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

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Whether the node in the order parameter characteristic of a \textit{d-wave} superconductor can or cannot be removed by an applied magnetic field has been a subject of debate in recent years. Thermal conductivity results on the high Tc superconductor $Bi_2Sr_2CaCu_2O_8$ originally explained by Laughlin in terms of such a node removal were complicated by hysteresis effects, and judged inconclusive. We present new tunneling data on $YBa_2Cu_3O_{7-x}$ that support the existence of the node removal effect, under specific orientations of the sample’s surfaces and magnetic field. We also explain the hysteretic behavior and other previous tunneling results so far not understood satisfactorily, attributing them to a combination of node removal and Doppler shift of low energy surface bound states.

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The excitation spectrum of a conventional superconductor (Low Tc) is characterized by an almost independent momentum ($s$-wave) energy gap, $\Delta$. This is not the case in the high Tc cuprate superconductors; there it is broadly agreed that the ground state superconducting order parameter (OP) is strongly momentum dependent, it is 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 $45^\circ$ between these axes (the node directions), where it changes sign. In contrast to the finite energy $\Delta$ required to excite a low energy quasi-particle in a Low Tc superconductor, such a quasi-particle can be excited with an infinitely small energy in a \textit{d-wave} superconductor along the nodes. This is no longer the case if an additional imaginary component is present in the OP, on that case the energy spectrum of the superconductor is fully gapped.

Theoretically, it has been suggested that such an imaginary component can result from instability of the \textit{d-wave} OP under perturbations such as surface pair breaking \cite{ref1}, impurities \cite{ref2}, proximity effect \cite{ref3, ref4} and magnetic field \cite{ref5}. Another view is that a phase transition occurs at a certain doping level \cite{ref6, ref7}, or magnetic field \cite{ref8} from pure \textit{d-wave} to a nodeless OP having the $d_x^2-y^2 + id_{xy}$ or $d_x^2-y^2 + is$ symmetry. The \textit{id}_{xy} component breaks both time and parity symmetries, hence, as pointed out by Laughlin \cite{ref9}, it involves boundary currents that flow in opposite directions on opposite faces of the sample. They produce a magnetic moment which, through interaction with the magnetic field, lowers the free energy by a term proportional to $B \cdot d_{xy}$, where $B$ is the magnetic field. 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.

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 node less OP. Measurements of the thermal conductivity $\kappa(H)$ on $Bi_2Sr_2CaCu_2O_8$ (Bi2212) single crystals have shown a decrease followed by a plateau at a certain field \cite{ref10}. This field was interpreted as that beyond which a finite \textit{id}_{xy} component appears at the finite temperature where the experiment is performed \cite{ref11}. The finite gap in the plateau region prevents the excitation of additional quasi-particles. Field hysteresis of the thermal conductivity has however led to a controversy as to the actual origin of the plateau, and this issue has remained unresolved \cite{ref12}.

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 \cite{ref13}. This conductance presents a peak at zero bias (known as Zero Bias Conductance Peak, ZBCP), which splits when the field is applied parallel to the film’s surface, and perpendicular to the $CuO_2$ planes. The ZBCP is one of the clearest manifestations of an OP having nodes, because it comes about due to a change of phase by $\pi$ upon reflection at a (110) surface, which generates low energy surface states, or Andreev bound states \cite{ref14} (the fact that ZBCPs are also observed for other in-plane orientations is generally interpreted as due to surface roughness \cite{ref15}). Peak splitting may indicate node removal, the new peak position, $\delta(H)$, giving the amplitude of the $d_{xy}$ component \cite{ref16}. However, a different explanation of the peak splitting was also offered, in terms of a Doppler shift of the Andreev bound states \cite{ref17}. This Doppler shift is equal to $v_s \cdot \mathbf{p}_F$, where $v_s$ is the superfluid velocity associated with the Meissner currents, and $\mathbf{p}_F$ the Fermi momentum of the tunneling quasi-particles. There are difficulties with both interpretations. The amplitude of the \textit{id}_{xy} component should be essentially reversible at the fields of inter-
east (in the Tesla range), where the thin film samples are well into the Bean complete penetration limit, while in fact a strong field hysteresis is observed. As for the Doppler shift, it should vanish at film thickness smaller than the London penetration depth where the Meissner superfluid velocity is much reduced, varying as \( V_s = e\lambda H\tanh(d/2\lambda) \), where \( d \) is the film thickness, \( \lambda \) the penetration depth and \( H \) is the magnetic field at the sample surface; while in fact it is slightly changes at \( d = (\lambda/2) \). A further difficulty is that, for reasons that have remained unclear until now, field splitting of the ZBCP is not always observed. For instance, it was not seen in La_{1.45}Sr_{0.15}CuO_{4} and YBCO grain boundary junctions, nor in junctions prepared on Bi2212 single crystals. Thus, a consensus has not yet been reached as to whether a field can induce a finite sub-gap in a d-wave superconductor.

We present in this Letter a new series of tunneling experiments that clarify the origins of the field splitting phenomenon, and establish the conditions under which node removal occurs. Our central result is that node removal can be observed in (110) oriented samples only. It is most clearly seen in decreasing fields, for which the ZBCP splitting is not affected by Doppler shift effects, and is thickness independent. Doppler shift does affect data taken in increasing fields, which are thickness dependent. Hysteresis is due to the properties of the Bean Livingston barrier, which is effective against flux penetration in increasing fields, but not against flux exit in decreasing fields. Data taken on (110) oriented samples in decreasing fields, starting from a field of up to 16T, are in quantitative agreement with Laughlin theory.

YBCO films nearly optimally doped, having thickness ranging from 600Å to 3200Å, were prepared in the (110) and (100) orientations by the template method, using SrTiO\(_3\) and LaSrGaO\(_4\) substrates of the appropriate orientation. Critical temperatures of all films were in the range of 88K to 90K. Junctions were prepared by pressing In (Indium) pads on the films fresh surface. All junctions were measured at 4.2K, and some were in the range of 88K to 90K. Junctions were prepared atate orientation. Critical temperatures of all films were in quantitative agreement with Laughlin theory. Therefore, when the field is decreased, the surface superfluid velocity of the Meissner current is the film thickness, \( \lambda \), the film thickness, \( H \) is the magnetic field at the sample surface; while in fact it is slightly changes at \( d = (\lambda/2) \). A further difficulty is that, for reasons that have remained unclear until now, field splitting of the ZBCP is not always observed. For instance, it was not seen in La_{1.45}Sr_{0.15}CuO_{4} and YBCO grain boundary junctions, nor in junctions prepared on Bi2212 single crystals. Thus, a consensus has not yet been reached as to whether a field can induce a finite sub-gap in a d-wave superconductor.

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the (110) orientation. 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 4.2K up to 6T. These results are consistent with a splitting dominated in the (100) orientation by the Doppler shift effect, with the Laughlin mechanism playing apparently no role.

Surface faceting is thought to be the reason for the ZBCP commonly observed in (100) oriented films \[1\]. Recently, some direct evidence has indeed been provided by STM measurements, suggesting that (110) faces are present in films of that orientation \[7\]. While the zero field ZBCP is similar for both macroscopic orientations, their field splitting is entirely different, as reported here. Our results demonstrate that in order to observe a substantial splitting in decreasing fields and in films smaller 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 are in agreement with the law of Laughlin, strongly suggesting that node removal does occur. Even though (100) oriented films do have (110) facets at their outer surface, the interface with the (100) LaSrGaO substrate and PrBaCuO intermediate layer is presumably quite flat. We conjecture that the absence of the second (110) surface prevents the flow of Laughlin’s currents on that face, making the establishment of the id_{xy} component energetically unfavorable.

In conclusion, the presented tunneling data is consistent with node removal in the d − wave superconductor YBCO under magnetic field if, and only if, the sample’s boundaries have the (110) orientation. As far as we know, this has not been predicted theoretically. Previously not well understood experimental results, such as the difference in field splitting between (110) and (100) oriented films and its hysteretic behavior, can now be explained. The absence of the ZBCP field splitting in grain boundary junctions \[4\] can be understood as a combination of two factors: first, the field being applied perpendicular to the surface, vortices penetrate at low fields, and there cannot be any substantial Doppler shift. Second, the geometry of the boundaries is unfavorable for the flow of Laughlin’s currents. The same applies to junctions produced at the edge of Bi2212 crystals \[6\] with the field being applied perpendicular to the surface. 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.

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FIG. 1: Normalized dynamical conductance $G = dI/dV$ vs bias $V$ for increasing (a) and decreasing (b) applied magnetic fields for YBCO (110) oriented film at 4.2K. Film characteristics: $T_c = 88K$, film thickness $d = 600\,\text{Å}$. The splitting ($\delta$) is defined as half of the distance between the positions of the conductance maxima. In increasing field it can be determined clearly from field of about 0.1T up to 5T, and in decreasing fields from 13T down to 0.9T. 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, 15.

(c) behavior of the same junction for magnetic field applied parallel to the CuO planes at fields (in Tesla): 0, 0.5, 1, 2, 4, 8, 12, 15.5. The strong anisotropy of the field effect confirms the good in-plane orientation of the c-axis.

FIG. 2: Comparison between the field splitting hysteresis curves for (110) and (100) in the presence of increasing ($\triangle$) and decreasing ($\triangledown$) external magnetic fields. (a) ZBCP splitting ($\delta$) and (b) ZBCP splitting difference ($\Delta\delta = \delta_\uparrow - \delta_\downarrow$) for (110) 600Å thickness films at 4.2K. The line in (b) is a guide to the eye.
FIG. 3: ZBCP Field splitting measured in decreasing fields for film thickness ranging from 3,200Å to 600Å as a function faceting square root of applied magnetic field (H). The line is a linear fit to all points with 1.1mV/\sqrt{T}$ slope.