Out-Of-Plane Superfluid Density Of A Layered Organic Superconductor: The Coherent Josephson Tunneling

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Abstract. Measurements of AC magnetic susceptibility in κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br show that the b-axis penetration depth below T_C exhibits behaviour different from that observed in the ac plane, which exhibits the T-linear dependence. In agreement with earlier measurements, a leading quadratic temperature dependence is found at low temperatures. The temperature dependence of the out-of plane superfluid density is shown to best agree with a model of d-wave superconducting layers coupled by coherent Josephson tunneling.

We are highly confident that the identification of the symmetry and the origin of the order parameter are one of the most important subjects in the newly discovered superconductors since 1979. These problems are in part answered for the hole-doped cuprate superconductors. Now it appears that the consensus is reached that they are d-wave and most likely of magnetic origin [1, 2]. Further, we have discovered that the BCS theory of d-wave superconductors works surprisingly well in describing many features of high-T_C cuprates [3]. For example, an alternative model like the interlayer tunneling (ILT) model [4] seems to be ruled out by a high-precision measurement of the out-of-plane magnetic penetration depth for Tl2201 and Hg2201 [5].

These findings have strong implication to organic superconductors in general, and to layered κ–(BEDT-TTF)$_2$X salts in particular [6]. We recall that both high-T_C cuprates and κ-(ET)$_2$X salts have the layered structure with strong anisotropy between the in-plane and the out-of plane properties. Further, they both reside in the vicinity of the antiferromagnetic phase implying the dominance of the Coulomb interactions [3, 7]. These two features suggest strongly d-wave symmetry in the superconducting order parameter in κ-(ET)$_2$X salts [3, 6]. Indeed, some experiments indicate the nodal structure in the superconducting order parameter of κ-(ET)$_2$X salts consistent with d-wave superconductors [8-10]. However, none of them is conclusive. Further, the reported results on the temperature dependence of the magnetic penetration depths are confusing and controversial [11]. Recently, we have performed new AC susceptibility measurements of both $\lambda_{ac}(T)$ and $\lambda_b(T)$ of κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br [12]. We have shown $\lambda_{ac}(T)$ and $\lambda_b(T)$ have different temperature dependence. We have found that the in-plane penetration depth is T-linear at low temperatures similar to what has been found in high-T_C cuprates YBCO [13] and Bi2212 [14]. On the other hand, the out-of-plane penetration depth follows T^2 behaviour like the one found in YBCO [15] and Tl2201 [5(c)]. The latter is consistent with the coherent Josephson tunneling between superconducting layers.

Since the calculation of the out-of-plane superfluid density $\rho_{s,out}(T)$ is not available yet in an accessible form [16], in this paper we describe this derivation in more detail. First, we recall that the Josephson tunneling between conducting layers in Bi2212 is established in 1994 [17]. Later in the same year the Josephson plasmon in Bi2212 was seen by microwave resonance [18] and then identified as such in 1995 [19]. The Josephson plasmon requires the coherent Josephson tunneling. In this case the out of plane superfluid density is given by [12, 16]:

$$\rho_{s,out} = \frac{\pi^2 T}{2\Delta_0} \sum_n \int \frac{d\phi\, d\phi'}{(2\pi)^2} \frac{|V(\phi,\phi')|^2 \Delta f\, \Delta f'}{\sqrt{\omega_n^2 + \Delta^2 f^2} \cdot \sqrt{\omega_n^2 + \Delta^2 f'^2}} \Bigg/ \int \frac{d\phi\, d\phi'}{(2\pi)^2} |V(\phi,\phi')|^2 \quad (1)$$

where Δ_0 and Δ are the superconducting order parameter at $T = 0$ K and the temperature dependent one, respectively. ω_n is the Matsubara frequency and ϕ is the angle between the quasi-particle momentum and the a-axis within the conducting plane. It should be noted that $f = \cos(2\phi)$ and $\sin(2\phi)$ in cuprate superconductors and κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br, respectively. $V(\phi,\phi')$ is the tunneling matrix element. In our model we assume a ϕ-dependent tunneling matrix element $|V(\phi,\phi')|^2 = C\cdot\delta(\phi-\phi')$. The conservation of the momentum direction within the adjacent conducting planes is a crucial assumption, which implies the coherent tunneling. On the other hand, if the tunneling is incoherent (i.e. no correlation between ϕ and ϕ'), one will have $\rho_{s,out}(T) = 0$ for d-wave superconductors. Then we have

$$\rho_{s,out} = \frac{\pi^2 T}{2\Delta_0}\sum_n \frac{\Delta^2 f^2}{\omega_n^2 + \Delta^2 f^2} = \frac{\pi}{2\Delta_0}\Delta\left\langle f \tanh\left(\frac{\Delta f}{2T}\right)\right\rangle$$
$$= 1 - \frac{\pi^2}{6}\left(\frac{T}{\Delta}\right)^2 - \frac{7\pi^4}{120}\left(\frac{T}{\Delta}\right)^4 - \ldots \qquad (2)$$

where < > means the angular average. Equation (2) is in essence the Ambegaokar-Baratoff formula [20] extended for d-wave superconductors. Using a reduced temperature scale $t = T/T_C$ Eq.(2) reads

$$\rho_{s,out} = 1 - 0.3592t^2 - \ldots \qquad (3)$$

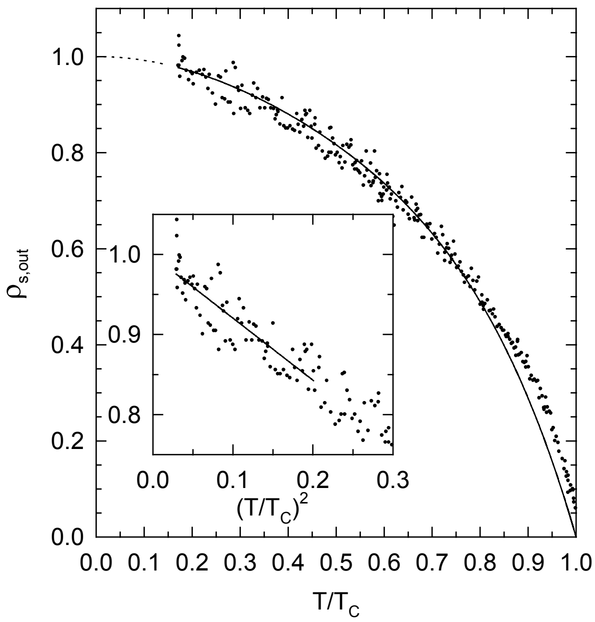

Figure 1: Out-of-plane superfluid density $\rho_{s,out}$ as a function of reduced temperature. Full line is a fit to the theory (see Text). Inset: $\rho_{s,out}$ plotted versus $(T/T_C)^2$ in the temperature range 1.6 K < T < 5 K.

Our experimental data for the out-of-plane superfluid density $\rho_{s,out}$ as a function of reduced temperature $t = T/T_C$ are displayed in Fig. 1. The calculated fit to these data according to theory, shown by full line, is

$$\rho_{s,out} = 1 - 0.78t^2 - 0.21t^3 + 1.22t^4 - 1.23t^5 \qquad (4)$$

It should be noted that the leading term, which describes the low temperature behaviour of the out-of-plane superfluid density $\rho_{s,out}$ is the T^2 term.

Until now the supercurrent along the c-axis in the high T_C cuprates has been considered in terms of either anisotropic 3D model or the incoherent Josephson tunneling. In the former approach it is assumed **k=k'** (the conservation of momentum), where **k** and **k'** are the quasi-particle momentum on the two sides of the barrier. This model is usually referred to as a tunneling model, but we believe this is the misuse of the word. The simplest version of this approach is by Radtke et al. [21] and as one might expect, it gives $\rho_{s,out}(t) \propto t$, the same as for $\rho_{s,in}(t)$. A more elaborate version of this approach was proposed by Xiang and Wheatley [22], who obtained $\rho_{s,out}(t) \propto t^5$. As to the incoherent tunneling model, the simplest version by Graf et al. [23] gives $\rho_{s,out}(t) = 0$ when it is applied for d-wave superconductors. A modified version by Hirschfeld et al. [24], where they introduced rather artificial ϕ and ϕ' correlation, gives $\rho_{s,out}(t) \propto t^3$. Therefore our alternative model "coherent tunneling model", where specular transmission is assumed, is the unique one, which gives $\rho_{s,out}(t) \propto t^2$. It is rather gratifying that the present model describes not only the present data but also $\rho_{s,out}(t)$ of some of high T_C cuprates like YBCO [15] and Tl2201 [5(c)].

In conclusion, our experimental data of the temperature-dependent out-of-plane superfluid density give clear evidence for the BCS-like Josephson tunneling between superconducting layers in the κ–(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br.

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