Magnetic Field Dependence of the Superconducting Gap and the Pseudogap in Bi2212 and $HgBr_2$-Bi2212, Studied by Intrinsic Tunneling Spectroscopy

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Intrinsic tunneling spectroscopy in high magnetic field (H) is used for a direct test of superconducting features in the quasiparticle density of states of pure Bi2212 and intercalated $HgBr_2$-Bi2212 high-T_c superconductors. We were able to distinguish with great clarity two coexisting gaps: (i) the superconducting gap, which closes as $H \rightarrow H_{c2}(T)$, and (ii) the c-axis pseudogap, which does not change either with H or with T. Strikingly different H dependencies, together with previously observed different temperature dependencies of the two gaps, speak against a superconducting origin of the pseudogap.

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A pseudogap (PG) in the electronic density of states (DOS) of high-T_c superconductors (HTSC) has been established by different experimental techniques [1–9]. Early surface tunneling measurements [2,4] indicated that the superconducting gap (SG) is almost temperature (T) independent, merging into the PG at the superconducting critical temperature T_c; the latter can exist up to $T \gg T_c$. This has led to a suggestion that the PG is a precursor of the SG [10].

Recently we reported on different T dependencies of the SG and the PG, which speak in favor of two coexisting gaps [1]. An even more crucial test for the superconducting origin of the two gaps is provided by their response to magnetic field (H). Both T and H are depairing parameters and suppress superconductivity when exceeding T_c or the upper critical field H_{c2}, respectively. However, they have a possibility to act differently on the two gaps. Namely, unlike T, H may selectively affect the SG. The ways in which both parameters (T, H) affect the gaps would help in understanding the natures of the two phenomena. Important clues can also be obtained by studying doping [6] and intercalation [11] dependencies on the two gaps.

So far the H dependence of the PG in HTSC is highly controversial. Surface tunneling measurements in Bi2212 revealed the existence of the PG inside the vortex core [12]. The authors argued that it is due to the precursor superconductivity mechanism, similar to the situation at $T > T_c$. The spin part of the PG, measured by NMR, was reported to decrease [7], increase [8], or to be independent [9] of H. Clearly, the H dependence of the PG is far from being established.

Intrinsic tunneling spectroscopy [1,13,14] is a powerful method to study the quasiparticle (QP) DOS inside bulk HTSC single crystals, thus avoiding the problem of surface deterioration. Recent observation of Fraunhofer modulation of Fiske steps in Bi2212 mesas [15] confirmed that such mesas represent stacks of intrinsic Josephson junctions, formed by double Cu0 planes.

In this Letter we analyze H dependencies of the SG and the PG in small near optimally doped ($T_c \simeq 92$–93 K) $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) and intercalated, overdoped $HgBr_2$-Bi2212 mesas. We observed that not only can the SG and the PG have different magnitudes, but they can also have strikingly different dependencies on both H and T: the SG closes as $H \rightarrow H_{c2}$ and $T \rightarrow T_c$, while the PG does not change either with H or T and persists in the superconducting state. Intercalated samples, besides having different doping and anisotropy compared to Bi2212, enabled direct measurements of QP resistances in a wide range of T and H, due to rapid quenching of the c-axis critical current in small magnetic fields.

Small mesa structures, of areas down to 2 μm^2, were made on top of Bi2212 single crystals by photolithography, Ar-ion etching, and a self-alignment technique [1]. Using small mesas, it is possible to decrease the number of defects and reduce self-heating in the mesa [16]. Thus clean and clear c-axis tunneling characteristics can be obtained and used for studying the DOS up to considerably high energies [1]. Upon intercalation with $HgBr_2$ molecules, the distance between cuprate layers increases and the c-axis resistivity increases while the critical current density decreases by a factor of 10–20 [11]. The intercalated samples are overdoped, as follows from a small PG and more metallic temperature dependence of the c-axis resistance [17]. T_c is decreased by intercalation to ~73 K. The c-axis current-voltage characteristics (IVC's) were measured in a three probe configuration. The differential conductance, $\sigma = dI/dV$, was measured by a lock-in technique with the ac current of 1–10 μA.

In Fig. 1, c axis $\sigma = dI/dV$ vs V curves are shown for a pure Bi2212 mesa (5×6.5 μm^2, $N = 7$, $T_c \simeq 92$ K) at four different $T < T_c$. Curves are displayed for both $H = 0$ (thin lines) and $H = 14$ T (thick lines) along the c axis. For clarity, the curves for different T are shifted sequentially by 7 mS along the vertical axis. The $\sigma(V)$ curves have T-independent resistances at large bias [1],

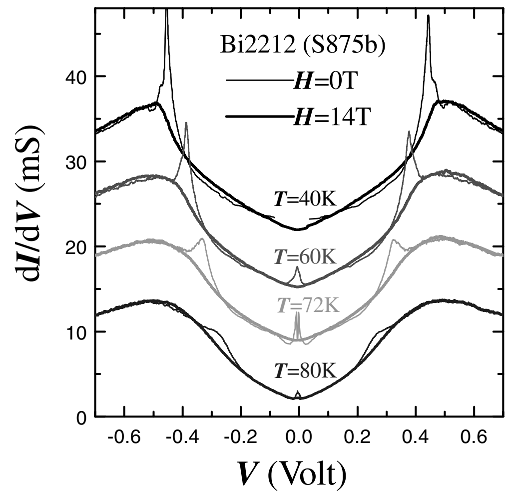

FIG. 1. $\sigma(V)$ curves of a pure Bi2212 mesa at different T for $H = 0$ (thin lines) and $H = 14$ T (thick lines). The existence of a (T, H)-dependent superconducting peak and the (T, H)-independent "background" PG dip and hump is clearly seen.

typical for pure tunnel junctions. At low T and H there are sharp peaks in $\sigma(V)$, which disappear simultaneously with superconductivity both as $T \rightarrow T_c$ and $H \rightarrow H_{c2}$, i.e., behave (and, therefore, identified) as superconducting peaks in superconductor-insulator-superconductor (SIS) junctions at the sum-gap voltage, $V_s = 2N\Delta_S/e$, where N is the number of junctions in the mesa and Δ_s is the maximal SG.

In Fig. 2, $\sigma(V)$ curves of the intercalated $HgBr_2$-Bi2212 mesa ($10 \times 20\ \mu m^2$, $N = 13$) are shown for different $H \parallel c$ at low temperature $T = 4.2$ K. It is seen that the superconducting peak reduces in amplitude with increasing field and systematically shifts to a lower voltage, as shown in inset (a). Likewise, the zero-bias conductance, $\sigma(V = 0)$, increases linearly with H, showing negative magnetoresistance; see inset (b). Such behavior is typical for SIS junctions at low temperature in perpendicular magnetic fields for both s-wave [18] and d-wave superconductors with uncorrelated vortices [19]. Here, the decrease of V_s reflects the decrease of Δ_S and the linear increase of $\sigma(V = 0)$ is associated with a linear increase of the vortex density.

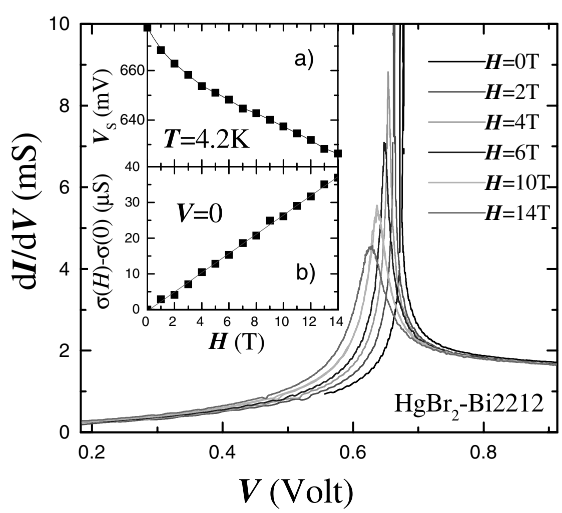

FIG. 2. Differential conductance of the intercalated mesa at $T = 4.2$ K, for different $H \parallel c$. Insets show (a) the decrease of the peak voltage, V_s, and (b) the linear increase of $\sigma(0)$ with H.

In Fig. 3, $\sigma(V)$ curves of the same Bi2212 mesa as in Fig. 1 are shown for high T: (a) 72 K and (b) 80 K, and for several $H \parallel c$. Unlike the case of low T, for $T > 70$ K the superconducting peak is completely suppressed at $H = 14$ T. With increasing H, the $\sigma(V)$ curves approach some H-independent background curve; e.g., from Fig. 3(b) it is clearly seen that there are no changes in the $\sigma(V)$ curves for $H > 10$ T. Taking the field at which the superconducting peak disappears and the magnetoresistance at $V \simeq V_s$ vanishes as H_{c2}, we estimate $H_{c2}(\parallel c) \simeq 10$ T at $T = 80$ K and $\simeq 14$ T at $T = 72$ K, in agreement with previously obtained values; see, e.g., Ref. [19].

However, despite vanishing of the superconducting peak, the IVC's remain nonlinear at $H > H_{c2}(T)$. The background $\sigma(V)$ curves exhibit a smooth depletion of $\sigma(0)$ (a dip) plus a hump at a certain voltage $V = V_{PG}$; see

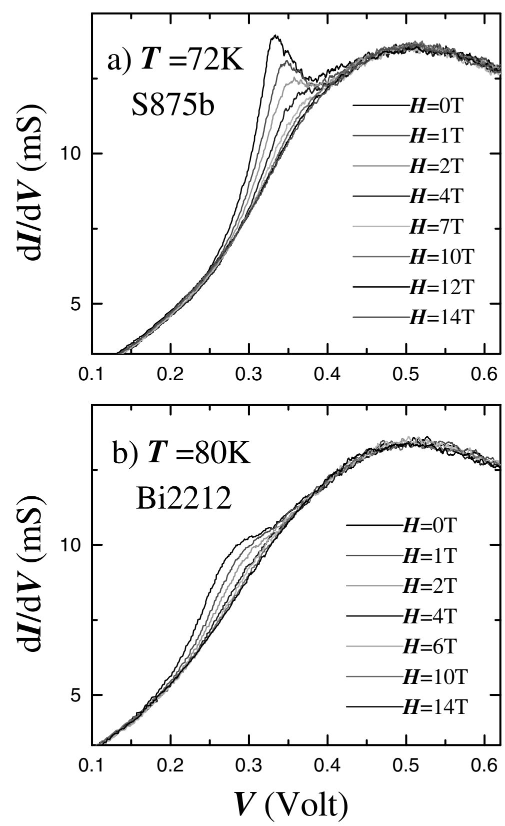

FIG. 3. $\sigma(V)$ curves of a pure Bi2212 mesa at (a) $T = 72$ K and (b) $T = 80$ K and for several $H \parallel c$. It is seen that the superconducting peak is completely suppressed at high fields, while the "background" PG dip-and-hump structure remains intact. It is clear that the superconducting peak and the PG hump appear at different voltages.

Fig. 1. The background curve is similar to that observed in the vortex core [12] and, in our opinion, represents the bare normal (nonsuperconducting) state with the remaining PG in the tunneling DOS even at $T < T_c$. Figure 1 demonstrates that V_{PG} is almost independent of T [1] and is independent of H within the accuracy of experiment (~0.1 mS) in the applied field range. The latter is most clearly demonstrated in Fig. 3(b), from which it is seen that there are no changes either of the shape or of the position of the PG hump with H. Moreover, it is seen that the PG hump voltage, V_{PG}, is distinctly different from the superconducting peak voltage, V_s. The striking contrast in magnetic field dependencies of the SG and the PG is the central observation of this paper.

At high T, interpretation of $\sigma(V, H)$ behavior is less straightforward: First, the superconducting peak does not move to lower voltages with increasing H and second, the small bias conductance becomes almost independent of H; cf. Figs. 2 and 3. To some extent such anomalous behavior may be due to the fact that at high T and H, the $\sigma(V)$ of a SIS junction does not follow the QP DOS. As a matter of fact, for $T/T_c \gtrsim 0.5$ the peak in $\sigma(V)$ can shift to a higher voltage, as a result of strong smearing, despite the decrease of Δ_S [18]. In addition, the peak in the spatially averaged DOS itself smears and shifts towards higher energies with H; see, e.g., Fig. 18 from Ref. [20]. Similarly, the $\sigma(0)$ can even decrease with H despite the increase of DOS $(E = 0)$ [18]. However, our numerical simulations showed that the subgap conductance of a SIS junction should still have a stronger H dependence than that at $V < 0.25$ V in Fig. 3(a).

We believe that the observed discrepancy between numerical simulations for conventional SIS junctions and experimental data at high T and H is due to the PG, persisting at $T < T_c$. Indeed, the phenomenon appears at high T, when the T-dependent SG becomes considerably less than the T-independent PG. Furthermore, the anomalous behavior is more pronounced for the near optimally doped Bi2212 with a larger PG, than for overdoped $HgBr_2$-Bi2212 samples with a smaller PG [17]. If so, suppression of the subgap conductance at $T > 60$ K, for the pure Bi2212 mesa in Fig. 1, is mostly due to the PG rather than to the SG.

Figure 4 shows T dependencies of the zero-bias resistance R_0 of the intercalated sample at several H. A remarkable feature of the intercalated sample is that the critical current can be completely suppressed by a small H. Thus it was possible to trace the QP resistance in the whole range of T and H. At low T, R_0 continuously decreases [$\sigma(0)$ increases] with field, as shown in inset (b) of Fig. 2. The range of variation of $R_0(H)$ decreases with increasing T. At high H and T, e.g., in Fig. 4 at $H > 12$ T and $T > 35$ K, the $R_0(T)$ curves approach a single semiconducting curve. This background, H-independent resistance represents the persisting PG, rather than the SG, as discussed above. Lines in the inset of Fig. 4 show the zero-bias conductance vs T^2 for the same data. It is seen that $\sigma(0) \propto A + BT^2$, at low T. In Ref. [19] such a behavior was attributed to a d-wave character of the SG. However, we should emphasize that in our case $\sigma(0)$ is not entirely determined by the SG, but a significant part of it originates from H-independent background PG conductance. The inset of Fig. 4 shows that the background conductance at $H = 14$ T and $T > 30$ K is still reasonably well described by the $A + BT^2$ dependence. This may indicate the d-wave symmetry of the PG [2].

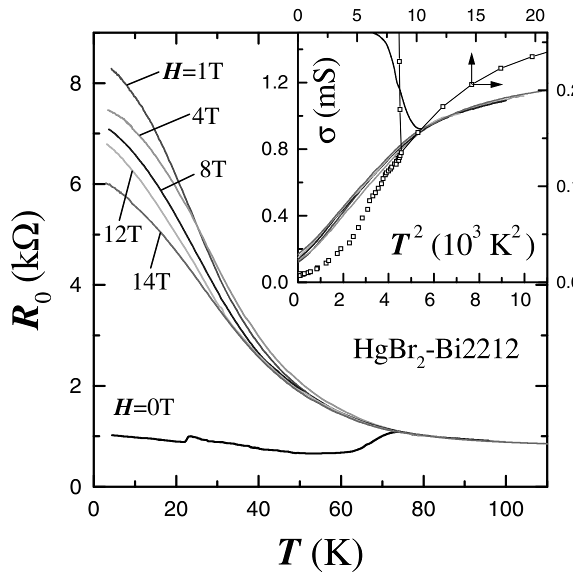

FIG. 4. R_0 vs T of the intercalated mesa at several $H \parallel c$. It is seen that R_0 decreases with H and approaches some background curve at high H. Inset shows $\sigma(0)$ vs T^2 for the same data (lines, left and bottom axes) and for a Bi2212 mesa at $H = 0$ (symbols, right and top axes).

Symbols in the inset of Fig. 4 represent $\sigma(0)$ vs T^2 at $H = 0$ for another optimally doped pure Bi2212 mesa ($3.5 \times 7.5\ \mu m^2$, $N = 10$, $T_c \simeq 93$ K). We should note that unlike the intercalated mesa, for pure Bi2212 mesas it was not possible to completely suppress the c-axis critical current by magnetic field at $T \ll T_c$. Moreover, zero-bias peaks, shown partly in Fig. 1 for $H = 0$, which are due to a finite retrapping current from the QP to the supercurrent branch, did not allow a direct measurement of the QP $\sigma(0)$. The $\sigma(0)$ at $T < T_c$ was obtained by extrapolation of the last QP branch to $V = 0$. This somewhat ambiguous procedure results in a relatively large error, especially at low T. Nevertheless, it is clear that for the optimally doped mesa $\sigma(0)$ deviates from the $A + BT^2$ dependence and decreases faster as $T \to 0$. This is probably due to a significantly larger PG in near optimally doped Bi2212 compared to overdoped $HgBr_2$-Bi2212. Another consequence of a larger PG is that the H-independent background resistance is a larger fraction of R_0 and the magnetoresistance at zero bias is considerably less for near optimally doped Bi2212 than for overdoped $HgBr_2$-Bi2212 samples.

Finally, we would like to discuss implications of our results to several HTSC scenarios. Magnetic field dependence of the fluctuation induced PG within the precursor of the strong coupling superconductivity scenario was studied recently in Ref. [21]. The authors noted that observation of an H-independent maximum in $1/T_1T$ at $T^* > T_c$ [9] does not necessarily rule out the precursor superconductivity scenario of the PG, since the characteristic field for suppression of superconducting fluctuations increases rapidly with departure from T_c. Nevertheless, there should be a strong suppression of superconducting fluctuations by H at $T \sim T_c(H)$. Here we have studied the H dependence of the PG at different T, including the vicinity of T_c. We have seen a clear suppression of the SG by H at $T \sim T_c$, while no evidence for a considerable suppression of the PG was observed. This speaks against the precursor superconductivity scenario of the PG. The spin gap origin of the PG [22] could in principle account for a weak H dependence. We should emphasize, though, that this is a charge gap, which is probed in our experiment. The behavior of the charge gap as well as an absence of the PG for the in-plane transport remain to be clarified within the charge-spin separation scenario. An interesting interpretation of the peak-dip-hump structure in tunneling conductance, suggesting its close connection to the resonant neutron peak, was given recently in Ref. [23]. We should also note that a dynamic Coulomb PG as a result of Coulomb blocking of interlayer tunneling in the 2D electron system [1] would naturally explain different behavior of the PG and the SG, the weak H dependence of the PG, and a metallic in-plane transport in HTSC. However, a detailed comparison of theoretical predictions with the observed different behavior of the SG and the PG has to be made for verification of various HTSC scenarios.

In conclusion, we have studied magnetic field dependencies of the superconducting gap and the c-axis pseudogap in HTSC using intrinsic tunneling spectroscopy. Our experiment provides a crucial test for the superconducting origin of the two gaps in DOS of HTSC, since high magnetic field is a strong depairing factor. We observed that the SG and the PG have strikingly different magnetic field dependencies: the SG vanishes both as $H \rightarrow H_{c2}(T)$ and $T \rightarrow T_c(H)$, while the PG does not change with either H or T. Our data indicate that the PG neither disappear nor continuously transform into the SG below T_c. At high H we were able to completely suppress the superconducting peak/gap and observed the bare pseudogap state clearly persisting at T well below $T_c(H = 0)$. In experiment, such a state is characterized by a vanishing magnetoresistance and the appearance of background, H-independent nonlinear conductance.

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[17] The values of the SG and the PG obtained from peak and hump voltages are $\Delta_S(4.2 \text{ K}) \simeq 33$ meV, $\Delta_{PG}(100 \text{ K}) \simeq 35$ meV for Bi2212, and $\Delta_S(4.2 \text{ K}) \simeq 26$ meV for $HgBr_2$-Bi2212. For the intercalated sample the PG is smaller than the SG even at $T \sim T_c$. Therefore, direct estimation of the PG from tunneling characteristics is difficult to do; cf. Figs. 1 and 2. However, we can roughly estimate the PG from the thermal-activationlike behavior $\sigma(0) \propto \exp(-T^*/T)$ at $T > T_c$; see Fig. 4. The fit gives $T^* \simeq$ 150 and 50 K for pure Bi2212 and $HgBr_2$-Bi2212, respectively, implying that the PG in $HgBr_2$-Bi2212 is $\sim$3 times less than in the Bi2212 sample.
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