INVITED, HTS Conf., Korea, 1995

CONF-9508207--2

Effects of c-Axis Josephson Coupling on Dissipation, Flux Dynamics and the Mechanism of High-T_c Superconductivity*

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Proceedings of the Conference on High T_C Superconductivity - Yongpyung '95, High Temperature Superconductivity Vol. 5, Yongpyung, Korea, August 15-17, 1995, edited by T.S. Hahn and S.Y. Lee

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*This research is supported by the U.S. Department of Energy, Division of Basic Energy Sciences-Materials Sciences, and Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology under contract #W-31-109-ENG-38 and the National Science Foundation Office of Science and Technology Centers under contract DMR #91-20000.

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Effects of c-Axis Josephson Coupling on Dissipation, Flux Dynamics and the Mechanism of High-T_c Superconductivity

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Introduction

Most of the high-temperature superconductors (HTS) are highly anisotropic, with reasonably metallic conduction in the Cu-O layers (i.e, in the ab planes) and poorer conduction normal to these planes, i.e., along the c-axis. A number of measurements, including the resistance anisotropy (which can approach 10^5) support the possibility of a different conduction mechanism along the c-axis. One notable exception is fully oxygenated $YBa_2Cu_3O_7$, which is viewed as a three-dimensional (3D) metal, but with an anisotropy greater than any conventional metallic superconductor. For the highly-anisotropic HTS, such as $Bi_2Sr_2Ca_2Cu_3O_x$, $Tl_2Ba_2CaCu_2O_y$ and oxygen-deficient $YBa_2Cu_3O_{7-\delta}$, there is strong evidence that the c-axis transport results from Josephson coupling between units consisting of closely-coupled Cu-O bilayers or trilayers.

The nature of this coupling is important for practical issues such as flux dynamics and dissipation and the current carrying capacity of conductors, but also for an understanding of the pairing mechanism in HTS cuprates. A Josephson coupling model[1] was introduced and successfully explained the irreversibility behavior of the highly-anisotropic HTS in a magnetic field and various manisfestations of Josephson coupling were dramatically demonstrated by Kleiner and Müller[2]. Direct measurements of c-axis transport have also been successfully explained[3] by the Josephson coupling model, and the possibility of an unusual c-axis transmission rate for Cooper pairs has been recently noted[4]. These effects are reviewed in the following.

Flux Dynamics and Dissipation

Beyond the high values of T_c, one of the first obvious differences between HTS and conventional superconductors was the significantly broadened HTS resistive transitions in a magnetic field. These are consistent with thermally-activated depinning of magnetic field vortex lines, and an experimental study by Kim, et al[1] also presented a model demonstrating that these results could be systematically understood by considering two energies: E_p, the conventional depinning of 2D 'pancake' vortices within the 2D Cu-O units; and E_j, the conventional Josephson energy to describe the c-axis coupling between pancakes in adjacent Cu-O units. Examples of fits using the conventional temperature and field dependences of E_p and E_j are shown in Fig. 1. Kim, et al[1] also found that E_j depends exponentially on the insulator spacing between Cu-O units, thus implying that the Josephson coupling is by quantum mechanical tunneling.

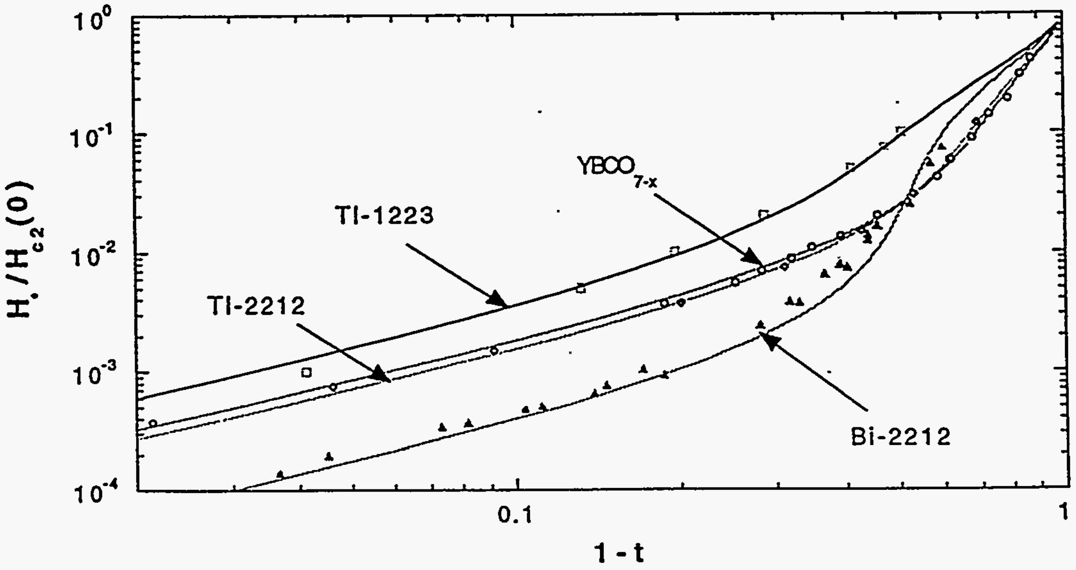

Fig. 1. The irreversibility fields (defined by $R=10^{-5}R_n$) for various highly-anisotropic HTS, together with fits from the model of Ref. 1. The magnitude of $H^*/(1-t)$ in the linear region (at high temperatures or small values of $1-t=1-T/T_c$) is proportional to E_j, and shows an exponential dependence on insulator spacing between Cu-O units for these cuprates.

Kleiner and Müller[2] have dramatically demonstrated various Josephson effects in single crystals of $Bi_2Sr_2CaCu_2O_z$. They see, e.g., hysteretic current-voltage curves, microwave emission and synchronization, etc. This work leaves no doubt as to the origin of c-axis transport. Directly measured transport in $Bi_2Sr_2CaCu_2O_z$ single crystals[5] was partially explained[3] using the same Josephson model of Ref. 1. The observed c-axis resistance peak, which became larger and shifted to lower temperatures as the magnetic field increased, agreed with the Josephson model with a value of E_j being consistent with the normal state c-axis resistance and a direct connection of the c-axis quasiparticle resistance with tunneling measurements[6] was shown. However, the temperature dependence of the c-axis resistance at lower temperatures implied a value of E_j which was 3-5 times larger.

The value of E_j is of significant interest. It can be obtained from the Josephson critical current, $I_{cj} \equiv eE_j/\hbar$, however, a direct measure of I_{cj} is complicated: the high currents needed can cause heating; but also the ab-plane crystal dimensions must be smaller than the Josephson penetration length. As an alternative, thermally-activated broadening of the Josephson junction resistance has been analyzed[4] within fluctuation theory to determine E_j/k_BT for oxygen-deficient $YBa_2Cu_3O_{7-\delta}$ crystals.

There is still a difficulty of establishing the correct junction area since both I_{cj} and E_j are extrinsic, depending on the junction resistance or area, and the Cu-O bilayers may not be coherent across the entire crystal. Also, for the expected strength of Josephson coupling, the broadening will be very small in zero-field and comparable to broadening by inhomogeneities (e.g., oxygen content). Fortunately both problems are overcome by applying a magnetic field parallel to the junction normal, which introduces a new length scale, $\sqrt{\Phi_o/B}$, so that e_j, the *intrinsic* E_j, per unit area, can be obtained from $E_j = e_j\ \Phi_o/B$. The validity of this length scale for Josephson coupling for fields parallel to the junction normal has been verified in experiments with discrete Nb-film junctions[7] (see Fig. 3a). Similar Arrhenuis plots for the $YBa_2Cu_3O_{7-\delta}$ crystal are shown in Fig. 3b, and they confirm the 1/B dependence of E_j.

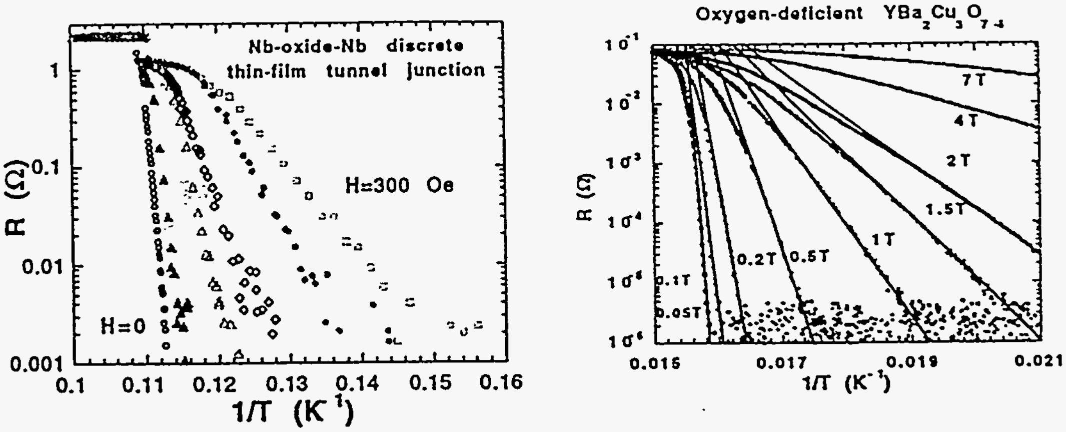

Fig. 3. Arrhenius activation plots for (a) a discrete Nb Josephson junction and for (b) the c-axis resistance of $YBa_2Cu_3O_{7-\delta}$, both with fields parallel to the junction normal. For the Nb junctions, the junction area coming into the activation energy E_j was Φ_o/B within experimental error.

To test that the c-axis dissipation is Josephson related, and not, e.g., due to flux flow, the measured c-axis resistance of a $YBa_2Cu_3O_{7-\delta}$ crystal is shown in Fig. 2 as a function of the angle, ϕ, between the field direction and the c-axis. The maximum R_c occurs for B||c, which corresponds to zero macroscopic Lorentz force on the Abrikosov vortices and it drops over three

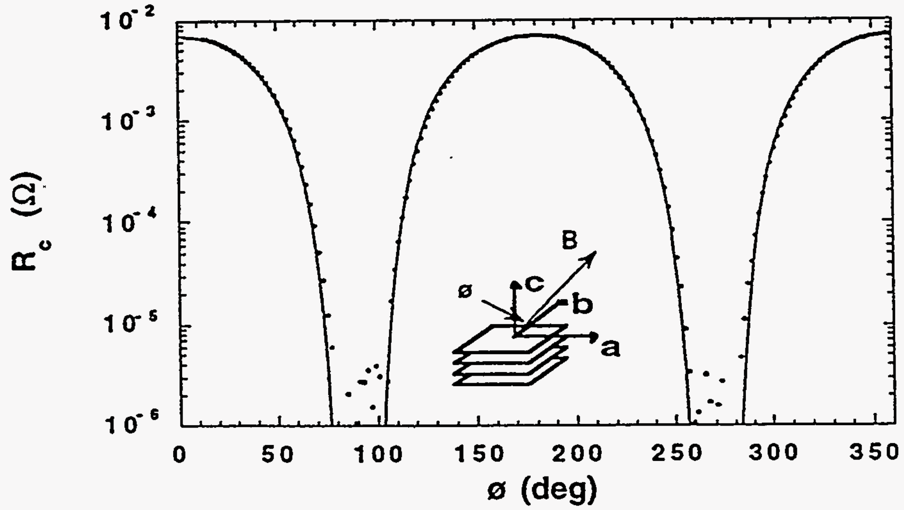

Fig. 2. Angular dependence of c-axis dissipation for an oxygen-deficient $YBa_2Cu_3O_{7-\delta}$ crystal in a field of 1 T at 60 K (T_c~65 K).

orders-of-magnitude into the noise for $B \| ab$ which is the *maximum* Lorentz force and *minimum* pinning direction for the applied flux. This rules out dissipation from the motion of external-field vortices, but it is consistent with Josephson coupling.

A more quantitative fit can be found by extending the Ambegaokar-Halperin model[8] for Josephson dissipation to the c-axis of the cuprates:

$$R_c(T) = R_{Nc}(T)\{I_o(E_j(T)/2k_BT)\}^{-2}, \qquad (1)$$

where I_o is the modified Bessel function and set $E_j(T)=e_j(T)\Phi_o/|B\cos\phi|$. We then find the solid line fit to the data shown in Fig. 2. If a complete set of e_j fits are compared to the conventional Ambegaokar-Baratoff calculation[9]

$$e_j(T) = \frac{\pi\hbar\Delta(T)}{2e^2 r_N}\tanh\left(\frac{\Delta(T)}{2k_BT}\right), \qquad (2)$$

where $\Delta(T)$ is the energy gap and r_N is the normal-state junction resistance for unit area, then e_j is larger than expected[9], when the measured normal-state c-axis resistance is used in r_N and a reasonable $\Delta(T)\sim 14$ meV is used.

A possible explanation of this discrepancy is that the tunneling matrix elements for Cooper pairs and normal-state quasiparticles are not the same as assumed in Ref. 9. While such a result has not been found in any conventional superconductors, several related theoretical ideas[10] have been proposed for HTS.

A similar analysis of published c-axis resistance data[11] on LaSrCuO single crystals leads to the same conclusion: at lower temperatures e_j is larger than expected from the normal-state c-axis resistance. This result is also seems to be the same effect that is found in the low-temperature c-axis resistance in $Bi_2Sr_2CaCu_2O_z$ single crystals[5] described above. Thus the behavior seems to be universal in the HTS cuprates.

In summary, measurements of the c-axis transport in highly-anisotropic HTS materials strongly indicate that Josephson coupling is involved. In detail this conclusion affects various properties of the HTS cuprates, including the irreversibility behavior *for transport in the ab planes*, the direct c-axis transport and potentially the mechanism of Cooper pairing.

This research is supported by the U.S. Department of Energy, Basic Energy Sciences-Materials Sciences, and Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under contract #W-31-109-ENG-38, and the National Science Foundation-Office of Science and Technology Centers under contract DMR 91-20000.

References

1. D.H. Kim, K.E. Gray, R.T. Kampwirth, J.C. Smith, D.S. Richeson, T.J. Marks, J.H. Kang, J. Talvacchio and M. Eddy, *Physica* **C177**, 431 (1991).
2. R. Kleiner, F. Steinmeyer, G. Kunkel and P. Müller, *Phys. Rev. Lett.* **68**, 2394 (1992); R. Kleiner and P. Müller, preprint.
3. K.E. Gray and D.H. Kim, *Phys. Rev. Lett.* **70**, 1693 (1993).
4. J.D. Hettinger, K.E. Gray, B.W. Veal, A.P. Paulikas, P. Kostic, B.R. Washburn, W.C. Tonjes and A.C. Flewelling, *Phys. Rev. Lett.* **74**, 4726 (1995).
5. G. Briceno, M.F. Crommie and A. Zettl, *Phys. Rev. Lett.* **66**, 2164 (1991).
6. D. Mandrus, L. Forro, D. Koller and L. Mihaly, *Nature* **351**, 460 (1991).
7. D.H. Kim, K.E. Gray and J.H. Kang, *Phys. Rev.* **B45**, 7563 (1992).
8. V. Ambegaokar and B.I. Halperin, *Phys. Rev. Lett.* **22**, 1364 (1969).
9. V. Ambegaokar and A. Baratoff, *Phys. Rev. Lett.* **10**, 486 (1963).
10. P.W. Anderson, in "Superconductivity, Proceedings of the ICTP Spring College in 1992", edited by P. Butcher and Y. Lu (World Scientific, Singapore); S. Chakravarty, A. Sudbo, P.W. Anderson and S. Strong, *Science* **261**, 337 (1993); and A.J. Leggett, private communication.
11. K. Kadowaki, S.L. Yuan, K. Kishio, T. Kimura and K. Kitazawa, *Phys. Rev.* **B50**, 7230 (1994).