## Josephson Junctions in $Y_1Ba_2Cu_3O_x$

Recent data[1,2] have shown an unusual current-voltage ($I$-$V$) relation near the superconducting transition temperature of $Y_1Ba_2Cu_3O_x$. Below a temperature $T_{c1}$, $T_{c1} \approx 91$ K (Ref. 1) or $T_{c1} \approx 82$ K,[2] a nonlinear relation $V \sim I^{a(T)}$ with $a(T) > 1$ is found in both ceramics[1] and single crystals.[2] The exponent $a(T)$ increases upon cooling and seems to diverge at $T_{c2} \approx 90$ K (Ref. 1); in Ref. 2 however, at $T = 79.4$ K, $a(T) \approx 8$ is still increasing with finite slope. Furthermore, the $I$-$V$ curves are extremely sensitive to magnetic fields $H$, resulting in a cusplike behavior of $T_c(H)$ for a suitably defined low-resistance state.[1]

In this Comment we propose that this behavior can be understood in terms of two-dimensional (2D) Josephson junctions, related to the presence of (110) twin boundaries in this compound.[3] The presence of such junctions has also been inferred from a series of microwave absorption lines whose position depends on the magnetic field component in the [110] direction.[4] Note that the junctions can be either *on* the twin boundaries or *in between* them. In the latter case, as found for some low-$T_c$ elements[5] and proposed[6] for $Y_1Ba_2Cu_3O_x$, enhanced superconductivity near the twin boundaries may be correlated with their unusual dynamics.[7]

We propose that at $T < T_{c1}$, thermal fluctuations on 2D junctions between the superconducting layers destroy the coherence between them. A second 2D transition occurs at $T_{c2}$ where phase coherence is established across the junctions, resulting in a 3D correlated superconductor with a finite threshold current. The junctions may vary in their parameters, resulting in a sequence of 2D transitions; the divergence of $a(T)$ at $T_{c2}$ is then smeared, as in Ref. 2.

A microscopic description of the second transition is obtained via the free energy of a 2D Josephson junction[8] with $\phi(x,y)$ the Josephson phase,

$$F = \phi_0 \int dx\, dy \{ I_J [(1-\cos\phi) + \tfrac{1}{2}\lambda_J^2 (\nabla\phi)^2] - 2\mathbf{H}\cdot\mathbf{n}\times\nabla\phi \}. \quad (1)$$

Here $\phi_0 = hc/2e$ is the flux quantum, $I_J$ and $\lambda_J$ are the Josephson current and penetration length, respectively, and $\mathbf{n}$ is a unit vector normal to the junction. The last term in (1) is the coupling of an external field $\mathbf{H}$ to the magnetization $\mathbf{n}\times\nabla\phi$ due to flux lines in the junction. We assume that $|\mathbf{H}|$ is below the threshold field $H_{c1}$ of the superconducting layers so that only the component of $\mathbf{H}$ parallel to the junction is relevant.

Equation (1) is identical to that of the commensurate-incommensurate transition with uniaxial symmetry.[9-11] We identify the phase transition of (1) with $T_{c2}$ and with a critical field $H_J(T_{c2})$ above which flux lines are induced in the junction. A peculiar result of 2D fluctuations is that the phase boundary near $T_0 = T_{c2}(H=0)$ has the form[9-11]

$$H_J \sim \exp[-b(T_0 - T_{c2})^{-1/2}], \quad (2)$$

where $T_0 \approx 8\pi\lambda_J^2 I_J \phi_0$ and $b$ is a constant. The behavior of $H_J(T_{c2})$ near $T_0$ accounts for the observed cusp in the data (Fig. 5 of Ref. 1) and is a significant evidence for 2D fluctuations.

At $T_{c1} > T > T_{c2}$ thermal fluctuations lead to $\langle\cos\phi\rangle = 0$ and there is no coherence across the junction. Thus each superconducting layer acts as a 2D film with a nonlinear $I$-$V$ relation due to vortex unbinding.[12] Note that the fluxes associated with a vortex pair can join through a junction with no cost in free energy if $T > T_{c2}$. Thus $a(T)$, which is proportional to a vortex length,[12] will increase with the thickness $d$ of the correlated superconducting layer. As more junctions become correlated, $d$ increases, accounting for the rapid increase of $a(T)$. This process must be modified[12] when eventually $d >$ (bulk penetration length)$^2$/(grain size).

In conclusion, while Eq. (2) is valid for 2D junctions in general, the $V \sim I^{a(T)}$ relation results from the more specific geometry of parallel junctions relating to a twin boundary array.

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1M. A. Dubson, S. T. Herbert, J. J. Calabrese, D. C. Harris, B. R. Patton, and J. C. Garland, Phys. Rev. Lett. **60**, 1061 (1988).

2P. C. E. Stamp, L. Forro, and C. Ayache, Phys. Rev. B **38**, 2847 (1988).

3For reviews, see J. Electron Microsc. Tech. **8**, No. 3 (1988).

4K. W. Blazey, A. M. Portis, K. A. Muller, and F. H. Holtzberg, Europhys. Lett. **6**, 457 (1988).

5I. N. Khlyustikov and A. I. Buzdin, Adv. Phys. **36**, 271 (1987).

6M. M. Fang, V. G. Kogan, D. K. Finnemore, J. R. Clem, L. S. Chumbley, and D. E. Farrel, Phys. Rev. B **37**, 2334 (1988).

7B. Horovitz, G. R. Barsch, and J. A. Krumhansl, Phys. Rev. B **36**, 8895 (1987).

8B. D. Josephson, Adv. Phys. **14**, 419 (1965); Gauge invariance of Eq. (1) is shown by M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1975), p. 198.

9H. J. Schulz, Phys. Rev. Lett. **46**, 1685 (1981).

10F. D. M. Haldane, P. Bak, and T. Bohr, Phys. Rev. B **28**, 2743 (1983).

11B. Horovitz, T. Bohr, J. M. Kosterlitz, and H. J. Schulz, Phys. Rev. B **28**, 6596 (1983).

12B. I. Halperin and D. R. Nelson, J. Low Temp. Phys. **36**, 599 (1979).