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Order-parameter-node removal in the d-wave superconductor $YBa_2Cu_3O_{7-x}$ in a magnetic field

Roy Beck,* Yoram Dagan,† Alexander Milner, Alexander Gerber, and Guy Deutscher
School of Physics and Astronomy, Raymond and Beverly Sackler faculty of Exact Sciences, Tel-Aviv University, 69978 Tel-Aviv, Israel

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We have measured the in-plane tunneling conductance of optimally doped $YBa_2Cu_3O_{7-x}$ films/In junctions as a function of magnetic field and film orientation. In zero applied field all samples exhibit a zero bias conductance peak (ZBCP) attributed to the d-wave symmetry of the order parameter. In junctions formed on (110) oriented films, the splitting $\delta_{\downarrow}(\mathrm{H})$ of the ZBCP in decreasing fields applied perpendicular to the CuO_2 planes follows the law $\delta_{\downarrow}(\mathrm{H})=\mathrm{A}\cdot\mathrm{H}^{1/2}$ with $\mathrm{A}=1.1\ \mathrm{mV/T}^{1/2}$. This law is obeyed up to 16 T for film thickness varying from 600 Å (less than the London penetration depth λ) up to 3200 Å (about twice λ). Since Meissner currents are negligible in decreasing fields and at thickness smaller than λ, this splitting cannot be attributed to a Doppler shift of zero energy surface bound states. The data taken in decreasing fields is quantitatively consistent with a field induced id_{xy} component of the order parameter. The effect of the Doppler shift is prominent in data taken in increasing fields and in the field hysteresis of the splitting.

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I. INTRODUCTION

The excitation spectrum of a conventional superconductor (low T_c) is characterized by an almost independent momentum s-wave energy gap, Δ. This is not the case in the high T_c cuprate superconductors; there it is broadly agreed that the ground state superconducting order parameter (OP) is strongly momentum dependent, being maximal in the direction of the crystallographic axes a and b. In most cases, it appears to have the pure $d_{x^2-y^2}$ symmetry, being zero at 45° between these axes (the node directions), where it changes sign. In contrast to the finite energy Δ required to excite a low energy quasi-particle in a low-T_c superconductor, such a quasi-particle can be excited with an infinitely small energy in a d-wave superconductor along the nodes. This is no longer the case if an additional imaginary component is present in the OP. In this case, the energy spectrum of the superconductor is fully gapped.

Theoretically, it has been suggested that such an imaginary component can result from an instability of the *d-wave* OP under perturbations such as surface pair breaking,[1] impurities,[2] proximity effect,[3,4] and magnetic field.[5] Another view is that a phase transition occurs at a certain doping level[6,7] or magnetic field[8] from a pure d wave to a nodeless OP having the $d_{x^2-y^2}+id_{xy}$ or $d_{x^2-y^2}+is$ symmetry. The d_{xy} component breaks both time and parity symmetries, hence it involves boundary currents that flow in opposite directions on opposite faces of the sample as previously pointed out by Laughlin.[8] These currents produce a magnetic moment which, through interactions with the magnetic field, lowers the free energy by a term proportional to $B\cdot d_{xy}$, where B is the magnetic field induction. On the other hand, in the zero temperature limit, node removal costs an energy proportional to id_{xy}^3. Minimization of the sum of the two contributions leads to an amplitude $d_{xy}=A\cdot B^{1/2}$, where A is a coefficient given by Laughlin.

Experimentally, two sets of experiments have been interpreted as indicating that a magnetic field, applied perpendicular to the CuO_2 planes, can indeed induce a nodeless OP. Measurements of the thermal conductivity $\kappa(\mathrm{H})$ on $Bi_2Sr_2CaCu_2O_8$ (Bi2212) single crystals have shown a decrease followed by a plateau at a certain field.[9] This field was interpreted as that beyond which a finite id_{xy} component appears at the finite temperature where the experiment is performed.[8] The finite gap in the plateau region prevents the excitation of additional quasiparticles. Field hysteresis of the thermal conductivity has, however, led to a controversy over the actual origin of the plateau; to date, this issue has remained unresolved.[10]

A second set of experiments possibly indicating the occurrence of a nodeless OP is the field evolution of the conductance of in-plane tunnel junctions formed at the surface of $YBa_2Cu_3O_{7-x}$ (YBCO) films oriented perpendicular to the CuO_2 planes.[11] The conductance of in-plane tunnel junctions formed at the surface of YBCO films having that orientation presents a peak at zero bias (ZBCP). This peak reflects the existence of zero energy surface bound states that come about due to a change of phase by π upon reflection at a (110) surface.[12] Its split, often observed for instance under magnetic fields applied parallel to the surface and perpendicular to CuO_2 planes, may indicate the occurrence of a fully gapped order parameter, having the symmetry $d+id$ or $d+is$. The new peak position $\delta(\mathrm{H})$ would indicate the amplitude of the id or is component. However there exists a different explanation of a field-induced split, in terms of a Doppler shift of the bound states energy.[13,14] The energy shift is equal to $v_s \cdot p_F$, where v_s is the superfluid velocity of the Meissner currents, and p_F is the Fermi momentum of the tunneling quasiparticles.

In order to distinguish between these two possible interpretations, we have taken detailed data in decreasing fields on (110)-oriented films having thickness d, down to well below λ. At such thickness the Doppler shift should be much reduced since $v_s=e\lambda H\cdot\tanh(d/2\lambda)$. Taking data in decreasing fields has also the effect of reducing Meissner currents and the corresponding Doppler shift. This is because there is

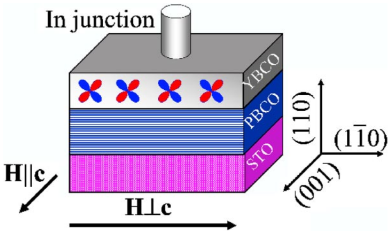

FIG. 1. (Color online) Schematic presentation of the measurement setup for the (110) films. Indium pads are pressed against the surface of the oriented thin film. The crystallographic orientation of the film enables one to apply a magnetic field parallel or perpendicular to the CuO_2 layers while it is been kept parallel to films' surface.

no Bean-Livingston barrier against flux exit (while there may be a strong one against flux entry).[15]

II. EXPERIMENTAL SETUP AND RESULTS

YBCO films near optimal doping, having thicknesses ranging from 600 to 3200 Å, were prepared in the (110) and (100) orientations by the template method, using $SrTiO_3$ and $LaSrGaO_4$ substrates of the appropriate orientation.[16,17] Critical temperatures of all films were in the range of 88–90 K. Junctions were prepared by pressing In (Indium) pads on a fresh films surface.[17,18] In almost 100% of the cases a good junction is formed by this method and the $I(V)$ characteristics are reproducible. The junctions were measured at 4.2 K, and some were also measured at 1.6 K. All junctions displayed an unsplit ZBCP in zero magnetic field, irrespective of the film orientation. The junctions' characteristics were measured as a function of field, applied parallel to the surface, either parallel or perpendicular to the CuO_2 planes (see Fig. 1 for the sample configuration and field orientation). Measurements were systematically taken in increasing and decreasing fields. Field splitting was only observed when the field was applied perpendicular to the CuO_2 planes, in agreement with previous results, confirming the uniaxial in-plane orientation of the c axis.[18] A total of 20 junctions were measured. A typical data set is shown Fig. 2 for a 600 Å, (110)-oriented film.

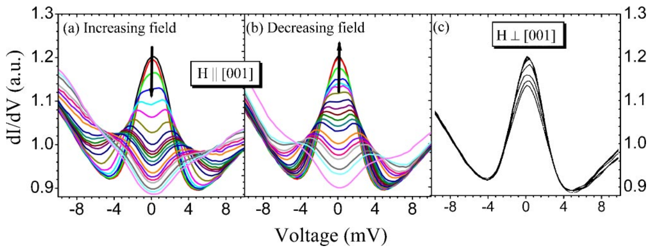

FIG. 2. (Color online) Normalized dynamical conductance $G = dI/dV$ vs bias V for increasing (a) and decreasing (b) applied magnetic fields for an YBCO (110)-oriented film at 4.2 K. Film characteristics: $T_c = 88$ K, film thickness $d = 600$ Å. The splitting δ is defined as half of the distance between the positions of the conductance maxima. In increasing field it can be determined clearly from a field of about 0.1 T up to 5 T, and in decreasing fields from 13 T down to 0.9 T. Applied fields (in Tesla): 0, 0.1, 0.3, 0.5, 0.7, 0.9, 1.2, 1.5, 1.8, 2.1, 2.5, 3.0, 3.5, 5, 6, 7, 11, 13, and 15. (c) Behavior of the same junction for magnetic field applied parallel to the CuO_2 planes at fields (in Tesla): 0, 0.5,1, 2, 4, 8, 12, and 15.5. The strong anisotropy of the field effect confirms the good in-plane orientation of the c axis.

We first address the question of the origin of the hysteretic behavior in field apparent in Fig. 2. In general the split, for a given field, is always higher in increasing fields. The peak position for the same sample as in Fig. 2 is shown in Fig. 3(a) in increasing and decreasing fields. In increasing fields, the peak position reaches about 4 meV at 5 T. At higher fields, the exact maximum point cannot be determined because the peak becomes smeared, possibly because it merges with the main gap structure. We define the hysteresis amplitude as the difference $\Delta\delta$(H) between the peak position at increasing, $\delta_{\uparrow}(\mathrm{H})$, and decreasing field, $\delta_{\downarrow}(\mathrm{H})$. For comparison, this hysteresis amplitude is shown in Fig. 3(b) for two films with different thicknesses: 600 and 3200 Å. It is apparent that the hysteresis saturates at about 2 T in the 3200 Å film, a field of the order of the thermodynamical critical field $\mathrm{H_c}$. The hysteresis amplitude is larger for the thicker film, about twice as high as for the thinner film. This hysteretic behavior can be understood within the Doppler shift model of the ZBCP splitting,[13] if we take into account the properties of the Bean-Livingston barrier. In samples thicker than the London penetration depth, this barrier prevents flux entry up to fields on the order of $\mathrm{H_c}$. Up to that field, the superfluid velocity of the Meissner currents increases almost linearly; beyond that field, it saturates. The Doppler shift, proportional to the superfluid velocity, follows the same behavior. By contrast, in decreasing fields, there is no barrier that prevents flux exit. This has been shown theoretically by Clem,[15] verified experimentally by Bussiere,[19] and shown also to apply in tunneling experiments by Moore and Beasley[20] and in YBCO system by Xu.[21] Hence, when the field is decreased, the surface superfluid velocity quickly reduces to zero, as does the Doppler shift. This is the origin of the hysteresis. The implication is that by subtracting $\delta_{\uparrow} - \delta_{\downarrow}$ [Fig. 3(b)] one measures

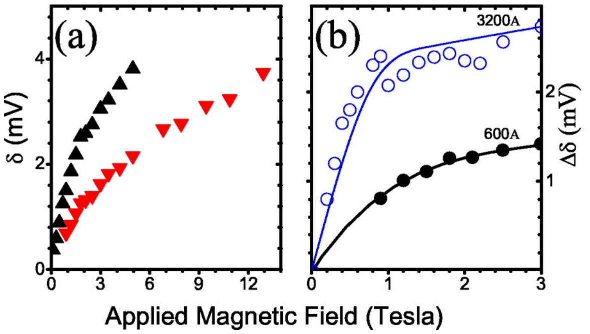

FIG. 3. (Color online) Field splitting hysteresis curve for a (110)-oriented film in increasing (▲) and decreasing (▼) magnetic fields. (a) ZBCP splitting (δ) for a 600 Å thick film, and (b) the difference $\Delta\delta = \delta_{\uparrow} - \delta_{\downarrow}$ between the position of the ZBCP splitting in increasing and decreasing fields for (110) 600 Å (full circles) and 3200 Å (open circles) thick films at 4.2 K. This is a measurement of the Doppler shift effect (see the text). The lines in (b) are a guide to the eye.

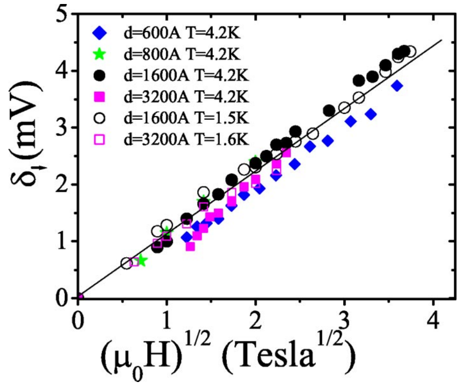

FIG. 4. (Color online) ZBCP field splitting in increasing and decreasing fields for (110) 600 Å (full circles) having thickness ranging from 3200 to 600 Å, as a function of the square root of the magnetic field (H) applied parallel to surface and to the crystallographic *c* axis. The line is a linear fit to all data points and has a 1.1 mV/T$^{1/2}$ slope.

only the Doppler shift effect. The results in Fig. 3(b) are in qualitative agreement with the Doppler shift model predicting the saturation at fields higher than H_c for the thicker film, and the thickness dependence observed. The influence of the Bean-Livingston barrier is, as expected, more apparent in the thicker film. As for the substantial $\delta_\downarrow(\mathrm{H})$, it must find a different explanation.

Our central result is shown in Fig. 4, which presents precisely the ZBCP splitting measured in decreasing fields for (110)-oriented films having thickness ranging from 3200 down to 600 Å, plotted as a function of the square root of the applied field. Data for all samples follow the law $\delta_\downarrow = A\cdot\sqrt{H}$, with $A = 1.1 \pm 0.2$ meV/T$^{1/2}$. For reasons explained above, this behavior cannot be attributed to a Doppler shift of the zero energy surface bound states. We attribute it to node removal.

These results are quite different from those previously reported for (100) (Ref. 17) and (103)-oriented[14,22,23] films. Generally speaking, field splitting values are smaller for these orientations. We demonstrate the difference between tunneling into (100)- and (110)-oriented films in Fig. 5. Here, we present the splitting versus increasing magnetic field, $\delta_\uparrow(\mathrm{H})$, for two films differing only by their crystallographic orientation. While the (110) oriented film exhibits splitting of 4.4 mV at 3 T, a splitting of only 1.1 mV is seen at the same field in the (100)-oriented film. Moreover, at high fields the splitting has a different behavior in these two orientations. In the (100) film $\delta_\uparrow(\mathrm{H})$ almost saturates at fields higher than 1 T, while in the (110) film the ZBCP keeps splitting rapidly. In addition, splitting values in the (100) orientation are strongly thickness dependent. For samples thinner than 1600 Å, we find that they are too small to be determined experimentally at 4.2 K up to 6 T (not shown). These results are consistent with a splitting dominated in the (100) orientation by the Doppler shift effect, with a different (additional) mechanism being responsible for the splitting behavior in (110)-oriented films.

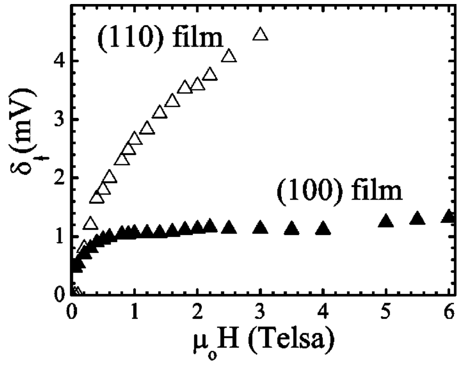

FIG. 5. ZBCP field splitting measured in increasing fields for (100)- (full triangle) and (110)- (empty triangle) oriented films. Film thickness is 3,000Å for both films and data taken at 4.2 K.

III. DISCUSSION

Surface faceting is thought to be the reason for the ZBCP commonly observed in (100)-oriented films.[13] Recently, some direct evidence has been provided by scanning tunneling microscopy measurements, suggesting that (110) faces are present in films of that orientation.[24] We have shown that while the zero field ZBCP is similar for both macroscopic orientations, their field-splitting behavior is entirely different. Our results demonstrate that in order to observe a substantial splitting *in decreasing fields and in films thinner than the London penetration depth*—namely, under conditions where the Doppler shift effect is very weak—one must use samples having the (110) orientation. Then, and only then, the experimental data show the H$^{1/2}$ law in the entire field range studied (up to 16 T), and at all film thickness. This strongly suggests that node removal occurs, but only for that film orientation. Although (100) films do have (110) facets at their outer surface, the inner surfaces at the interface with the (100) $\mathrm{LaSrGaO_4}$ substrate and $\mathrm{PrBa_2Cu_3O_7}$ intermediate layer presumably quite flat and have the (100) orientation. The presence of (110)-oriented surfaces on both sides of the film appears to be a necessary condition for node removal.

Our data are in agreement with the expression given by Laughlin for the amplitude of the field induced id_{xy} component, $\delta = A\cdot B^{1/2}$. Under our experimental condition, thin films and high magnetic fields, we can assume that $B = \mu_0 \cdot \mathrm{H}$. The coefficient A in his theory is proportional to the square root of the gap and the Fermi velocity. For the compound Bi2212 he calculates $A = 1.6$ mV/T$^{1/2}$. Taking into account the respective values of the gap in this compound (about 30 meV) and in YBCO (about 20 meV), our experimental result $A = 1.1$ mV/T$^{1/2}$ can be considered to be in good agreement. Yet, it must be emphasized that Laughlin has not considered the effect of the orientation of the samples boundaries. Therefore, one cannot say directly whether our observation that node removal only occurs in (110)-oriented films is in agreement with his model or not. For similar reasons, one cannot say whether there is a connection between our results and the thermal conductivity measurements of Krishana *et al.*[9] carried out in a different geometry, which Laughlin has interpreted within the framework of his theory.

In a previous publication,[16] we reported ZBCP field splitting data taken in increasing fields. We noted that the $H^{1/2}$ behavior seen up to about 0.5 T is incompatible with the Doppler shift model, which predicts a linear behavior at low fields. Likewise, we also noted that a field splitting that persists in films having a thickness of order λ or less is incompatible with this model. We believe that the data presented here, particularly taken in decreasing fields and at even smaller film thickness, reinforce this conclusion and make a much more compelling case in favor of the node removal effect.

In addition, we would like to point out that the absence of ZBCP field splitting in geometries different from ours may now be understood. This is the case in grain boundary junctions[25] and for junctions grown on single crystal edges.[26] With the field applied perpendicular to the surface, vortices penetrate at low fields, and there cannot be any substantial Doppler shift because there are no large screening currents. Second, the geometry of the boundaries is unfavorable for the flow of Laughlin's currents. It could be that the contradictory results reported in thermal conductivity experiments, concerning the existence of a field induced gap, also stem from the ability or inability of the samples to carry boundary currents under the specific experimental conditions.

IV. CONCLUSIONS

In summary, a ZBCP field splitting is observed in tunnel junctions fabricated on optimally doped (100)- and (110)-oriented films. The ZBCP splits as a function of magnetic field with a hysteresis which is thickness dependent, i.e., the hysteresis increases with the film thickness. The splitting is generally weaker in (100)-oriented films, particularly in decreasing fields where it is negligible. In (110)-oriented films, splitting is strong even in decreasing fields, where it is found to be thickness independent and to have a square root dependence on magnetic field for fields ranging from 0 to 16 T. We attribute the hysteretic behavior to the Doppler shift effect predicted by Fogelstrom *et al.*,[13] and the splitting in decreasing fields to node removal. Our data in decreasing fields for which Meissner currents are negligible are in good agreement with the existence of a field induced id_{xy} component predicted by Laughlin.[8] His theory, however, does not take into account the orientation of the samples boundaries, which we find to be crucial. We conjecture that the presence of (110) surfaces on opposite faces of the sample is necessary for the flow of Laughlin's currents, and thus for the establishment of the id_{xy} order parameter. Furthermore, his model does not take into account the presence of vortices, as pointed out by Li *et al.*[27] More theoretical work is necessary to establish whether Laughlin's model can explain the effect of films orientation on the field-splitting of the zero bias conductance peak.

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*Email address: Roy@tau.ac.il, Home page: www.tau.ac.il\~supercon

†Present address: Center for Superconductivity Research, Department of Physics, University of Maryland College Park, College Park, Maryland 20742, USA.

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