Correlation between *d*-wave pairing behavior and magnetic-field-dependent zero-bias conductance peak

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We consistently observe a magnetic-field-dependent conductance peak at zero-bias voltage in a wide range of superconductor/noble-metal junctions fabricated from oxide superconductors ($YBa_2Cu_3O_{7-\delta}$ and $Tl_2Ba_2CaCu_2O$) that have been reported to exhibit d-wave pairing behavior; however, no measurable peak appears in similar junctions made from an s-wave oxide superconductor ($Nd_{1.85}Ce_{0.15}CuO_4$). Explanations of this correlation are considered in terms of the Appelbaum-Anderson model for magnetic interface scattering and the midgap-state model for d-wave interface states. [S0163-1829(97)04845-5]

We report the effects of magnetic field up to 12 T on the ubiquitous zero-bias conductance peak[1] (ZBCP) in low-resistance c-axis $YBa_2Cu_3O_{7-\delta}$ (YBCO)/noble-metal junctions, a geometry that is of practical importance for electrical contacts in high-temperature superconductor (HTS) electronics. Evidence is also presented for the general occurrence of magnetic-field-dependent ZBCP's at noble-metal junctions made with the $Tl_2Ba_2CaCu_2O$ oxide superconductor system, which, similar to YBCO, has shown d-wave pairing behavior. In contrast, we observe no measurable ZBCP's in noble-metal junctions made with the s-wave oxide superconductor $Nd_{1.85}Ce_{0.15}CuO_4$. This intercomparison of ZBCP effects in multiple oxide systems indicates a novel correlation between the occurrence of ZBCP's and evidence for d-wave pairing behavior.

ZBCP's in oxide superconductor junctions have been interpreted in terms of magnetic scattering centers at HTS interfaces[2] using the Appelbaum-Anderson theory.[3] Recently, ZBCP's have been predicted by Hu to arise also from midgap interface or surface states that are unique to d-wave pairing symmetry.[4] Implications of this broad range of data for both models and the need for theoretical predictions of magnetic field effects in both cases are discussed briefly at the end.

The symmetry of the superconductor order parameter impacts our basic understanding of mechanisms responsible for high-temperature superconductivity[5] and can set theoretical limits on practical parameters such as the microwave surface impedance.[6] Several significant and elegant experiments have made a strong case for d-wave symmetry for the pair-wave function in $YBa_2Cu_3O_{7-\delta}$ (YBCO), to a lesser extent in $Tl_2Ba_2CaCu_2O$ (TBCCO), and most recently in $Tl_2Ba_2Cu_1O$. One set of experiments finds direct evidence for a π phase shift of the order parameter in orthogonal directions, which has been observed in specific junction geometries, depending on the crystal orientation.[7,8] Another set of experiments probes the large anisotropy of the magnitude of the order parameter through photoemission studies[9] and the temperature dependence of the penetration depth.[10] On the other hand, the oxide superconductor $Nd_{1.85}Ce_{0.15}CuO_4$ (NCCO) shows s-wave behavior, having for example, an exponential temperature dependence of the penetration depth expected for s-wave, BCS-like superconductors.[11]

Explanations other than d-wave pairing symmetry have been offered for these phenomena, based particularly on magnetic scattering coupled with anisotropic suppression of the order parameter in s-wave superconductors.[12] A π phase shift has been predicted to occur, for example, across junction interfaces if enough magnetic scattering centers are present;[13] specifically this π shift occurs at the interface rather than within the body of the superconductor as for the d-wave symmetry model. Also, the non-BCS-like temperature dependence of the penetration depth has been predicted to result from magnetic-scattering-induced gaplessness.[14] Evidence for such magnetic-scattering centers is based on the observation of a magnetic-field-dependent zero-bias conductance peak in junction measurements, interpreted through the Appelbaum-Anderson theory for magnetic interface scattering.[2] This interpretation has prompted the present investigation to test for a correlation between d-wave phenomena and the occurrence of ZBCP's.

Earlier work has shown the widespread presence of ZBCP's in the conductance-vs-voltage (G-V) characteristics of $YBa_2Cu_3O_{7-\delta}$ junctions.[1] Near zero voltage bias, a peak is evident in the G-V curves of Fig. 1, which decreases with temperature and disappears for temperatures above

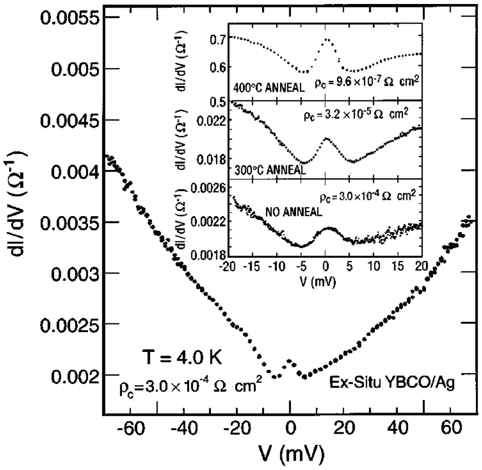

FIG. 1. Conductance dI/dV as a function of bias voltage V for a planar, c-axis YBCO/Ag interface ($\sim 8 \times \sim 8\ \mu$m) formed *ex situ*, that is, after exposing the YBCO surface to air. Inset: Low-bias data indicating the similarity of the zero-bias conductance peak after exposing the interface to 30-min oxygen anneals at progressively higher temperature.

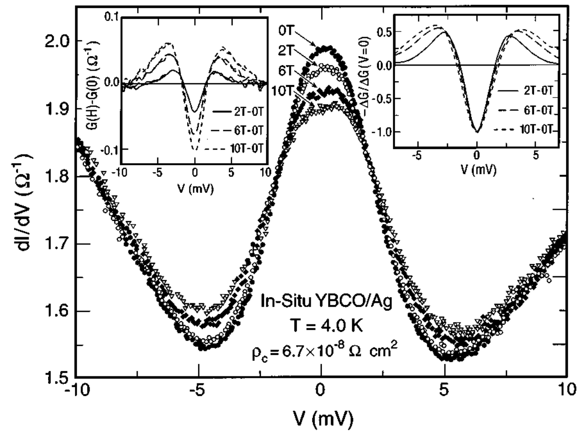

FIG. 2. Magnetic field dependence of the low-bias conductance for an *in situ* YBCO/Ag interface ($\sim 4 \times \sim 4\ \mu$m). Left inset: Change in conductance $\Delta G \equiv G(H) - G(0)$, showing a magnetic-field suppression of G at low bias voltage (between ± 2 mV) and ΔG peaks on either side. Right inset: Normalized change in conductance $\Delta G/\Delta G(V=0)$, showing slight magnetic-field broadening of the width at the half minimum of ΔG, and greater field broadening of the ΔG peak separation.

~ 30 K.[2,15] The zero-bias conductance peak is nearly independent of film manufacturer, junction resistivity (from $10^{-8}\ \Omega\ \mathrm{cm}^2$ to $10^{-3}\ \Omega\ \mathrm{cm}^2$),[15] and the counter-electrode material (including noble metals such as Au, Ag, and Pt,[16] metals having a high oxygen affinity, such as Pb, Ag, Cu, In, and Al,[1,2,15] as well as metallic oxides[17]). Furthermore, oxygen annealing does not significantly alter the ZBCP even though the junction conductance changes by several orders of magnitude, as shown by the inset in Fig. 1. Thus, the combination of these data leads to a picture of a ZBCP in YBCO with notable consistency.

In order to investigate the magnetic response of the ZBCP and its possible occurrence in oxide superconductor systems other than YBCO, we fabricated a series of YBCO, TBCCO, and NCCO superconductor junctions with noble-metal counter electrodes. YBCO films, 200-nm thick, were grown on heated (100)MgO or (100)$LaAlO_3$ substrates using pulsed-laser deposition. Counter-electrode noble-metal films 200- to 1500-nm thick of evaporated Ag, Au, or sputtered Pt were deposited on the superconductor films after cooling in oxygen without exposure to air (to form *in situ* interfaces)[18] or after the superconductor films were exposed to air and later cleaned with a light (300 eV) Ar ion mill (to form *ex situ* interfaces).[19] Au coatings for the TBCCO films were deposited *ex situ* and either annealed to form low resistivity interfaces or left unannealed to test the properties of high resistivity junctions. The counter-electrode material for the NCCO films was *in situ* deposited Au. Thus, in all cases, the junction impedance arises as a natural property of the degraded superconductor surface rather than from an artificial barrier. The low-temperature conduction of these junctions is dominated by tunneling across the interface as evidenced in Fig. 1 by the presence of the gaplike feature at bias voltages below about ± 20 mV and the parabolic shape of the background G-V characteristic.[20] These two features were observed as an HTS tunneling signature in YBCO junctions with Pb and In.[21]

Results reported here are for noble-metal/c-axis junctions having high interface conductivity. However, it is known that the surface of c-axis YBCO films usually contain a large number of exposed Cu-O plane edges, as confirmed by scanning tunneling microscopy.[19] Therefore, it is possible that a,b-plane conduction contributes significantly to electrical transport across these nominal c-axis interfaces. Previous measurements on c-axis YBCO junctions have shown a zero-bias conductance peak (for pressed In counter electrodes[21]) as well as a conductance dip (for thermally evaporated Pb counter electrodes[2]). We believe the low oxygen affinity of our noble-metal counter electrodes maintain the conduction along the Cu-O plane edges.

The effect of magnetic field on the G-V characteristics of YBCO is shown in Fig. 2. Conductance curves were obtained by differentiating the I-V data using a sliding three-point fit. High magnetic field measurements were made at 4 K in a 12-T solenoidal magnet, with field oriented parallel to the junction interface to within 1 or 2 degrees. As the applied-field magnitude increases from 0 to 12 T, the conductance at zero bias monotonically decreases and the conductance near ± 5 mV increases. This is more easily observed if we plot the difference $\Delta G \equiv G(H,V) - G(0,V)$ between the conductance curves at zero and high fields, as shown in the left inset of Fig. 2. In such a plot there is a negative peak at $V=0$ (a minimum) and two positive peaks on either side of the minimum, all of which increase with increasing field. Moreover, the separation of the side peaks appears to widen noticeably with field. However, if we reanalyze the data by normalizing the ΔG curves at each field by its value at $V=0$, i.e., plotting $-\Delta G/\Delta G(V=0) \equiv -[G(H,V) - G(0,V)]/[G(H,0) - G(0,0)]$ as shown in the right inset of Fig. 2, we see that the width of the suppressed region is about ± 1 mV at half minimum, which widens at a much lower rate with magnetic field than the separation of the two peaks in ΔG on either side of the minimum.

The results for TBCCO, which has also been reported to exhibit d-wave behavior, are shown in Fig. 3. High-field conductance measurements were carried out using both unannealed, high-resistivity TBCCO/Au interfaces (Fig. 3) and annealed, low-resistivity junctions (not shown). A zero-bias conductance peak was consistently observed in these

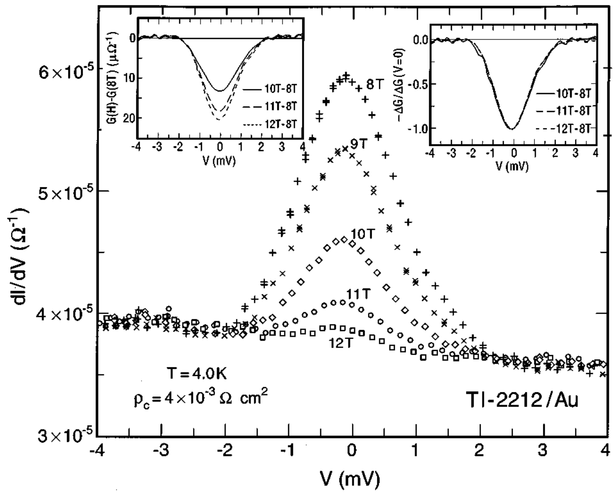

FIG. 3. Magnetic field dependence of the low-bias conductance for an *ex situ* TBCCO/Au interface ($\sim 4 \times \sim 4\ \mu$m). Left inset: Change in conductance $\Delta G \equiv G(H) - G(0)$, showing a strong magnetic-field suppression of G at low-bias voltages (between ± 2 mV, similar to the YBCO data presented in Fig. 2). Right inset: Normalized change in conductance $\Delta G/\Delta G(V=0)$, showing no measurable broadening of the ΔG minimum with magnetic field amplitude at 4 K.

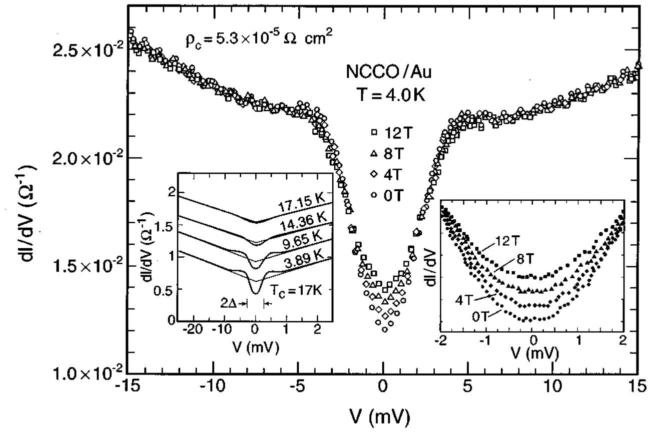

FIG. 4. Magnetic field dependence of the low-bias conductance for an *in situ* NCCO/Au interface ($\sim 8 \times \sim 8\ \mu$m). Left inset: V-like normal background conductance (different temperature curves have been displaced vertically for clarity). Right inset: Expanded voltage scale around zero bias. The data show no evidence for suppression of the conductance with magnetic field, unlike the YBCO and TBCCO systems; instead a gradual *increase* is observed, consistent with field reduction of the superconducting energy gap.

junctions. At low magnetic fields (<8 T), however, the background conductance level decreased with magnetic field and changed shape, presumably from magnetic-field suppression of weak links within the TBCCO films. At 8 T and above, however, the parabolic background conductance level stabilized and the effect of magnetic field on the zero bias conductance can be seen in Fig. 3 for a TBCCO/Au junction with a high interface resistivity of $4 \times 10^{-3} \Omega$ cm^2. The conductance peak width is about ± 2 mV. The peak is strongly suppressed by magnetic field and the width of the suppressed region is about ± 1 mV at half minimum, similar to the YBCO system. Unlike the YBCO system, however, no enhancement with magnetic field was seen in the conductivity on either side of the central peak, and no widening of the suppressed region with magnetic field was observed. TBCCO/Au junctions with vastly different specific interface resistivities (five orders of magnitude lower than that shown in Fig. 2) showed ZBCP's that were also suppressed by magnetic field, although at a lower rate. Thus, a zero-bias conductance peak appears to be a feature of TBCCO/Au junctions over a very wide interface resistivity range; it is also suppressed by magnetic field, but unlike YBCO shows no noticeable widening.

Conductance data are shown in Fig. 4 for a gold junction with the s-wave superconductor NCCO (Ref. 22) (250-nm-thick NCCO layer with a 200-nm-thick *in situ* deposited Au counter electrode). The junction, which has a V-like background conductance (left inset of Fig. 4), shows no observable ZBCP. Furthermore, application of a magnetic field parallel to the junction interface does not result in suppression of G, but rather a gradual *increase* in conductivity over the voltage region below the gap edge and a reduction of the conductivity peaks at the gap edge. This behavior is consistent with the usual effects of a gap reduction as field approaches the upper critical field of this low-T_c (17 K) oxide superconductor. Thus, in contrast to the YBCO and TBCCO systems, no measurable conductance peak is observed at zero bias voltage, and the conductivity is not suppressed by the application of an external magnetic field.

Taken together with the earlier YBCO results, these conductance data in TBCCO and NCCO junctions suggest a correlation between the occurrence of a magnetic-field dependent conductance peak at zero bias in superconductors showing d-wave phenomenon and, *vice versa*, the absence of a ZBCP in oxide superconductors exhibiting s-wave behavior. The origin of the ZBCP appears to be intrinsically linked to d-wave behavior and is not, as was thought earlier, an extrinsic barrier or surface-damage effect. We now briefly describe two models proposed for the origin of the ZBCP's in the oxide superconductors: the Appelbaum-Anderson magnetic scattering model,[23] and the d-wave surface-states model.[4]

The Appelbaum model assumes the existence in the tunnel barrier of impurities with localized magnetic moments. Tunneling electrons scatter off these impurities via spin-exchange interactions, giving rise to additional conduction channels, which lead to the ZBCP. An applied field suppresses the tunneling conductance in the bias range corresponding to an energy width $e|V| \leqslant g\mu_B H$ (the Zeeman energy), and splits the conductance peak into two peaks located at $eV_{\pm} = \pm g\mu_B H$. Here μ_B is the Bohr magneton and g is the Landé g factor for the impurity spin. From the right inset of Fig. 2 it is evident that both the width of the suppressed region and the separation of the two side peaks are increased with the field, at a rate of 0.027 mV/T for the former and 0.13 mV/T for the latter. Equating these rates to $g\mu_B$ we obtain g values of 0.5 and 2.2, respectively. Although simple-minded, the reasonableness of the estimate suggests that the Appelbaum model is consistent with the general trend displayed by our *in situ* (001)-YBCO/Ag junction. We point out that in the case of a (103)-YBCO/Pb junction,[2] the observed field dependence implied a much larger g value. The behavior of an *ex situ* TBCCO/Au junction, shown in Fig. 3 and insets, is different in a couple aspects. First, there is no evidence for side peaks. We recall that in the past it has always been difficult to identify side peaks except perhaps for a few cases.[24] Second, the width of the conductance suppression is apparently field independent, which may imply an extremely small g value, coupled with severe thermal smearing. It has been proposed that the formation of magnetic moments in the TBCCO material[25] is different from that of the YBCO system.[12,26] A rigorous test of the magnetic-scattering model will require extension of these measurements to higher magnetic fields and lower temperatures in the same junction system, as well as generalization of the Appelbaum model to include impurity correlations and superconducting electrodes.

We turn now to the midgap surface states model, which represents another possible explanation for the observed correlation based on d-wave pairing symmetry.[4] In this model the conductance peak arises from surface states formed by a particle alternately experiencing specular reflection and a unique Andreev reflection in which an electron changes momentum $\mathbf{k}$ into a hole of momentum $-\mathbf{k}$. This situation occurs only with d-wave pairing symmetry over a range of scattering angles, non-{100} surfaces, and would not arise with s-wave symmetry, either isotropic or anisotropic. Originally considered to occur at low symmetry surfaces, zero-energy midgap states have more recently been proposed to occur also for c-axis junctions where the superconducting film has grains boundaries or microscopic facets.[27] The surface-states model predicts a reduction in ZBCP height as temperature is raised, but little increase in peak width, in agreement with the dependence seen experimentally. Qualitatively, the model accounts for a reduction of the peak amplitude from applied magnetic field in terms of field penetration into the sample; however, no clear test of the surface-states model can be made until a theory is forthcoming to quantitatively predict the effects of magnetic field on the tunneling current.

Thus, a wide range of conductance measurements, extending across three oxide systems with different counter electrode materials, show a correlation between the presence of a ZBCP and the purported d-wave nature of the Y and Tl compounds and, *vice versa*, its absence for the possible s-wave Nd oxide compound. This by itself suggests a correlation of the ZBCP with the symmetry of the pair wave function, independent of any theoretical modeling of the ZBCP.

Note added. We have become aware of a calculation of magnetic field effects for a,b-axis junctions by Fogelström *et al.*[28] using the surface-states model, something that has been lacking until now. Among other results, the model predicts a splitting of the ZBCP at zero field in a limited symmetry phase space, which may shed some light on a zero-field splitting observed in very high conductivity a-axis YBCO/Au junctions.[29] The challenge of the d-wave surface-states model, it would seem now, is to extend the predictions of magnetic-field effects to the practical high-conductivity c-axis case for comparison with the wide body of data reported here. The experimental correlation of these ZBCP data with purported d-wave behavior is pervasive and would provide a broad-based critical test.

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