Point-Contact Spectroscopy on RuSr$_2$GdCu$_2$O$_8$

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Abstract

We present Point-Contact experiments on polycrystalline RuSr$_2$GdCu$_2$O$_8$ samples. The majority of tunneling curves shows a zero-bias conductance peak, which is modeled by assuming a d-wave pairing symmetry of the superconducting order parameter. The magnetic field dependence of the conductance spectra has been measured in very stable junctions. In some cases, due to the granularity of the samples, clusters of grains in series introduce peculiar features in the conductance spectra.

1. Introduction

The symmetry of the order parameter gives important information to understand the mechanism of the superconductivity in high-$T_c$ superconductors. A standard technique to investigate the pairing symmetry and the presence of nodes in the superconducting energy gap is the Point-Contact Andreev Reflection Spectroscopy (PCAR), which consists in establishing a contact between a tip of a normal metal and a superconducting sample (N–S junction).

Recently a new compound of the cuprate family, the RuSr$_2$GdCu$_2$O$_8$ (Ru-1212) [1], has drawn great attention among theorists and experimentalists in the field of solid state physics. Indeed, the Ru-1212 compound presents a similar structure to YBa$_2$Cu$_3$O$_7$, with the substitution of Cu-O chains by magnetic Ru-O$_2$ planes, so that coexistence of superconductivity and magnetic ordering is present. The $T_c$ of Ru-1212 depends strongly on the preparation conditions [2] with some reports showing transition onset as high as 50K [3]. The rutheno-cuprate materials also show magnetic order around 135K. The magnetic order of the Ru moments seems to be predominantly antiferromagnetic along the c-axis [4], while a ferromagnetic component has been observed in plane [5].

In this paper we report PCAR results obtained on Ru-1212 synthesized pellets. In the majority of the cases, the conductance curves show a triangular peak structure at zero bias. We will show that the experimental data are well fitted by a modified d-wave BTK model.

2. Experiments and theoretical modeling

Our Ru-1212 samples were directionally solidified pellets, prepared starting from a Ru-1212 and Ru-1210 (RuSr$_2$GdO$_6$) powders mixture (in a Ru-1212/ Ru-1210 = 0.2) by means of Top-Seeded Melt-Textured. The details of the preparation pro-
procedure are reported in Ref. [6]. X-Ray diffraction patterns were recorded at room temperature using a Philips PW-1700 diffractometer equipped with a Ni-filter for CuKα radiation. The diffraction patterns were collected over 2θ range 5°-100° with a step of 0.05° and a time per step of 20s. A typical diffraction pattern for a Ru-1212 sample is shown in Fig. 1. The only phase detectable is Ru-1212 (the main reflections are indexed) and the sample is polycrystalline. Zero-field resistivity is shown in the inset of Fig. 1. The sample is metallic down to 90 K where a saturation in the resistivity starts to appear. This persists down to 49 K where a weak increase of the resistivity is present at temperatures just above the onset of the superconducting transition ($T_{c0}^{on}=43$ K). The sample exhibits zero resistivity at a temperature $T_{c0}=24$ K.

To realize our experiments we used a Pt-Ir tip, chemically etched in a 37% solution of HCl and in an ultrasound bath. Current-voltage ($I-V$) characteristics were obtained and a standard lock-in technique was used to measure the differential conductance $(dI/dV-V)$ spectra. Different kinds of conductance curves have been observed, majority of which exhibiting a triangular Zero Bias Conductance Peak (ZBCP) [7] with an energy width of about 10 mV, as reported in Fig. 2.

The triangular structure of the ZBCP can be explored in term of PCAR Spectroscopy, however there is no possibility to model this peculiar shape by assuming an s-wave symmetry of the superconducting order parameter. Indeed we have assumed a d-wave symmetry of the superconducting gap in a BTK modified model [8,9]. In a d-wave superconductor, the electron-like and hole-like quasiparticles, incident at a N–S interface, experience a different sign of the order parameter, with the consequent formation of bound states at the Fermi energy. These states, named Andreev Bound States, are responsible for an increase of the tunneling conductance at zero-bias, in some case higher than 2, the theoretical limit for conventional superconductors [10].

The BTK model describes the $I-V$ characteristics of a N–S junction separated by a barrier of arbitrary strength, which is modeled by a dimensionless parameter $Z$: varying $Z$ one ranges from Andreev Reflection regime (small $Z$) to the tunneling limit ($Z \gg 1$). For an anisotropic d-wave superconductor, at the given energy the tunnel current depends both on the incident angle $\varphi$ of the electrons at the N–S interface as well as on the angle $\alpha$ of the order parameter, namely $\Delta_\pm = \Delta \cos[2(\alpha \mp \varphi)]$. It is well known that in PCAR experiments there is no preferential direction of the quasiparticle injection into the superconductor, so the tunneling current results by an integration over all directions inside a hemisphere weighted by the scattering probability term. Moreover since our experiments deal
with polycrystalline samples, more than one grain can be touched by the tip, consequently the angle \( \alpha \) is a pure average fitting parameter, which depends on the experimental configuration.

Fig. 2 shows an experimental conductance curve at \( T = 4.2 \) K, with a satisfactory best fitting curve. The used fitting parameters are: the superconducting energy gap \( \Delta = 2.6 \text{ meV} \), the barrier strength \( Z = 0.94 \), the angle \( \alpha = 0.45 \) and the smearing factor \( \Gamma = 0.27 \text{ meV} \). The factor \( \Gamma \) is a phenomenological parameter introduced to take into account pair breaking effects, possibly due to magnetic ordering [11]. We notice that both the shape of the ZBCP the dips occurring in the ZBCP at about \( \pm 1 \text{ mV} \).

In the case of very highly stable junctions we studied the effect of the magnetic field from zero up to 2 Tesla (Fig. 3). We observed a reduction of the height of the ZBCP, but a complete suppression to 2 Tesla (Fig. 3). We observed a reduction of the studied voltage is expressed as the sum of two contributions [17], one coming from the N–S point contact one. The measured voltage is expressed as the sum of two contributions [17], one coming from the N–S point contact one.

In some cases, in our experiments, we have found ZBCPs with a wider energy amplitude, as reported in Fig. 4. We speculate that the intergrain weak-coupling effect in polycrystalline samples plays a fundamental role in the tunneling process. Indeed a S–N–S or S–I–S Josephson junction can be formed in series with the N–S point contact one. The measured voltage is expressed as the sum of two contributions [17], one coming from the N–S point contact (\( V_{PC} \)) and the other from the intergrain S–N–S (S–I–S) Josephson junction (\( V_J \)):

\[
V(I) = V_{PC}(I) + V_J(I), \tag{1}
\]

\[
dI \frac{dV}{dV}(V) = \left( \frac{dV_{PC}}{dI(V)} + \frac{dV_J}{dI(V)} \right)^{-1}. \tag{2}
\]

The \( I(V) \) characteristics are obtained by inverting Eq. (1). We assume that the Josephson capacitance is small and write the Josephson voltage as follows:
Fig. 4. Conductance curve measured on Ru-1212/Pt-Ir point-contact junction at T=4.2K. This spectrum is fitted according to our model of Josephson junction in series with the point contact, with a gap amplitude $\Delta = 3\text{meV}$.

$$V_J = 0 \quad \text{for } I < I_c,$$
$$V_J = R_J I_c \sqrt{[I/I_c^2 - 1]} \quad \text{for } I > I_c,$$

(3)

where $I_c$ and $R_J$ are the critical current and the resistance of the Josephson junction, respectively.

The point-contact contribution to the total conductance is again expressed in terms of the $d$-wave BTK model, because an $s$-wave symmetry, even in presence of a Josephson junction in series, would never yield a triangular structure of the conductance curves. In Fig. 4 we present an example of experimental conductance with a wider ZBCP, with the corresponding theoretical fitting according to our model of two junction in series. We observe that, the best fitting parameters, shown in figure, are compatible with those used for other measured junctions, and in particular the amplitude of the superconducting energy gap ($\Delta = 3.0\text{meV}$) is consistent with the estimated value by our previous $d$-wave fittings.

3. Concluding Remarks

We have performed Point-Contact spectroscopy experiments on Ru-1212 synthesized pellets and we have obtained different conductance curves, all characterized by a Zero Bias Conductance Peak. The conductance curves with a narrow peak were selected to estimate the magnitude of order parameter. By fitting these spectra we have inferred a $d$-wave symmetry of the superconducting order parameter with a maximum value of the gap amplitude $\Delta = (2.8 \pm 0.2)\text{meV}$. For the spectra with wider zero bias structures we hypothesized that the granularity of the samples causes the formation of a Josephson junction in series with the PC one. In this case, by using simplified model of a Josephson junction in series with the N–S point contact, we were able to fit our spectra, with a value of the order parameter $\Delta$ in agreement with the previous results. To investigate the interplay between superconducting and magnetic orders, we followed the dependence of the conductance curves from an applied magnetic field, concluding that the critical field of these samples is greater than 2 Tesla.

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