Evidence for a Quasi-1D Topological-Excitation Liquid in Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ from Tunneling Spectroscopy

A. Mourachkine

Université Libre de Bruxelles, CP-232, Blvd du Triomphe, B-1050 Brussels, Belgium

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Tunneling measurements have been carried out on heavily underdoped and slightly overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi2212) single crystals by using a break-junction technique. We find that in-plane tunneling spectra below $T_c$ are the combination of incoherent part from the pseudogap and coherent quasiparticle peaks. There is a correlation between the magnitude of the pseudogap and the magnitude of the superconducting gap in Bi2212. We find that the quasiparticle conductance peaks are caused by condensed soliton-like excitations.

Recent intrinsic $c$-axis tunneling data obtained in Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi2212) mesas show that the pseudogap (PG) is a normal-state gap, and the PG and the superconducting gap (SG) coexist below $T_c$. Thus, the PG in Bi2212 arises either from charge-density waves (CDW) or from local antiferromagnetic (AF) correlations (or spin-density waves (SDW)). There is a consensus on doping dependence of the PG in cuprates: the magnitude of the PG decreases with increase of hole concentration.

Figure 1(a) shows a theoretical $I(V)$ tunneling characteristic in a superconductor-insulator-normal metal (SIN) junction (fig. 6 in ref. [2]). In the $I(V)$ curve at high positive (low negative) bias, depending on the normal resistance of the junction, lies somewhat below (above) the normal-state curve. In conventional superconductors (SCs), the Blonder-Tinkham-Klapwijk (BTK) predictions are verified by tunneling experiments [3]. However, in cuprates, the BTK theory is violated. Figure 1(b) shows the SC-insulator-SC (SIS) $I(V)$ curve measured in an underdoped Bi2212 single crystal with $T_c = 83$ K (fig. 1 in ref. [4]). In fig. 1(b), one can see that the $I(V)$ curve at high positive (low negative) bias passes not below (above) the normal-state curve. In conventional superconductors, the $I(V)$ curve at high positive (low negative) bias passes not below (above) the normal-state curve. This fact cannot be explained by the $d$-wave symmetry of the order parameter. To our knowledge, this question has never been raised in the literature before. This finding is the main motivation of the present work.

To the best of our knowledge, the soliton SC was for the first time considered in ref. [5] in order to explain the SC in organic quasi-one-dimensional (quasi-1D) conductors. Later, Davydov [6] applied the model of soliton SC to cuprates. The theory is based on the concept of $bisolitons$, or electron (or hole) pairs coupled in a singlet state due to local deformation of the lattice.

Tunneling spectroscopy is an unique probe of SC state in that it can, in principle, reveal the quasiparticle (QP) excitation density of states (DOS) directly with high energy resolution. In this paper, we present tunneling measurements performed on heavily underdoped and slightly overdoped Bi2212 single crystals by using a break-junction technique. We find that in-plane tunneling spectra below $T_c$ are the combination of incoherent part from the pseudogap and coherent QP peaks. There is a correlation between the magnitude of the PG and the magnitude of the SG in Bi2212. We find that the QP conductance peaks are caused by condensed soliton-like excitations.

The overdoped Bi2212 single crystals were grown using a self-flux method as described elsewhere [7]. The underdoped samples were obtained from the overdoped single crystals by annealing them in vacuum. The $T_c$ value was determined by the four-contact method. The transition width is less than 1 K in the overdoped crystals, and a few degrees in the underdoped Bi2212.

Experimental details of our break-junction setup can be found elsewhere [8]. In short, many break-junctions were prepared by gluing a sample with epoxy on a flexible insulating substrate, and then were broken in the $ab$-plane by bending the substrate with a differential screw at low temperature in a He ambient. The electrical con-

FIG. 1. (a) Theoretical $I(V)$ tunneling characteristic in a SIN junction of a SC with the isotropic energy gap. The dash line shows the normal-state curve. (b) Measured $I(V)$ curve in a SIS junction of an underdoped Bi2212 with $T_c = 83$ K. The dash line which is parallel to the $I(V)$ curve at high bias is a guide to the eye. The arrows show the offset from the dash line. One can immediately notice the difference between the two plots.
contacts (typically with the resistance of a few ohms) are made by attaching gold wires to a crystal with silver paint. The $I(V)$ and $dI/dV(V)$ characteristics are determined by the four-terminal method by using a standard lock-in modulation technique. At low (constant) temperature, in one junction, we usually obtain a few tunneling spectra by changing the distance between broken parts of a crystal, going back and forth etc., and, every time, the tunneling occurs most likely in different places.

Figure 2(a) shows the SIS $dI/dV(V)$ and $I(V)$ obtained in an underdoped Bi2212 single crystal, which look like usual spectra in Bi2212 [14]. In fig. 2(a), the Josephson $I_cR_n$ product is estimated to be 13.4 mV. The gap magnitude, $\Delta_{sc} = 64$ meV, is in good agreement with other tunneling measurements [14]. The $dI/dV(V)$ and $I(V)$ shown in fig. 2(b) are obtained within the same underdoped single crystal as those in fig. 2(a). In fig. 2(b), the gap having $\Delta = 130$ meV is too large to be a SG. It is suggestive that the spectra in fig. 2(b) correspond to the PG. The SC in Bi2212 is weak in the heavily underdoped region [3,4]. This may explain why it is possible to observe separately the PG in the heavily underdoped Bi2212 by taking into account that tunneling spectroscopy probes the local DOS. The absence of the Josephson current in the spectra shown in fig. 2(b) indicates that the humps in the conductance are incoherent. The differences between the spectra shown in figs 2(a) and 2(b) are presented in the inset of fig. 2(b), which correspond to a "pure SG". Some parts of the $dI/dV(V)$ in the inset of fig. 2(b) are slightly below zero because the spectra in figs 2(a) and 2(b) are not taken under the exact same conditions. The small humps in the $dI/dV(V)$ shown in the inset of fig. 2(b) are discussed below. The $dI/dV(V)$ and $I(V)$ curves in fig. 2(b) resemble the characteristics of a bound state of two solitons (a bi-soliton) [3,18]. The gap is shown schematically in grey (the $I(V)$ of the gap is not shown). The height of conductance peaks depends on the density of added (removed) electrons [21].

![Figure 2](image2.png)

**FIG. 2.** SIS $dI/dV(V)$ and $I(V)$ measured at 14 K within the same underdoped Bi2212 single crystal with $T_c = 51$ K. The $dI/dV(V)$ in both plots are normalized at -400 mV. The inset in the plot (b) shows the differences $(dI/dV)_a - (dI/dV)_b$ and $I_{a, norm} - I_{b, norm}$. The inset in the plot (a) shows how $I_a$ and $I_b$ are normalized: $I_a$ is normalized at -400 mV, and $I_b$ is adjusted to be parallel at high bias to $I_a$ (such procedure is equivalent to the normalization at $\pm \infty$).

![Figure 3](image3.png)

**FIG. 3.** SIS $dI/dV(V)$ and $I(V)$ measured at 14 K within the same overdoped Bi2212 single crystal with $T_c = 88$ K. The inset in the plot (a) shows SIN $dI/dV(V)$ and $I(V)$ measured at 9 K in an overdoped Bi2212 with $T_c = 87.5$ K (the same axis parameters as main plot). The dash lines in the plot (a) and in the inset, which are parallel at high bias to the $I(V)$ curves, are guides to the eye. The inset in the plot (b) shows the normalized characteristics of a bound state of two solitons (a bisoliton) [3,20]. The gap is shown schematically in grey (the $I(V)$ of the gap is not shown). The height of conductance peaks depends on the density of added (removed) electrons [21].
in the spectra shown in fig. 3(b) is small in comparison with the contribution from the QP peaks, at least, at low bias. This is most likely due to the fact that, in slightly overdoped cuprates, the SC is the strongest, and the "strength" of the PG is weak \[15,16\]. At high bias, the contribution from the PG will be always predominant, even, if the PG is weak.

We also performed measurements in Ni-doped Bi2212 single crystals (overdoped in oxygen): the measured data which are presented in an extended paper \[17\] are similar to the data in the overdoped Bi2212, shown in fig. 3. From the temperature dependence of \(dI/dV(V)\), it is clear that the small humps which appear in \(dI/dV(V)\) at bias twice as large as the bias of the QP peaks, shown in fig. 3(b), relate to the QP peaks and not to the PG. The humps are also observed in the Ni-doped Bi2212. In the inset of fig. 2(b), a similar hump is present in the conductance at negative bias. These humps can be well understood in terms of a nanopteron soliton \[8\] which is discussed below.

Since the spectra measured in an underdoped Bi2212, shown in the inset of fig. 2(b), and the spectra measured in an overdoped Bi2212 (and Ni-doped Bi2212), shown in fig. 3(b), are similar, the data obtained in underdoped and overdoped Bi2212 are consistent with each other.

In order to be sure that we observe not a SIS-junction effect but an intrinsic effect, we performed measurements in the overdoped Bi2212 crystals by SIN junctions. Pt-Ir wires sharpened mechanically are used as normal tips. The inset of fig. 3(a) shows the SIN \(dI/dV(V)\) and \(I(V)\) obtained in an overdoped Bi2212. In fig. 3(a), one can see that, basically, there is no difference between the \(I(V)\) characteristics measured in SIS and SIN junctions [see the dash lines in fig. 3(a) and in the inset of fig. 3(a)].

First, we give a description of a topological soliton. The topological soliton is an extremely stable nonlinear excitation which can be moving or entirely static \[8,10,21\]. The solitons have particlelike properties, and, in solids, they occupy the intragap states in a CDW or SDW gap. The inset of fig. 3(b) shows the bisoliton characteristics. Since we consider a general solution, the gap shown schematically in the inset of fig. 3(b) is either a CDW or SDW gap.

We now compare the measured data with theory. Soliton and bisoliton characteristics are described by hyperbolic functions \[18,19,20\]. Since the bisoliton conductance peaks shown in the inset of fig. 3(b) look very similar to the conductance peaks not only of high-\(T_c\) SCs but also of low-\(T_c\) SCs (not the background), we rely here exclusively on the \(I(V)\) characteristics which are conceptually different for the two models: the BTK model for 3D case and the model based on the concept of quasi-1D topological excitations.

Figure 3(a) shows the measured \(I(V)\) curve from the inset of fig. 2(b). In fig. 4, for simplicity, we analyze the data only at positive bias. As shown in fig. 4(a), the data from the inset of fig. 2(b) can be fitted very well by the hyperbolic function \(f(V) = A \times \tanh[(eV - 2\Delta)/eV_0] + \tanh[(eV + 2\Delta)/eV_0]\), where \(e\) is the electron charge; \(V\) is the bias; \(\Delta\) is the maximum SC energy gap, and \(A\) and \(V_0\) are the constants. In fig. 4(a), we also present the measured \(I(V)\) of the PG from fig. 2(b). We find that any \(I(V)\) characteristic obtained in Bi2212 can be resolved into the two components shown in fig. 4(a): from the quasi-1D topological excitations and from the PG. The "usual" \(I(V)\) and \(dI/dV(V)\) spectra in Bi2212 show the presence of both components [see figs 2(a) and 3(a)]. The absence [see fig. 2(b)] or weak contribution of one component [see fig. 3(b)] in spectra makes the appearance of the spectra "unusual".

Figure 4(b) shows the data from ref. \[7\], the \(f(V)\) fit, and their difference. Figure 4(c) depicts the two components in the \(I(V)\) curve from fig. 3(b). As shown in fig. 4(d), the contribution from the QP peaks in the SIN \(I(V)\) from the inset of fig. 3(a) seems to be weaker than that in SIS junctions. As seen in fig. 4, all plots are similar. To fit the SIN \(I(V)\), we use the same \(f(V)\) function by substituting 2\(\Delta\) for \(\Delta\) \[22\]. In figs 4(b)–4(d), the amplitude, \(A\), of the \(f(V)\) fit can be changed, this only affects the scale but not the shape of the differences which correspond to the PG. The \(I(V)\) curves in fig. 3(a) and in refs \[8\] and \[14\] can be resolved into the two components in the same manner. So, we conclude that, in Bi2212, the \(I(V)\) characteristics of the QP peaks definitely disagree with the BTK theory, and are in good agreement with the theory of quasi-1D topological
Consequently, the of PG becomes larger than 130 meV at lower doping. The large enough to fit the data. Moreover, the magnitude of PG, shown in fig. 2(b), is too large to be explained by an analysis of the data: The magnitude of PG, $\Delta = 130$ meV, is not large enough to fit the data. Consequently, the tunneling PG is most likely a CDW gap.

It is important to emphasize that the PG in transport measurements is different from the tunneling PG. In transport measurements, the PG relates to a spin gap into local AF domains. As an example, if a molecular chain is embedded into a medium, a frictional force acts on the soliton.

We now turn to the model of SC in cuprates. The "flat" (constant) asymptotics of $I(V)$ characteristics are the fingerprints of one-dimensionality. To the best of our knowledge, there are only two theoretical models of SC in cuprates which are based on the presence of one-dimensionality: the bisoliton model and the stripe model. In the stripe model, charge stripes are assumed to be metallic, thus contrary to the experiment. By contrast, the bisoliton model is quantitatively in good agreement with the data: the bisoliton model predicts that by increasing the hole concentration the magnitude of the pairing gap decreases (see fig. 3 in ref. [1]). However, the bisoliton model is a theory of soliton pairing, but the mechanism of the establishment of phase coherence is not considered. Experimentally, spin fluctuations mediate the phase coherence in cuprates. The bisolitons are formed due to electron-phonon interactions which are moderately strong and nonlinear.

Lastly, it is worth noting that the analysis of many data measured in cuprates shows that the data can be naturally understood in the framework of the quasi-1D topological-excitation-liquid scenario.

In summary, tunneling measurements have been carried out on underdoped and overdoped Bi2212 single crystals. Tunneling spectra below $T_c$ are the combination of incoherent part from the pseudogap and coherent quasiparticle peaks. There is a correlation between the maximum magnitude of the pseudogap and the distance between the quasiparticle peaks. The $I(V)$ characteristics of the quasiparticle peaks are in good agreement with the theory of quasi-1D topological excitations. The solitons and bisolitons reside most likely on charge stripes. It seems that magnon-like excitations which cause the appearance of the magnetic resonance peak in inelastic neutron scattering spectra are in resonance with the bisolitons. The bisoliton model of superconductivity in cuprates is correct in the description of pairing characteristics, but it lacks the mechanism of the establishment of phase coherence.

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