Intrinsic tunneling spectroscopy: A look from the inside at HTSC.

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Layered structure of Bi-2212 high \( T_c \) superconductor (HTSC), provides a unique opportunity to probe quasiparticle density of states inside a bulk single crystal by means of intrinsic (interlayer) tunneling spectroscopy. Here I present a systematic study of intrinsic tunneling characteristics of Bi-2212 as a function of doping, temperature, magnetic field and intercalation. An improved resolution made it possible to simultaneously trace the superconducting gap (SG) and the normal state pseudo-gap (PG) in a close vicinity of \( T_c \) and to analyze closing of the PG at \( T^* \). The obtained doping phase diagram exhibits a critical doping point for appearance of the PG and a characteristic crossing of the SG and the PG close to the optimal doping. All this points towards coexistence of two different and competing order parameters in Bi-2212.

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I. INTRODUCTION

Existence of a pseudo-gap (PG) in the electronic density of states (DOS) of High \( T_c \) superconductors (HTSC) at temperatures above the superconducting critical temperature, \( T > T_c \), remains one of the main challenges for understanding the HTSC phenomenon. Theoretical explanations of the PG can be divided into superconducting or non-superconducting classes. A pre-formed pair scenario emphasizes that a (very) strong electron coupling interaction may cause formation of pre-formed electron pairs at \( T > T_c \), which undergo Bose-Einstein condensation at \( T_c \), similar to a superfluid transition in a liquid He [1]. A precursor superconductivity scenario emphasizes the strength of phase fluctuations in HTSC due to a small coherence length, low density of charge carriers, quasi-2D structure and high temperature. Strong phase fluctuations can cause a destruction of macroscopic phase coherence at \( T > T_c \), where the mean-field \( T_{c0} \), by a mechanism similar to the Kosterlitz-Thouless transition [2]. The PG temperature, \( T^* \) is then associated with the mean-field \( T_{c0} \), which is higher than a true \( T_c \) at which the macroscopic phase coherence is established. The amplitude fluctuations of the superconducting order parameter at \( T_c \) are supposed to be relatively small, in contrast to conventional low-\( T_c \) superconductors. Recently it was claimed that vortex-like excitations exist at \( T \) several times larger than \( T_c \), supporting the phase-fluctuation scenario [3]. However, phase-fluctuation scenario alone puts more question marks than answers as it would need to explain the \( T_c \) in the range of 1000 K in underdoped HTSC.

Alternatively, several non-superconducting scenarios of the PG were proposed. According to those the PG is associated with an additional order parameter, such as charge, spin [4] or d-density [5] waves, independent and competing with the superconducting order parameter. This idea is substantiated by a reasonable nesting of the Fermi surface in HTSC. Finally, charge-spin ordering may cause formation of one-dimensional metallic stripes, which may be favorable for appearance of HTSC [6]. In this case three characteristic temperatures may exist: the temperature of stripe formation, \( T_{c0} \) at the stripe and the \( T_c \) at which the phase coherence between stripes is achieved.

Unfortunately, discrimination between those distinct scenarios is restricted by the lack of consensus in experimental data, obtained by different techniques. Various direct spectroscopic techniques provide conflicting results. For example, ARPES indicated that the energy gap (PG) vanishes at \( \sim 100-110 \) K in optimally doped Bi-2212, i.e., \( \sim 15 \) K above \( T_c \) [7]; break junction technique reveals a significant temperature dependence of the gap at \( T < T_c \), but does not show any PG at \( T > T_c \) in optimally doped Bi-2212 [8]; while the surface tunneling shows literally no temperature dependence of the energy gap and persistence of the PG up to almost room temperature [9].

The present state of confusion requires further studies using advanced experimental techniques. One of those is an interlayer tunneling spectroscopy, which is unique in its ability to measure properties inside HTSC single crystals. This method is specific to strongly anisotropic HTSC, like Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_{8+\delta}\) (Bi-2212), in which mobile charge carriers are localized in double CuO\(_2\) layers, while the transverse (c-axis) transport is due to interlayer tunneling [10,11]. Interlayer tunneling has become a powerful tool for studying both electron [12-14] and phonon [15] DOS of HTSC. It has several important advantages compared to surface tunneling techniques: (i) it probes bulk properties and is insensitive to surface deterioration or surface states; (ii) the current direction is well defined; (iii) the tunnel barrier is atomically perfect and has no extrinsic scattering centers; (iv) mesa structures are mechanically stable and can sustain high bias.
FIG. 1. \(dI/dV\) curves for a slightly OD sample \(T_c = 93\) K: a) below and just above \(T_c\), b) just below and above \(T_c\).

in a wide range of temperatures \((T)\) and magnetic fields \((H)\).

Here I present a systematic study of intrinsic tunneling characteristics of Bi-2212 as a function of doping, temperature, magnetic field and intercalation. An improved resolution made it possible to simultaneously trace the superconducting gap (SG) and the normal state pseudogap (PG) in a close vicinity of \(T_c\) and to analyze closing of the PG at \(T^*\). The obtained doping phase diagram exhibits a critical doping point for appearance of the PG and a characteristic crossing of the SG and the PG close to the optimal doping. This points towards coexistence of two different and competing order parameters in Bi-2212.

II. TEMPERATURE AND DOPING DEPENDENCIES

Small \((2-5\mu m\) in the ab-plane) mesa structures were made on top of Bi-2212 single crystals by a microfabrication technique. Mesas typically contained 7-12 intrinsic Josephson junctions in series. Measurements were performed in a three probe configuration. A nonlinear contact resistance was approximately equal to the resistance of one intrinsic junction, most probably caused by a suppression of superconductivity in the top CuO layer due to a proximity effect with the normal electrode and surface deterioration. For details of sample fabrication and measurements see Ref. [12]. Effect of self-heating in such small mesas was shown to be of a minor significance [16], thus contributing to an improved spectroscopic resolution.

In Figs. 1 and 2, experimental \(dI/dV\) curves for slightly overdoped (OD) and underdoped (UD) samples are shown. Below \(T_c\) a sharp peak, corresponding to the knee in IVC’s, is seen. The peak voltage, \(V_{peak}\), decreases as \(T\rightarrow T_c\). Above \(T_c\) the peak disappears (therefore we associate the peak with the superconducting gap (SG)), but a distinctly different dip-and-hump structure remains, representing the persisting PG [12]. Interestingly, IVC’s are nonlinear even above \(T^*\), see Fig. 1 b). The \(\sigma(V)\) curves have an inverted parabolic shape, which might indicate the presence of van-Hove singularity close to the Fermi level in slightly OD samples. The behaviour of the SG in UD samples at \(T\rightarrow T_c\) is one of the most important and yet controversial issues [12,17]. For UD samples the peak is much weaker than for OD samples even at low \(T\), cf. Figs. 1 a) and 2 a), and it rapidly smears out with increasing \(T\).

Remarkably for the UD sample the hump is clearly observable at any \(T\). Below \(T_c\) the PG hump and the SG peak coexist and shift simultaneously to higher voltages with decreasing \(T\) (for more details about doping and temperature dependence of the SG and PG see Ref. [18]). Furthermore, it is seen that \(V_{peak}(T \ll T_c)\) is
III. MAGNETIC FIELD DEPENDENCY

A response to magnetic field \( (H) \) provides a crucial test for the superconducting origin of the two gaps observed in intrinsic tunneling experiments [13]. 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.

In Fig.3 magnetic field dependencies of \( dI/dV \) curves for an intercalated HgBr\(_2\)-Bi2212 sample with \( T_c \approx 73K \) are shown at a) \( T = 15K \) and b) \( T = 53K \). Two effects should be recognized: (i) the zero bias conductance increases (negative magnetoresistance) roughly linearly with field (see Ref. [13] for more details). This is typical for SIS junctions in which the linear increase of conductance with \( H \) is due to a linear increase of the amount of vortices in S-electrodes, see inset in Fig. 5. (ii) It is seen that at low \( T \) the superconducting peak in \( dI/dV \) is strongly suppressed and is shifted towards lower voltages with magnetic field. This is also typical for SIS junctions and is caused by a suppression of the maximum SG in the presence of the vortex lattice. At higher \( T \) the peak can be suppressed completely in 14 T (see Ref. [13]) and is shifted slightly outwards with field. Such behavior is somewhat less transparent, however is also fully consistent with the behavior of SIS junctions. Indeed numerical simulations clearly demonstrate that at elevated temperatures the peak in spatially averaged DOS is smeared out and moves outwards with field, see Fig. 18 in Ref. [19].

To get a deeper insight into the magnetic field dependence of the SIS junction, numerical simulations for a conventional s-wave SIS junction with s-wave order parameter has been performed within a circular cell approximation [20]. Results of simulation are shown in Figs. 4 and 5. In this model an explicit analytic solution for the DOS is available at \( H_{c2} - H \ll H_{c2} \). As \( H \rightarrow H_{c2} \) the superconducting order parameter \( \Delta \rightarrow 0 \), as seen in Fig. 5. On the contrary, the energy of the peak in spatially averaged DOS first saturates and then increases with \( H/H_{c2} \) [20]. As shown in Fig. 5, even at very low \( T \) SIN tunneling,
which senses the spatially averaged DOS, does not provide clear information about the superconducting gap. The peak in SIS tunneling characteristics follows much closer the superconducting gap, however even SIS fails to provide clear information at $H \to H_{c2}$. This has to be taken into account when analyzing experimental data in strong magnetic fields, obtained by different experimental techniques.

In conclusion, temperature [12], magnetic field [13] and doping [18] dependent intrinsic tunneling spectroscopy provides strong evidence for independent and competing origins of the superconductivity and the pseudo-gap phenomenon in HTSC. This is supported by observation of (i) coexistence of the pseudo-gap and the superconducting gap at $T < T_c$; (ii) correlated temperature dependence of the PG hump and the SG peak at $T < T_c$; (iii) closing the SG at $T \to T_c$ and $H \to H_{c2}$; (iv) different magnetic field dependence of the SG and the PG; (v) crossing of the SG and the PG at the doping phase diagram and indication for the existence of the critical doping point.

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