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Search for magnetic field induced gap in a high-T_c superconductor

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Abstract

Break junctions made of the optimally doped high-temperature superconductor $Bi_2Sr_2Ca_2CuO_8$ with T_c of 90 K has been investigated in magnetic fields up to 12 T, at temperatures from 4.2 K to T_c. The junction resistance varied between 1 and 300 kΩ. The differential conductance at low biases did not exhibit a significant magnetic field dependence, indicating that a magnetic field induced gap (Science, 277 (1997) 83), if exists, must be smaller than 0.25 meV. © 2000 Elsevier Science Ltd. All rights reserved.

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Much of what we know about the electronic states in high-T_c superconductors has been learned by using tunneling devices different from the metal–insulator–metal layer junctions so successful in exploring traditional superconductivity [1]. Superconductor–insulator–superconductor (SIS) tunneling on break junctions provided one of the first clear indications for the failure of a fully gapped s-wave density of states (DOS) in these materials [2–4]. Optimally doped samples were studied by tunneling in great detail [5–7]. More recently, the oxygen doping dependence of the gap has been investigated on SIS junctions created by proper manipulation of a normal metal point contact [8]. Superconductor–insulator–normal metal (SIN) junctions were used very successfully in scanning tunneling spectroscopy studies [9,10], and in point contact measurements [11–13]. Although many of these junctions are much less controlled than the traditional metal oxide layer junctions, there is a reasonable level of consistency between the various techniques, indicating that the features observed are intrinsic to the materials.

The present study was motivated by a recent report of Krishana et al. on the magnetic field dependence of the thermal conductivity [14,15], and by theoretical arguments about the behavior of d-wave superconductors in magnetic field [16–18]. The apparent non-analytical behavior reported by Krishana et al. raised the intriguing possibility of a magnetic field induced instability of the d-wave superconducting state with the appearance of a complete gap at temperatures below 20 K and magnetic fields of the order of 1 T. Theoretical foundations in terms of mixing a (complex) d_{xy} component to the $d_{x^2-y^2}$ state were suggested by Balatsky [16] and Laughlin [17].

We performed break junction tunneling measurements in magnetic fields, with the goal of testing these conjectures directly. The tunneling device used in this work is an advanced version of an earlier one [2], used most recently in the study of the superconducting gap of Rb_3C_{60} [19]. In short, a very thin optimally doped $Bi_2Sr_2Ca_2CuO_8$ (BSCCO) single crystal of $T_c = 90$ K was mounted on a flexible support, and contacted with gold wires. The sample was cooled in He atmosphere, and a break junction was created in situ by bending the support. (A similar method has been employed for Al and Nb point contacts by Scheer et al. [20] and Muller et al. [21], respectively.) A piezoelectric rod was used for fine tuning of the junction. The tunneling current was parallel, and the magnetic field was perpendicular to the copper oxide planes. Early reports of point contact spectroscopy [22] and break-junction tunneling on BSCCO superconductor in magnetic field by

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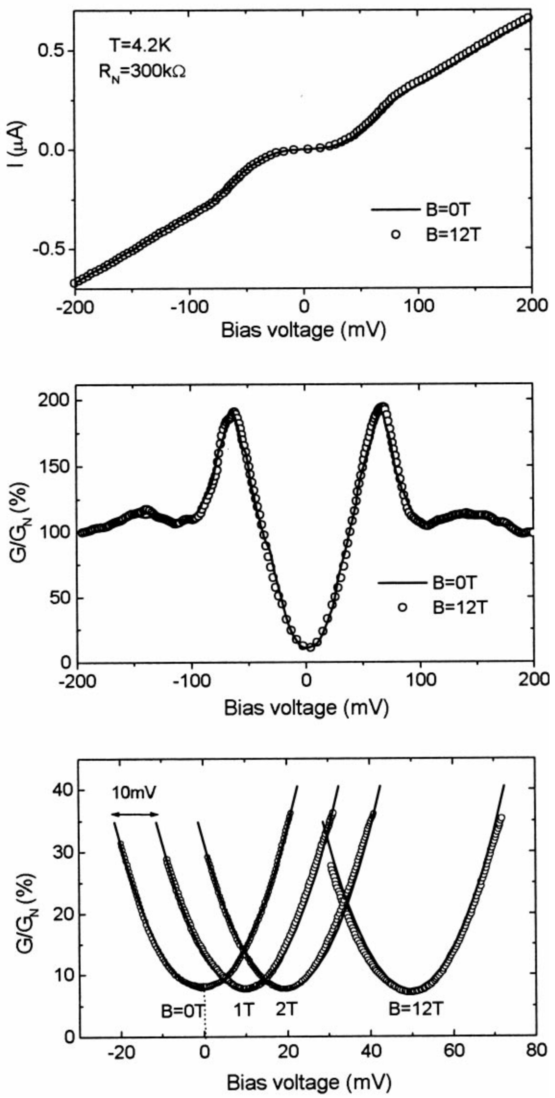

Fig. 1. Upper panel: Tunneling current vs. voltage (I–V) characteristics for SIS break junction at 4.2 K on an optimally doped BSCCO crystal in zero and 12 T magnetic field. Middle panel: The corresponding differential conductance curves obtained by numerical derivation of the I–V characteristics of the upper panel. The conductance is normalized to its zero field value at the bias voltage of 200 mV. The resistance of the junction is $R = 300$ kΩ at 200 mV. Lower panel: the low-bias portion of the differential conductance curves, measured in various magnetic fields (circles). The curves in non-zero magnetic fields are shifted for a better view. The solid line, supplied as a reference, represents the same quadratic function. A complete gap of magnitude Δ' in the density of states should result in a $4\Delta'/e$ wide region of zero conductivity around zero bias.

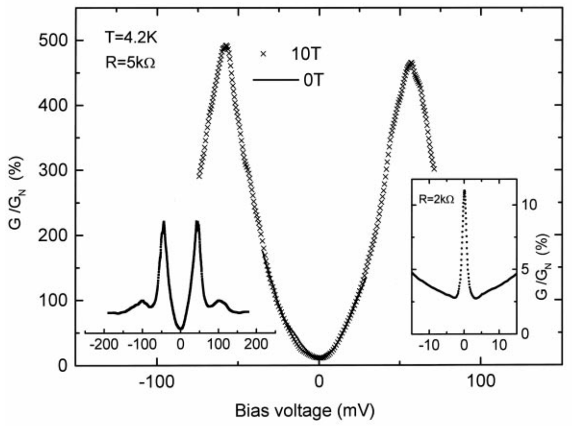

Fig. 2. Main panel: Differential conductance calculated by numerical derivation of the I–V curve of a break junction at $T = 4.2$ K The large-bias resistance of the junction is $R = 5$ kΩ. The continuous line denotes the data taken in zero magnetic field. Crosses represent the data points in high magnetic field. There is no measurable change in the tunneling characteristic due to the application of the magnetic field. The differential conductance at zero magnetic field over a wider range of bias voltages is also plotted in the main panel. The inset demonstrates the voltage resolution of the experiments: it shows the Josephson-peak observed in a $R = 2$ kΩ junction.

Vedeneev et al. [23] did not address the same issue; they did not have sufficient resolution to investigate the effect of the magnetic field on the shape of the low bias region of the conductance curves and furthermore their data were interpreted within a thermally broadened s-wave symmetry BCS gap.

In zero-field and at low temperatures, earlier results of ours [2–4] and others [11–13] have been reproduced. At low temperatures, the zero bias conductance of the junctions was close to zero. At finite bias voltages, the differential conductance followed an approximately quadratic bias dependence at low voltages and exhibited peaks around ^ 60 mV. The corresponding peak-position in the density of states of the d-wave superconductor (the d-wave gap) is at $\Delta = 40$ meV.[3] This is in general agreement with the values reported for an optimally doped sample [2,4,5].

If the magnetic field induces a gap Δ' in the density of states, then the differential conductance is expected to change: in the low temperature limit, a fully gapped DOS results in vanishing tunneling conductivity for voltages up to $2\Delta'/e$. Numerous junctions were measured in search of this effect. In Figs. 1 and 2, two examples are shown, representing high and low resistance junctions, respectively. In the upper panel of Fig. 1, the I–V characteristics at $B = 0$ and 12 T fields are shown in the ^ 200 mV range. The middle panel displays the corresponding conductance curves normalized to the value at 200 mV in zero magnetic field.

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[3] The straightforward argument, resulting in the maximum differential conductance of the SIS junction at $V_{\mathrm{peak}} = 2\Delta$, works only for the isotropic s-wave condensate. Otherwise V_{peak} can be determined only after calculating the convolution of the density of states, as discussed in Ref. [2].

The low bias part of the conductance curve is blown up in the lower panel of Fig. 1. The curves at $B = 1$, 2 and 12 T are shifted in respect to the zero field value for the sake of a better view. The same parabola (corresponding to a linear density of state) is drawn as an eyeguide over the experimental points for scans at different magnetic fields. It is evident from these curves that no change was found in the shape of the tunneling characteristic in the temperature and magnetic field range where the thermal conductivity anomaly was observed by Krishana et al. [14,15]. The absence of magnetic field dependence of the tunneling conductance at 4.2 K is illustrated in Fig. 2 for the case of a low resistance junction. Similar conclusions were reached for temperatures up to 30 K on all the samples investigated.

It should be mentioned that the finite size of the junctions averages the physical properties on the involved area. For a d-wave superconductor, a full gap should be expected only for pure tunneling along a–a or b–b directions (on a microscopic scale). In these junctions, the tunneling averages the density of states for many k-values, and we always see a quadratic voltage dependence of the conductance at low biases. Nevertheless, if the magnetic field would suppress the nodes in the gap, the conductance would be zero below the lowest gap value on the Fermi surface, no matter how is the average done in different k-directions.

Josephson current is observed in low resistance junctions. In the differential conductance, calculated from the measured currents and voltages, this feature shows up as a sharp peak, centered at zero voltage. Ideally, the peak should be very narrow. The width of the peak is a good measure of our experimental resolution — an example is shown in the inset of Fig. 2. From the half width of the curve, we deduce a voltage resolution of about ≈ 1 mV from these measurements. Combining the results illustrated in Figs. 1 and 2 with the resolution deduced from the Josephson current measurements, a magnetic field induced gap of $\Delta' > 0.25$ meV is excluded by the present study. (Note that a gap of Δ' produces a conductivity change over the voltage range of $4\Delta'/e$.)

From a purely experimental perspective, the thermal conductivity (κ) data of the Princeton group [14,15] places a lower limit on Δ'. According to the interpretation favored by the authors, the absence of all field dependence in κ is due to an exponentially vanishing quasiparticle population — in other words, it is due to a gap that is significantly larger than the temperature. For example, at $B = 2$ T and $T = 10$ K the gap should be Δ' q 1 meV, and it is expected to *increase* at higher magnetic fields and decreasing temperatures. This is not compatible with our observations, in particular with the 4.2 K data shown in the figures.

The review of current theories reveals several of possibilities for introducing a new energy scale to the problem. We will use a representative magnetic field of $B = 10$ T for quantitative comparison. The cyclotron energy, on the order of $\hbar\omega_c \propto a v_F(eB/c)$ is about 1 meV at this field (using reasonable values of the lattice spacing a and Fermi velocity v_F). A fine structure on this scale is close the limit of the voltage resolution in the present experiment, and it can not be entirely excluded. Janko [18] describes the states in the Abrikosov vortices, obtaining characteristic energies in the order of magnitude of the geometric mean of the superconducting gap and the cyclotron frequency, $\Delta' \propto \sqrt{\Delta\hbar\omega_c}$. The energy is of the order of 15 meV, clearly excluded by our measurement. Finally, Laughlin [17] describes a mechanism where the new gap is $\Delta' = \hbar\nu\sqrt{2(eB/\hbar c)} =$ 5 meV (here $\hbar\nu = 4.5 \times 10^6$ cm s^{-1} was used for the root mean square velocity of the d-wave node). A fully gapped DOS of $\Delta' = 5$ meV should result in reduced conductivity over a 20 mV wide voltage range, which is clearly contradicted by the experimental results shown in Figs. 1 (lower panel) and 2.

In conclusion, our tunneling measurements on break junctions place an upper limit of $\Delta' \approx 0.25$ meV on the magnetic field induced gap in BSCCO. The field-induced anomaly in the thermal conductivity must have some other explanation, possibly along the lines suggested by Aubin et al. [24].

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References

[1] E. Wolf, Principles of Electron Tunneling Spectroscopy, Oxford University Press, New York, 1985.

[2] D. Mandrus, L. Forró, D. Koller, L. Mihály, Nature 351 (1991) 460.

[3] D. Mandrus, J. Hartge, C. Kendziora, L. Mihály, L. Forró, Europhys. Lett. 22 (1993) 199–204.

[4] J. Hartge, L. Forró, D. Mandrus, M.C. Martin, C. Kendziora, L. Mihály, J. Phys. Chem. Solids 54 (1993) 1359.

[5] H. Hancotte, et al., Physica C 280 (1997) 71–76.

[6] P. Romano, J. Chen, J. Zasadzinski, Physica C 295 (1997) 15–21.

[7] H.J. Tao, Farun Lu, E.L. Wolf, Physica C 282–287 (1997) 1507–1508.

[8] N. Miyakawa, P. Guptasarma, J.F. Zasadzinski, D.G. Hinks, K.E. Gray, Phys. Rev. Lett. 80 (1998) 157.

[9] Y. De Wilde, et al., Phys. Rev. Lett. 80 (1998) 153.

[10] Ch. Renner, B. Revaz, J.-Y. Genoud, K. Kadowaki, O. Fischer, Phys. Rev. Lett. 80 (1998) 149.

[11] Q. Huang, J.F. Zasadzinski, K.E. Gray, J.Z. Liu, H. Klaus, Phys. Rev. B 40 (1989) 9366.

[12] J. Kane, K.-W. Ng, Phys. Rev. B 53 (1996) 2819.

[13] J. Kane, K.-W. Ng, D. Moecher, Physica C 294 (1998) 176.

[14] K. Krishana, N.P. Ong, Q. Li, D. Gu, N. Koshizuka, Science 277 (1997) 83.

[15] K. Krishana, N.P. Ong, Q. Li, D. Gu, N. Koshizuka, J. Phys. Chem. Solids 59 (1998) 2088.
[16] A.V. Balatsky, Phys. Rev. Lett. 80 (1998) 1972–1975.
[17] R.B. Laughlin, Phys. Rev. Lett. 80 (1998) 5188.
[18] B. Jankó, Phys. Rev. Lett. 82 (1999) 4703.
[19] D. Koller, M.C. Martin, L. Mihály, G. Mihály, G. Oszlányi, G. Baumgartner, L. Forró, Phys. Rev. Lett. 77 (1996) 4082.
[20] E. Scheer, P. Joyez, D. Esteve, C. Urbina, M.H. Devoret, Phys. Rev. Lett. 78 (1997) 3535.
[21] C.J. Muller, A.M. van Ruitenbeek, L.J. de Jong, Physica C 191 (1992) 485–504.
[22] S.I. Vedeneev, et al., Z. Phys. B 83 (1991) 343.
[23] S.I. Vedeneev, et al., Phys. Rev. B 49 (1994) 9823.
[24] H. Aubin, K. Behnia, S. Ooi, Science 280 (1998) 9a.