN model also predicts new types of surface states[4], in which the superconductivity is different on the top surface from the bulk. These surface states can explain the apparent anisotropy of the quasiparticle gap observed in angle-resolved photoemission spectroscopy (ARPES)[5], plus the differences in the quasiparticle tunneling DOS observed on different crystal surfaces[6, 7, 8].

More recently, the entire penetration depth components $\lambda_a(T), \lambda_b(T), \lambda_c(T)$ were measured on untwinned YBCO single crystals[9]. These data were fit quantitatively[10] using a quasiparticle band structure consisting of tight-binding two-dimensional planes and one-dimensional chains, with d-wave interlayer pair tunneling as the superconducting mechanism. This unphysical pairing model was used to argue that the SN model could not be made to fit the above data. However, we showed[11] that for an appropriate choice consistent with the local density approximation of the electronic band structure, the qualitative features of the $\lambda_{a,b,c}(T)$ curves could be closely approximated with s-wave intralayer pairing. The apparent problem with the SN model fits is that $\lambda_a(T)$ and $\lambda_b(T)$ data[9] are nearly proportional to one another, but differ in magnitude by 30-60%. However, as noted elsewhere[12], this apparent discrepancy can easily be accounted for in a very simple model. Here we present the details of that simple model, which easily can fit all three $\lambda_a(T)$, $\lambda_b(T)$, and $\lambda_c(T)$ data of [9] in untwinned YBCO.

2. THE MODEL

We assume [1] there are two quasiparticle bands per unit cell. In order to fit the in-plane anisotropy, we assume two concentric bands with elliptical cross-sections. For simplicity, we make them identical in the absence of interlayer hopping, and split the bands[1] by inequivalent hopping strengths $J_1 \neq J_2$. We also assume the effective mass components on the two bands satisfy $m_{x1}/m_{x2} = m_{y1}/m_{y2} \equiv \beta$, where $\beta \approx 5$ to account for strong coupling effects and/or layer number counting[1]. We define the in-plane anisotropy to be $m_{x1}/m_{y1} = m_{x2}/m_{y2} \equiv \epsilon$. We conserve the in-plane momentum upon interlayer hopping, $k_{F1} = k_{F2} \equiv k_F$, so that the energies

* Supported by USDOE Contract No. W-31-109-ENG-38.

E_{Fn} relative to the bottoms of their bands satisfy $E_{F2}/E_{F1} = \beta$. The quasiparticle bands then satisfy $\xi_{02} = \beta\xi_{01}$, where $\xi_{0n}(\mathbf{k}) = [k_x^2/m_{xn} + k_y^2/m_{yn}]/2 - E_{Fn}$, for $n = 1, 2$. Letting $k_x = k\cos\theta_{\mathbf{k}}$, etc., $k_F(\theta_{\mathbf{k}}) = [2m_{x1}E_{F1}]^{1/2}/\mathcal{A}(\theta_{\mathbf{k}})$, where $\mathcal{A}^2(\theta_{\mathbf{k}}) = \cos^2\theta_{\mathbf{k}} + \epsilon\sin^2\theta_{\mathbf{k}}$. We set $\hbar = k_B = c = 1$.

3. RESULTS

The diagonal conductivity tensor has elements[1]

$$\sigma_{ii} = 2e^2T\sum_{\omega}\int\frac{d^3k}{(2\pi)^3}\sum_{n,n'=1}^{2} v_{in}v_{in'} \times (G_{nn'}G_{n'n} + F_{nn'}F^{\dagger}_{n'n}) \quad (1)$$

$$\sigma_{zz} = 2e^2T\sum_{\omega}\int\frac{d^3k}{(2\pi)^3}v_z^2\sum_{n\neq n'}(G_{nn}G_{n'n'} + F_{nn}F^{\dagger}_{n'n'} + G_{nn'}G_{nn'} + F_{nn'}F^{\dagger}_{nn'}), \quad (2)$$

where $i = x, y$ (or $i = a, b$), ω are the Matsubara frequencies, $v_z = d\epsilon_{\perp}/dk_z$, $\epsilon_{\perp}^2(k_z) = J_1^2 + J_2^2 + 2J_1J_2\cos k_zs$, s is the c-axis repeat distance, $v_{x1} = [2E_{F1}/m_{x1}]^{1/2}\cos\theta_{\mathbf{k}}/\mathcal{A}(\theta_{\mathbf{k}})$, $v_{y1} = \epsilon[2E_{F1}/m_{x1}]^{1/2}\sin\theta_{\mathbf{k}}/\mathcal{A}(\theta_{\mathbf{k}})$, and $v_{x2}/v_{x1} = v_{y2}/v_{y1} = \beta$. In analogy with [1], we let $\int d^3k = 2\pi N_1(0)\sqrt{\epsilon}\int d\xi_{01}\int_{-\pi}^{\pi}d\theta_{\mathbf{k}}\int_{-\pi}^{\pi}d\eta\mathcal{A}^{-2}(\theta_{\mathbf{k}})$, where $\eta = k_zs$ and $N_1(0) = [m_{x1}m_{y1}]^{1/2}/(2\pi s)$ is the effective single spin DOS at E_{F1}.

We note that the $G_{nn'}$ and $F_{nn'}$ are functions of ξ_{01}, $\epsilon_{\perp}$, and the order parameter $\Delta(\theta_{\mathbf{k}})$. Hence, for s-wave intralayer pairing, the only dependences of the integrands in Eqs. (1,2) upon $\theta_{\mathbf{k}}$ arise from $\mathcal{A}^{-2}(\theta_{\mathbf{k}})$ and the v_{in}. Thus, σ_{xx} and σ_{yy} are *proportional* to one another. We may find this proportionality constant by merely performing the integrals over $\theta_{\mathbf{k}}$. Since σ_{xx}, σ_{yy}, and σ_{zz} are proportional to averages over $\theta_{\mathbf{k}}$ of the quantities $\cos^2\theta_{\mathbf{k}}/\mathcal{A}^4(\theta_{\mathbf{k}})$, $\epsilon^2\sin^2\theta_{\mathbf{k}}/\mathcal{A}^4(\theta_{\mathbf{k}})$, and $\sqrt{\epsilon}\mathcal{A}^{-2}(\theta_{\mathbf{k}})$, respectively, the integrals over $\theta_{\mathbf{k}}$ are easily performed, with the results

$$\frac{\sigma_{yy}(\epsilon)}{\sqrt{\epsilon}\sigma_{yy}(1)} = \frac{\sqrt{\epsilon}\sigma_{xx}(\epsilon)}{\sigma_{xx}(1)} = \frac{\sigma_{zz}(\epsilon)}{\sigma_{zz}(1)} = 1. \quad (3)$$

Thus, the only changes incurred for s-wave intralayer pairing by the in-plane anisotropy is that $\sigma_{aa} = \sigma_{xx}$ and $\sigma_{bb} = \sigma_{yy}$ are respectively reduced and enhanced by the factor $\sqrt{\epsilon}$. Since the penetration depths $\lambda_{ii}(T) = [4\pi/\sigma_{ii}(T)]^{1/2}$ for $i = a, b, c$, the in-plane penetration depth anisotropy is $\lambda_a(T)/\lambda_b(T) = \sqrt{\epsilon}$. Hence, this model with s-wave pairing can easily fit the data of [9] quantitatively for $\lambda_a(T)$, $\lambda_b(T)$, and $\lambda_c(T)$, by using our previous parameter choices[1], setting $\epsilon \approx 2-3$, and adjusting E_{F1}. We note that for d-wave pairing, $\lambda_a(T)/\lambda_b(T)$ is not a constant in this model, and $\lambda_c(T)$ doesn't fit the data[1, 9].

4. DISCUSSION

We have shown[4] that this model with $\epsilon = 1$ gives rise to surface states. It is clear that for concentric Fermi surfaces, surface states will also appear for $\epsilon \neq 1$. Hence, the difficulties with regard to ARPES and tunneling measurements will also apply to this modified model. Finally, we[11] showed that qualitative agreement with the untwinned YBCO data could be obtained with a realistic band structure. This much simpler model, however, gives quantitative agreement.

We remark that YBCO contains three layers: two of which are CuO_2 layers. This model is justified if the chains give rise to an orthorhombic modification of the CuO_2 bands. The SN nature arises from pairing in one of the two CuO_2 bands (i. e., either the bonding or the antibonding band), the other band being nominally normal. This would require setting $\beta \rightarrow \beta/2$. Such a scenario would naturally require $J_1 \neq J_2$, and also be appropriate for other two-layer systems, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$.

REFERENCES

[1] R. A. Klemm and S. H. Liu, Phys. Rev. Lett. 74, 2343 (1995).
[2] D. A. Bonn *et al.*, Phys. Rev. B 50, 4051 (1994).
[3] M. Yethiraj *et al.*, Phys. Rev. Lett. 71, 3019 (1993).
[4] S. H. Liu and R. A. Klemm, Phys. Rev. Lett. 73, 1019 (1993); Phys. Rev. B 52, 9657 (1995).
[5] Z.-X. Shen *et al.*, Phys. Rev. Lett. 70, 1553 (1993).
[6] M. Gurvitch *et al.*, Phys. Rev. Lett. 63, 1008 (1989).
[7] A. G. Sun, A. Truscott, A. S. Katz, R. C. Dynes, B. W. Veal, and C. Gu, (unpublished).
[8] M. Nantoh *et al.*, J. Appl. Phys. 75, 5227 (1994).
[9] D. A. Bonn *et al.*, J. Phys. Chem. Solids 56, 1941 (1995).
[10] T. Xiang and J. M. Wheatley, Phys. Rev. Lett. 76, 134 (1996).
[11] R. A. Klemm, M. Ledvij, and S. H. Liu, in SPIE Conference # 2697 on *Oxide Superconductors and Nano-Engineering II*, ed. by D. Pavuna and I. Bozović (1995, in press).
[12] R. A. Klemm, M. Ledvij, and S. H. Liu, (unpublished).