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Asymmetry in the normal-metal to high-T_c superconductor tunnel junction

Karsten Flensberg,* Per Hedegård, and Michael Brix
H. C. Ørsted Institute, Universitetsparken 5, DK-2100 Copenhagen Ø, Denmark
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We show that the observed asymmetry in the I-V characteristics of high-T_c material to normal-metal junctions can be explained within the resonating-valence-bond model. For a bias current with electrons moving from the superconductor to the normal metal, the current is quadratic in the bias voltage, and in the opposite case, with electrons moving from the normal metal to the superconductor, the current is linear in V.

Because of the lack of a theory for the high-T_c phenomenon, it has not been easy to analyze experiments. It has not been clear whether a given feature in a spectrum has intrinsic or extrinsic causes. In this contribution we will discuss one such feature which may prove to be intrinsic and therefore interesting from a theoretical point of view. If it, however, proves to be extrinsic, it will be fatal to the most promising theory on the high-T_c market: namely, the resonating-valence-bond (RVB) theory by Anderson and co-workers.

In very many of the published normal-metal to high-T_c tunneling spectra,[1-7] there is an asymmetry in the conductance. In Fig. 1 we have reproduced the data from Kirtley *et al.*,[5] which are typical. For one sign of the bias voltage, the conductance rises linearly, whereas for the other sign it seems to saturate at a finite value. This last feature is what is to be expected in the conventional Bardeen-Cooper-Schrieffer (BCS) theory for superconductivity, and Anderson and Zou[8] have shown that the linear rising is what is expected in the RVB theory. We will show that the BCS-type behavior is a consequence of the RVB theory as well when the high-T_c material is at a higher voltage than the normal metal.

The RVB theory has been discussed by many people after Anderson introduced it a year ago, and a useful physical picture has emerged. The quasiparticles were

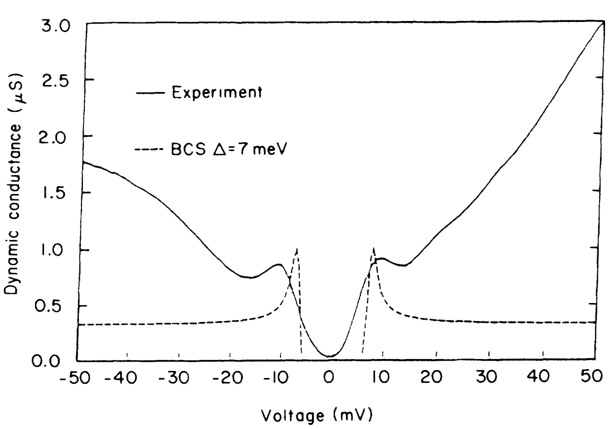

FIG. 1. The tunneling spectrum for a point contact between $La_{1.85}Sr_{0.15}CuO_{4-y}$ and PtIr. The dashed line is a fit to the BCS model (taken from Ref. 5).

first described by Kivelson, Rokhsar, and Sethna,[9] and an alternative description has since then been given by Dzyaloshinskii, Polyakov, and Wiegmann[10] with the same conclusion, which is as follows.

The important electrons are those belonging to the CuO_2 planes, and in the RVB state they pair up two and two in spin-singlet pairs. Loosely spoken, the RVB state is the superposition of all possible ways of pairing up the electrons in singlet pairs, with the constraint that no site is allowed to host two electrons. There are two important quasiparticles in such a system: *spinons* and *holons.* The spinons consist of unpaired electrons moving around in the RVB medium. They carry no charge, have spin $\frac{1}{2}$, and are fermions with an effective mass of order $\hbar^2/(a^2J)$ where a is the lattice constant and J is the exchange energy between spins; i.e., they are somewhat heavier than electrons since $J \approx 1000$ K. Holons are the carriers of the system; they are located at the empty sites and therefore have charge $+e$ and spin 0. Holons obey Bose statistics and have an effective mass which is of the order of the electron mass. A real electron hole, i.e., a fermion with charge and spin is, in this picture, a composite particle consisting of a holon and a spinon.

Anderson and Zou have in a recent work[8] shown how a number of unusual "normal" state properties can be explained within this picture. One of their examples is tunneling between a system described by the RVB model and a normal metal. Their discussion is, however, incomplete, in the sense that they only discuss tunneling in the case where the bias voltage is such that the electron current is from the high-T_c material to the normal metal. We will show that the situation for the opposite bias voltage is quite different and that one should expect an asymmetric I-V characteristic.

In Fig. 2 we have illustrated the two cases. On the left-hand side we have the normal metal with its filled Fermi sea of electron holes, and on the right-hand side we have the RVB system with the Bose distribution of holons and the Fermi sea of spinons. Applying a bias voltage corresponds to moving the bottom of the Bose distribution, i.e., the Bose chemical potential, with respect to the Fermi level of the holes in the normal metal. The Fermi level of the spinons will not change since the spinons carry no charge. In case (a), where the holes move from left to right, we are in the situation described by Anderson and Zou in which each electron hole splits up into a holon and a spi-

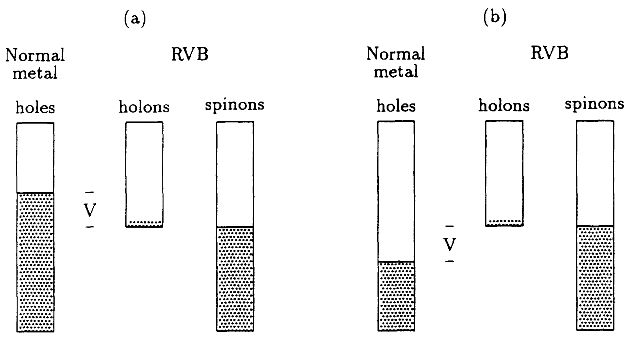

FIG. 2. A schematic illustration of the tunneling situation.

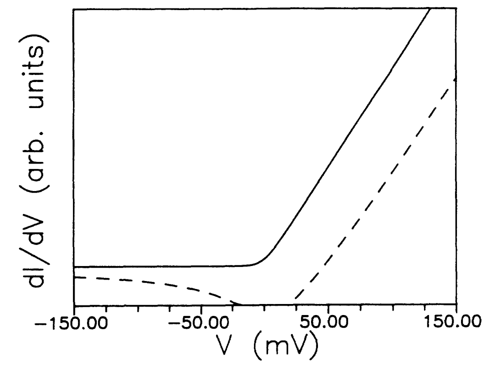

FIG. 3. The calculated conductance curves. The solid line shows the conductance when the RVB side is in the "normal" state. The superconducting RVB state gives the dashed curve.

non, distributing its energy among the two particles, which can be done in a number of ways proportional to the energy of the incoming hole. As a result, we get a term in the current which is proportional to V^2. Since bosons have a tendency to accumulate in the same state, there is also a term where the holon ends in the bottom of the Bose distribution and the spinon takes all the remaining energy. This will result in a contribution to the current which is proportional to V.

In the other case (b), where the holes move from right to left, all the holons have to come from the narrow region of width $k_B T$ at the bottom of the Bose distribution and the spinon energy must have a value so that the resulting hole can enter the unfilled part of the hole Fermi sea. In this case, there is *no* extra phase space since the holons are essentially monoenergetic and we therefore get a current which is proportional to V as in the usual normal-metal to normal-metal tunneling case.

In order to calculate the current we apply the standard theory of tunneling based on the Hamiltonian

$$H = H_N + H_{\mathrm{RVB}} + H_T \,, \tag{1}$$

where $H_T = \sum_{kp}(T_{kp} c_k^\dagger c_p + \text{H.c.})$ is the tunneling part of the Hamiltonian which carries an electron from one side of the junction to the other. When an electron hole enters the RVB side, it splits up into a holon and a spinon, which mathematically can be modeled by $c^\dagger = e^\dagger s^\dagger$, where $e^\dagger$ and $s^\dagger$ are holon and spinon creation operators, respectively. The current can now be calculated in the usual way and we get

$$I(V) = \frac{e}{\hbar} T^2 \int_{-\infty}^{\infty} d\epsilon\, A_N(\epsilon + eV) \times A_{\mathrm{RVB}}(\epsilon)[n_F(\epsilon) - n_F(\epsilon + eV)] \,, \tag{2}$$

where $A_N(\epsilon)$ is the density of states on the normal side, which is constant, and $A_{\mathrm{RVB}}(\epsilon)$ is the density of two particle states on the RVB side, the two particles being a holon and a spinon. At reasonably low temperatures, the conductance of the junction is proportional to this latter function, which is easily seen by differentiating (2) with respect to V. Assuming that the spinons and the holons are independent we obtain, for A_{RVB},

$$A_{\mathrm{RVB}}(\epsilon) = \frac{N_S(0)}{t_{\mathrm{eff}}} \int_{-\mu}^{\infty} d\omega \int_{-\infty}^{\infty} d\xi [n_B(\omega) + 1 - n_F(\xi)] \delta(\epsilon - \omega - \xi) \,, \tag{3}$$

where $N_S(0)$ is the density of spinon states at the Fermi level, and t_{eff} is the holon bandwidth. μ is the chemical potential for the holons and it is always negative and approaches 0 for $T \to 0$.

In Fig. 3, we have plotted the differential conductance with the solid line. For large negative voltages $A_{\mathrm{RVB}}(eV)$ approaches the value $N_S(0)\delta$, where δ is the number of holons per site.

The above calculation is unrealistic for low values of the bias voltage, where superconductivity plays a role. The detailed mechanism for superconductivity has not been well described in the RVB theory, so a theory for this regime is difficult. Wheatley, Hsu, and Anderson[11] have suggested that Josephson tunneling between the CuO layers can stabilize the Bose condensation, which is impossible in two dimensions. In a Josephson tunneling event, a singlet pair is broken and the two electron holes tunnel and form a singlet pair in the next layer. It should be noted that tunneling of a single hole is not operational in making the holon gas three dimensional, since such a tunneling event will create an unpaired spin: i.e., a spinon. The above discussed Josephson tunnel processes give rise to a term $\Delta e^\dagger e^\dagger + \text{H.c.}$ in the Hamiltonian, where $\Delta = \langle ee \rangle$. The effective Hamiltonian can now be diagonalized by a Bogoliubov transformation as in the BCS theory, with the important difference that the Cooper pairs now consist of bosons instead of fermions. We have calculated A_{RVB} when such a condensate of Bose-Cooper pairs is present. The result is

$$A_{\mathrm{RVB}}(\epsilon) = \frac{N(0)}{t_{\mathrm{eff}}} \int_{\Delta}^{\infty} dE\, \rho(E) \int_{-\infty}^{\infty} d\xi \{u(E)^2 [n_B(E) + 1 - n_F(\xi)] \delta(\epsilon - \xi - E) + v(E)^2 [n_B(E) + n_F(\xi)] \delta(\epsilon - \xi + E)\} \,, \tag{4}$$

where coherence factors are given by $u(E)^2=\frac{1}{2}[1/\rho(E)+1]$, $v(E)^2=\frac{1}{2}[1/\rho(E)-1]$ with $\rho(E)=E/\sqrt{E^2+\Delta^2}$. The gap $\tilde{\Delta}$ is defined as $\sqrt{\mu^2-\Delta^2}$.

We have plotted the differential conductance using this $A_{\rm RVB}$ with the dashed line in Fig. 3, where parameters have been chosen so that $\tilde{\Delta}=20$ meV which seems relevant for $YBa_2Cu_3O_x$. Again we find the asymmetry, this time with a gap. For large negative voltages the spectrum approaches the same value as in the other case, however with a slow $1/V$ behavior.

The tunnel junctions are often made with powder samples or crystals where it is very likely that the real measured junction is a series connection of the normal-metal to high-T_c material and one or more high-T_c material junctions.

The I-V characteristic for an RVB to RVB junction is symmetric and in the large voltage limit it can be shown, by using the RVB density of states on both sides of the junction in Eq. (2), that the current is given by

$$I_{\rm RVB\text{-}RVB}=\frac{e}{\hbar}|T|^2\frac{\delta N_S(0)^2}{2t_{\rm eff}}(eV)^2\,. \tag{5}$$

A series connection between a RVB-RVB junction and a normal-metal RVB junction will also have an asymmetric characteristic. For voltages where the chemical potential for the normal metal is raised with respect to that of the superconducting side of the junction, the situation is unchanged; i.e., there is a linearly rising conductance. The reverse case will give an Ohmic resistance in series with a quadratic characteristic. We have analyzed this situation and get the following simple result for the differential conductance:

$$\frac{dI}{dV}=G\left[1-\frac{1}{\sqrt{1+V/V_0}}\right], \tag{6}$$

where G is the normal metal to RVB conductance. The voltage V_0 is given by

$$eV_0=\frac{|T_{NS}|^2}{|T_{SS}|^2}\frac{N_N(0)t_{\rm eff}}{N_S(0)}, \tag{7}$$

where $N_N(0)$ is the normal-metal density of states. Since the holon effective mass is of the order of the electronic mass, the voltage V_0 is roughly determined by the spinon density of states and the ratio between the two tunneling matrix elements. The spinon density of states is of the order $J\sim100$ meV. This voltage determines the crossover between a regime where the conductance rises linearly and a regime where the conductance is constant. In Fig. 4, we have plotted the result of this analysis: A linear conductance for a positive voltage and a conductance given by Eq. (6) for a negative voltage. It should be emphasized that these results are only valid outside the gap region. For a voltage within the gap region the situation is more complicated, but the theory presented above and the predictions made are independent of the details of condensate, which are still an open question. More work has to be done to understand the BCS-type gap-edge structure. Adding phonon-enhanced tunneling to this picture may give the peaks around energies in the gap-edge region, that are found experimentally. The temperature will only play a role for voltages that are comparable to k_BT/e which always lies in the gap region and will therefore not affect the above results.

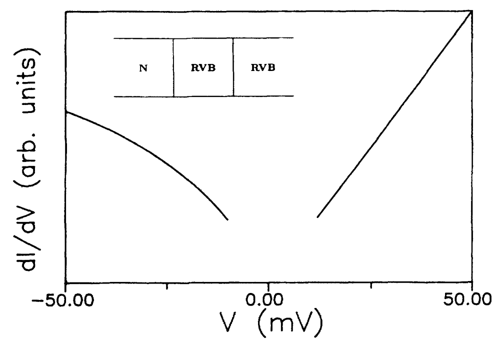

FIG. 4. The differential conductance for a series connection of two tunnel junctions: a normal-metal to a RVB-state tunnel junction and a tunnel junction with RVB states on both sides. The parameters are $V_0=25$ meV and the slope for positive voltage is $0.013G$ (meV)$^{-1}$.

In summary, we have calculated the conductance for a tunnel junction between a normal metal on the one side and a system described by the RVB model on the other side. The result is asymmetric in the bias voltage. This is a consequence of the fact that in the RVB state there is no particle-hole symmetry. If an electron hole enters the RVB side, it splits into two particles: a holon and a spinon. If, on the other hand, an antiparticle (namely, an electron) enters, it will *not* become an antiparticle of the holon (i.e., a doubly occupied site) and a spinon hole, unless we are in a half-filled band situation where the RVB state is insulating. The experimentally observed asymmetry in the high-T_c superconductor–normal-metal junctions is a strong indication that the RVB model is relevant for these new materials.

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*Also at Physics Laboratory I, The Technical University of Denmark, DK-2800 Lyngby, Denmark.

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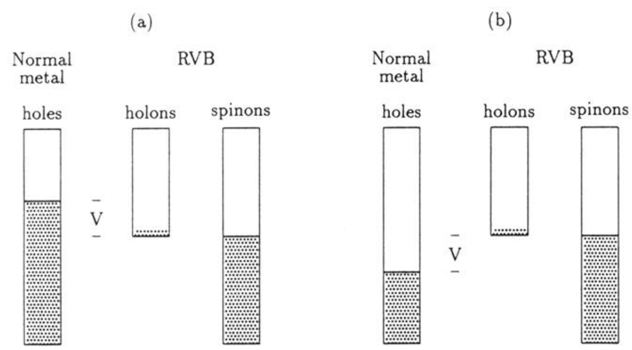

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