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# c-axis tunneling on YBCO films

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**Abstract.** We have measured $I(V)$ characteristics of $c$-axis planar tunnel junctions on $Y_1Ba_2Cu_3O_{7-\delta}$ films. Our results and their analysis provide experimental support for the importance of the two-dimensional character of the YBCO band structure, and a method to measure the ratio between the Fermi energy of YBCO and the barrier height. The analysis is based on the relation between the linear conductance background, related to the inelastic tunneling component, and the zero bias conductance, related to the elastic one.

**PACS.** 74.50.+r Proximity effects, weak links, tunneling phenomena, and Josephson effects – 74.25.Jb Electronic structure

## 1 Introduction

It is well known that elastic tunneling between metals in their normal state, can lend no information on their density of states $N(\varepsilon)$ or, more generally, on their spectral function $A(\mathbf{k}, \omega)$ [1]. In this case the conductance should be voltage independent. However, a nonlinear $I(V)$ dependence is obtained if inelastic scattering occurs in the vicinity of the barrier. This property has been used as a spectroscopic tool for molecules placed in the barrier [2]. Similarly, it has been shown that scattering from magnetic impurities can give a nonlinear $I(V)$ characteristics, with an approximately linear conductance $g(V)$ [3]. Both effects are unrelated to the properties of the electrode studied.

Tunneling characteristics into High $T_c$ Superconductors (HTS) are strongly affected by their anisotropy and hence should differ significantly when measured along the directions of poor conductivity (the $c$-axis) and of good conductivity (the $a$–$b$ planes) [4]. $c$-axis tunneling is characterized by a rising linear background at high voltages [5,6]. Specifically, Littlewood *et al.* [7] have proposed that this background comes from tunneling into very short lifetime states, such as given for instance by the Marginal Fermi Liquid model [8], characterized by a broad spectral function.

In this work, we show that tunneling between a normal metal and a two dimensional (2D) material does lend information on the spectral function of the 2D material and that the ratio of the Fermi energy and the barrier height can be extracted.

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## 2 Tunneling conductance into a two dimensional material

We discuss the case of a planar junction in which the momentum parallel to the barrier is conserved. The principle of the analysis is based on the observation [7], that when the tunneling barrier is parallel to the conducting planes of a quasi-two-dimensional metal, the respective fractions of the elastic and inelastic tunneling channels are strongly affected by the thickness of the barrier. For a thick barrier, the charge carriers coming from the counter-electrode are strongly focused in the direction perpendicular to the conducting planes (in our case, the $c$-axis direction) and are therefore injected at the bottom of the band ($k_a \cong k_b \cong 0$), while in the final state $k_a^2 + k_b^2 = k_F^2$. Since the transition to such a state requires an energy equal to the Fermi energy in the 2D conductor, it can only be achieved through the inelastic channel. If, on the other hand, the barrier is thin, the focusing effect is reduced and the fraction of elastic tunneling increases.

In our $c$-axis tunneling configuration the carriers are injected from the counter- electrode near the bottom of the conduction band of the two-dimensional cuprate. Littlewood *et al.* [7] obtained a $\mathbf{k}$ dependent transfer function.

$$T(\mathbf{k}) \propto \kappa_0 \frac{a}{t} \exp\left(-2\kappa_0 t - \frac{\varepsilon_{\mathbf{k}} + \varepsilon_0}{U} \kappa_0 t\right) \quad (1)$$

where $\kappa_0 = (2mU/\hbar^2)^{1/2}$, $a$ is the junction area, $U$ is the barrier height, $t$ is the barrier thickness and $-\varepsilon_0$ is the energy at the bottom of the band where we set the chemical potential $\mu = 0$. For tunneling between a quasi-two dimensional (such as a cuprate) and a normal metal, whose density of states can be considered constant, the conductance at low temperatures $kT \ll eV$ is:

$$g(V) \propto \int_{-\varepsilon_0}^{\infty} T(\mathbf{k}) A\left(\varepsilon_{\mathbf{k}}, V\right) \mathrm{d}\varepsilon_{\mathbf{k}} \tag{2}$$

where $A(\varepsilon_{\mathbf{k}}, \omega)$ is the spectral function of the cuprate and $V$ is the applied voltage. The upper limit can be taken to infinity due to the fact that both the transfer function and the spectral function decay at energies higher than the Fermi level. Since it is a general property of a spectral function that it becomes a delta function at $V = 0$, the conductance at zero bias is:

$$g(0) = G \exp\left(-2\kappa_0 t - \frac{E_{\mathrm{F}}}{U}\kappa_0 t\right). \tag{3}$$

Here $G = e^2\kappa_0 a/(2\pi h t)$ is a conductance determined by the lateral geometry of the barrier and $E_{\mathrm{F}}$ is the Fermi energy of the cuprate measured relative to the bottom of the band. Equation (3) is unrelated to any inelastic scattering mechanism since the conductance at zero bias is only due to the elastic channel resulting from the momentum cone which is not infinitely narrow. We note that in comparison to the case of tunneling into a three dimensional material, the zero bias conductance in the two dimensional case has an additional factor, $\exp(-\kappa_0 t E_{\mathrm{F}}/U)$, which reduces significantly the conductance at zero bias. For example, a junction with an area of $1\,\mathrm{mm}^2$ and an $Al_2O_3$ barrier, which has a typical height of 2 eV [9] and a typical oxide thickness of few tens of Å, should have $\kappa_0 t \approx 10$ and a resistance of $10-100\ \Omega$ [10]. But the same junction, placed with the barrier parallel to the $CuO_2$ planes, should yield a resistance of $10-100\ \mathrm{k}\Omega$ for $E_{\mathrm{F}} = 1$ eV.

For a strong barrier ($\kappa_0 t > 1$), the integral in equation (2) can be approximated by

$$g(V) \approx g(0) + G\frac{U}{\kappa_0 t}\exp(-2\kappa_0 t) A(-\varepsilon_0, V). \tag{4}$$

We note that the conductance is proportional to the spectral function $A(-\varepsilon_0, V)$ namely, unlike the case of conventional (3D metal) tunneling, one *can* learn about the spectral function although probing the non superconducting state. As mentioned above in the HTS, $c$-axis tunneling, the conductance is linear in voltage. Assuming that these are clean tunneling experiments we conclude that the spectral function is linear in $V$.

## 3 Determination of the ratio $E_F/U$

From equation (4) one can obtain:

$$\frac{\mathrm{d}\ln(g')}{\mathrm{d}\ln(g_0)} = \frac{2U}{E_{\mathrm{F}} + 2U} + \text{logarithmic correction} \tag{5}$$

where $g' = \frac{\mathrm{d}g}{\mathrm{d}V}\big|_{V=\tilde{V}}$, $\tilde{V}$ is a certain voltage and $g_0$ is the conductance at zero bias. In the case of the HTS where the conductance at high voltages ($V \gg \Delta$) is linear, $g'$ is simply the conductance slope. The value of the ratio ($E_{\mathrm{F}}/U$) can then be directly extracted from a plot of $\ln(g')$ *versus* $\ln(g_0)$ for junctions having different barrier thicknesses.

## 4 Sample preparation and measurements

27 $c$-axis oriented YBCO films were grown as described in [11]. We used a scanning electron microscope (SEM) in order to examine the surface morphology and search for $a$-axis grains, holes and particulates. A X-ray diffractometer was also used in order to detect the presence of $a$-axis grains. A correlation between the SEM and X-ray measurements was found; when $a$-axis grains are observed by SEM microscopy on the surface of a sample, traces of $a$-axis orientations also show up in the X-ray scan. We examined our films by atomic force microscope (AFM) and obtained a surface roughness of 25 Å rms. After the YBCO growth, the films were exposed to ambient air for about 5 minutes, before a 1000 Å thick Al film was evaporated through a mask in a cross configuration, the junction dimensions being about 0.5 mm × 0.5 mm. As established by Racah *et al.* [12], the barrier formed is an $Al_2O_3$ thin layer that is created at the YBCO/Al interface. This is due to oxygen from the YBCO film diffusing and oxidizing the Al layer. The detailed process by which the barrier is created is described elsewhere [12]. Junctions that are grown on smooth $c$-axis films are stable on the scale of a few days at room temperature. For example, such a junction changes its zero bias resistance by less than 10% within 7 days; on the other hand a junction contaminated with $a$-axis grains undergoes a zero bias resistance increase of 70% within a similar time interval.

$I(V)$ characteristics were measured digitally using a current source, and were differentiated using a computer program. Each measurement is comprised of two successive cycles, to check the absence of heating-hysteresis effects. The positive bias corresponds to a positive voltage being on the YBCO film side.

## 5 Results

We measured junctions with a wide range of zero bias resistances ranging from 1 Ω to 100 kΩ. We divide our junctions into two major groups: The first one consists of junctions grown on films which typically have no traces of $a$-axis orientation in X-ray examination, nor are any $a$-axis grains found on the surface by SEM inspection. These junctions have a typical resistance of 1-100 kΩ. Junctions which belong to the second group have weak traces of $a$-axis orientation. They are characterized by lower resistances, typically, of the order of 1 Ω to 1 kΩ. As mentioned, the high resistance junctions are more stable than the low resistance ones. The junctions' resistances at zero bias exhibit a very weak temperature dependence in the normal state. For example, in the sample shown in Figure 1 it changes by less than 0.3% as the temperature is increased from $T_{\mathrm{c}} = 88$ to 100 K.

The low resistance junctions exhibit in-plane features at voltages of the order of the generally accepted energy gap value, ~18 meV [5,13] and sometimes zero bias anomalies. At high biases, we observe in all the junctions (of the two groups) conductance characteristics having the widely reported [5,6] linear background. As the resistance

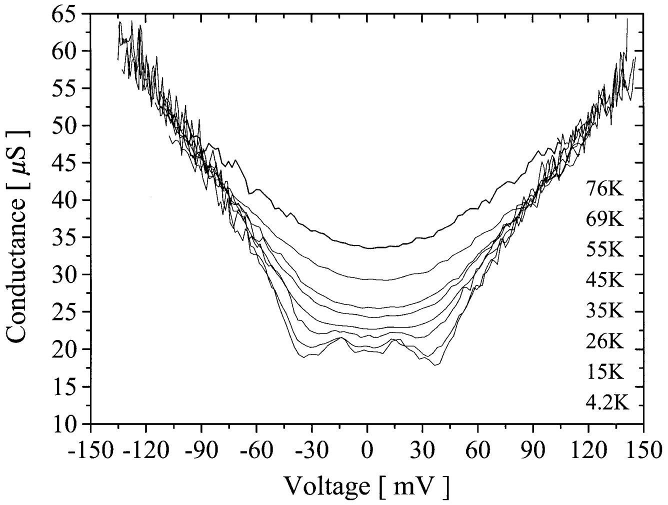


**Fig. 1.** Conductance *versus* voltage at various temperatures for a high resistance junction grown on a pure $c$-axis film with a resistive downset of 89 K and $\Delta T_c = 0.5$ K.

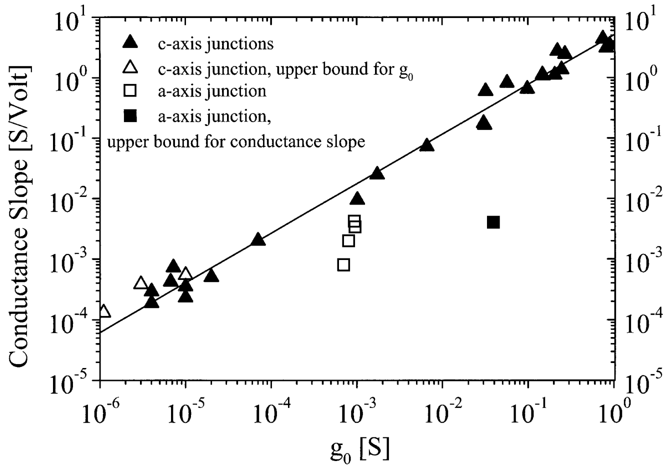


**Fig. 2.** The slope of the conductance linear background *versus* the extrapolation to zero bias. Each data point represents a junction. The triangles represent our $c$-axis tunnel junctions and the squares are $a$-axis tunnel junctions measured by Racah *et al.* [12,14]. The straight line is a least square fit to the $c$-axis data with a slope of $0.81 \pm 0.02$. From this slope one can extract the Fermi level of YBCO in a method described in the text. The deviation from a slope of unity is an indication for the YBCO being a two dimensional material. One can note the difference between in-plane tunneling ($a$-axis junctions) and $c$-axis tunneling. The hollow triangles represent an upper bound for the zero bias conductance for junctions with a well defined slope but with a linear background which extrapolates approximately to zero. The solid square represents an upper bound for the conductance slope, which seems to be almost flat.

increases the tunneling characteristic changes gradually: the zero bias anomaly disappears completely, the gap features at 18 meV are weakened and a flat conductance region appears at low voltages up to a few tens of millivolts. This flat region disappears at high temperatures. In Figure 1 we present the conductance *versus* voltage of a junction with a high resistance ($R \approx 50$ k$\Omega$) formed on a pure $c$-axis film. The temperature dependence is shown up to 76 K.

In Figure 2 (triangles) we present the slope of the linear background on the negative bias side, $g'$, *versus* the extrapolation of the linear conductance to zero bias, $g(0)$, on a log-log scale. All of these measurements were taken at 4.2 K; however, these are normal state measurements since the voltages considered here are well above the gap value. The straight line is a least squares linear fit to the data, giving a slope of $0.81 \pm 0.02$. Although the films on which the junctions with the lowest resistance contain a small amount of $a$-axis grains, we have kept them on the graph. Upon removing these data points no appreciable change in the least square fit slope is obtained.

The data points presented as squares in Figure 2 are from a different set of measurements [12,14]; these junctions were grown on $a$-axis oriented YBCO films with $Al_2O_3$ used as an oxide barrier as in our set of measurements. The $a$-axis junctions do not fit into the series of $c$-axis tunneling measurements. One junction exhibits a background which is close to be flat, its error bar is therefore reflecting the uncertainty in the conductance slope.

According to the experimental observations that the conductance is linear at high voltages, one may induce that $A(-\varepsilon_0, V)$ is linear in $V$ at high voltages, or at least may be expanded in series and yield a dominant linear term. Using equation (5) and the slope of the graph in Figure 2 we determine the ratio $E_F/U = 0.47 \pm 0.07$. If we take the value of the barrier height known for $Al_2O_3$, $U \approx 2$ eV we find the Fermi level of YBCO to be $E_F \approx 1$ eV. A similar value is obtained from angle resolved photoemission spectroscopy [15].

We should emphasize that for an extrinsic scattering mechanism, such as inelastic scattering from impurities in the vicinity of the barrier with a broad, continuous, flat spectral weight as suggested by Kirtley *et al.* one can also obtain the result (5) which expresses the two dimensional character of the samples providing that the impurities concentration is not very different from one sample to another.

Cucolo *et al.* [16] have presented a graph similar to that of Figure 2 for their junctions grown on $c$-axis etched surfaces. They obtained a slope of $0.92 \pm 0.02$ for YBCO rather than our result of $0.81 \pm 0.02$. The difference between these two results can be due to a strong elastic tunneling component in the experiment made by Cucolo *et al.* We note that for pure in-plane tunneling, in the case of a rising linear background one should obtain a slope of unity. Therefore a deviation from pure $c$-axis tunneling should somewhat increase the graph slope. This may be the case for the samples of Cucolo *et al.* that had undergone an etching process, which can expose $a{-}b$ facets. While Cucolo *et al.* have claimed that the relation found between $g'$ and $g(0)$ is an indication that the linear conductance background is intrinsically due to the density of sates, our analysis shows that an extrinsic mechanism such as that proposed by Kirtley *et al.* cannot be excluded by the relation found by Cucolo *et al.*

A plot of $\log(g')$ *versus* $\log(g(0))$ for $Ba_{0.7}K_{0.3}BiO_3$ was shown by Sharifi *et al.* [17], with a slope 1.04. We note that $Ba_{0.7}K_{0.3}BiO_3$ is cubic rather than two-dimensional. In that case both $g(0)$ and $g'$ are proportional to $\exp(-2\kappa_0 t)$, and our analysis predicts a slope of unity, as obtained.

A linear dependence of $\log(g')$ on $\log(g(0))$ is expected for both mechanisms possibly responsible for the linear background: the extrinsic one (impurities, barrier effects) as well as the intrinsic one (density of states effects), but with different slopes for the two dimensional and three dimensional cases, the two dimensional slope being determined by the ratio of the Fermi energy to the Barrier height, and the three dimensional slope being equal to unity.

## 6 Summary

We have shown that directional tunneling perpendicular to the conducting planes of a two dimensional material ($c$-axis tunneling) results in a conductance proportional to the spectral function $A(-\varepsilon_0, V)$ namely, unlike the case of conventional (3D metal) tunneling, one *can* learn about the spectral function by probing the non superconducting state.

We have also shown that the two-dimensional nature of the YBCO's dispersion relation, renders tunneling into the $c$ direction significantly different from that in the $a-b$ directions. First, for a given barrier, there is a difference of two to three orders of magnitude in the junction resistance. Second, we have shown that the log of the zero bias conductance $g(0)$ is a linear function of the log of the conductance slope $g'(V)$ over 5 decades, with a slope definitely smaller than unity. From the value of the slope, $0.82 \pm 0.02$, we have extracted the ratio of the Fermi energy to the barrier height, $E_F/U = 0.47 \pm 0.07$. This gives for the Fermi level of YBCO $E_F = 1$ eV consistent with ARPES measurements.

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