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Macroscopic quantum phenomena in high-T_c superconducting material

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The observation of macroscopic quantum phenomena in a high-T_c superconducting material [$YBa_2Cu_3O_{9-y}$ (Y-Ba-Cu-O), T_c=93.4 K] is reported. Relationships between current, voltage, and magnetic fields of Sn–Y-Ba-Cu-O and Y-Ba-Cu-O–Y-Ba-Cu-O point contacts were measured. In both cases the critical current is periodic in the magnetic field, which is typical for double point contacts (dc superconducting quantum interference devices). In the Sn–Y-Ba-Cu-O contacts the oscillations were observed below the T_c of tin. In the Y-Ba-Cu-O–Y-Ba-Cu-O contacts the oscillations were observed at temperatures up to 66 K, clearly demonstrating macroscopic quantum phenomena in this high-T_c material.

One of the most important properties of normal superconductors is the existence of a superconducting wave function with phase coherence throughout the material.[1] It is this property which leads to macroscopic quantum effects such as the Meissner effect, flux quantization, and the ac and dc Josephson effects. In order to characterize the observations of the low resistivity in high-T_c materials[2,3] in terms of classical superconductivity, it is essential to prove that macroscopic quantum phenomena do exist also in these materials. In this Rapid Communication results will be reported of experiments on systems where a weak coupling between two pieces of bulk material is established by means of a point contact.[4] It will be shown that macroscopic quantum effects exist in $YBa_2Cu_3O_{9-y}$ (Y-Ba-Cu-O) at least at temperatures up to 66 K.

The principle of the method is the following: a dc current I is applied to a rather blunt point contact. The current usually does not flow through one single channel, but through a small number of channels, due to the irregularities of the contact area.[5] When an external magnetic field B is applied, the area between each pair of channels and the bulk material contains a certain amount of magnetic flux. The quantum interference of supercurrents in the channels is determined by the flux and leads to a dependence of the *total* critical supercurrent I_c on B. The dc voltage V (for $I > I_c$) across the junction is field dependent accordingly.

The I-V-B dependences often show *double-point-contact* behavior, which results in periodic oscillations of I_c and V as functions of B. Each period corresponds to one flux quantum $\Phi_0 = h/2e$ in the area between the channels and the bulk materials.

In this Rapid Communication macroscopic quantum phenomena, as described above, are demonstrated using point contacts of which one or two of the bulk materials is Y-Ba-Cu-O. The preparation and the properties of this material are described in Ref. 6. The resistivity shows a sharp drop around 94 K. From the lower limit of the decay time of shielding currents in the material the resistivity was deduced to be less than 10^{-18} Ω m at liquid-nitrogen temperatures. Neither tip nor anvil were mechanically or chemically treated.

The I-V characteristics were determined using a four-terminal method (Fig. 1). The point contact was manually adjusted from outside the dewar.

In the first experiment the upper (moving) part was made of tin using a knife to cut it into a point. The bottom plate was Y-Ba-Cu-O. The temperature was below 3.7 K. The contact was adjusted so that the value of the critical current I_c was on the order of 100 μA. A set of I-V characteristics for several different magnetic fields is given in Fig. 2. The I_c-B dependence (not shown here)

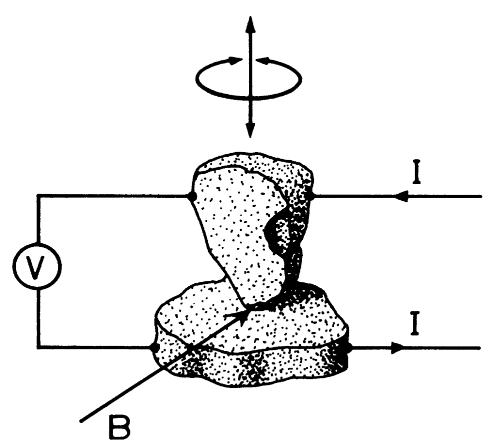

FIG. 1. Schematic diagram of the experimental setup. A little block (sizes on the order of a few mm) of tin or Y-Ba-Cu-O can be lifted up and down, and rotated around a vertical axis. It is pressed against a plate of Y-Ba-Cu-O. The I-V relationship is determined with a four-terminal method. A magnetic field is applied in the horizontal direction.

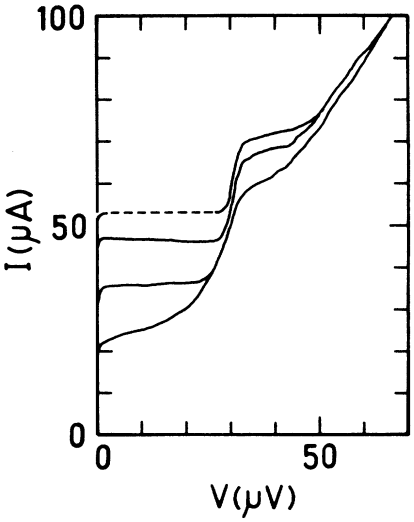

FIG. 2. I-V characteristics of the Sn–Y-Ba-Cu-O contact at 3.65 K. The different curves correspond to different magnetic field values.

was periodic (period 15 μT), demonstrating quantum interference of supercurrents in a double contact.

Inspection of the tin point, after the experiment, with an optical microscope showed an imprint of the sinter material.

In the second experiment both pieces of bulk material were Y-Ba-Cu-O. An edge of the material was taken as the tip (see Fig. 1). First the system was cooled to 4.2 K. Even at this temperature the contacts usually showed a linear I-V dependence. Only after many readjustments and applying a high pressure on the contact (to the level that the sample almost cracked), it was possible to obtain I-V characteristics with a superconducting part, and a field-dependent I_c. Once the contact was adjusted, it was stable.

The fact that the I-V characteristics usually were linear suggests that the material has a strong normal-conducting surface layer. The contact properties, in relation to the surface treatment and the porosity of the material, are under investigation.

The set of two I-V characteristics, given in Fig. 3(a), corresponds with the maximum and the minimum values of I_c as a function of B. The maximum critical current I_m was about 5 μA, which is rather low compared with what usually can be achieved in superconducting point contacts.[4] The minimum I_c is practically zero. The interference between the supercurrents in the channels leads to complete extinction of the total supercurrent. This can happen when $LI_m/\Phi_0 \ll 1$, where L is the self-inductance of the double point contact,[4] which usually is on the order of 2 to 10 pH.

Figure 3(b) represents the V-B dependence for various I. Again the periodic behavior is characteristic for a double point contact. The period was 70 μT, corresponding with an area of about 30 μm^2.

After measuring the I-V-B dependence at 4.2 K, the system was warmed up, leaving the contact adjustment unchanged, and monitoring the I-V-B dependence. The

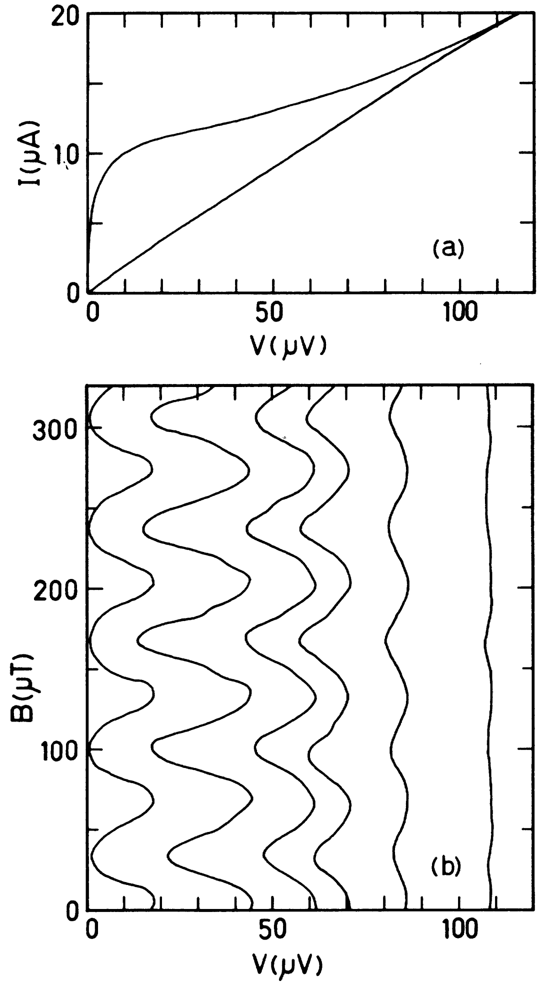

FIG. 3. The I-V-B dependence of the Y-Ba-Cu-O–Y-Ba-Cu-O contact at 4.2 K. (a) I-V characteristics. The set of two curves represents the two extremes between which the characteristics oscillate when B is varied. (b) V-B characteristics for several different currents. The periodicity is the result of a double point contact in the junction between the two pieces of Y-Ba-Cu-O.

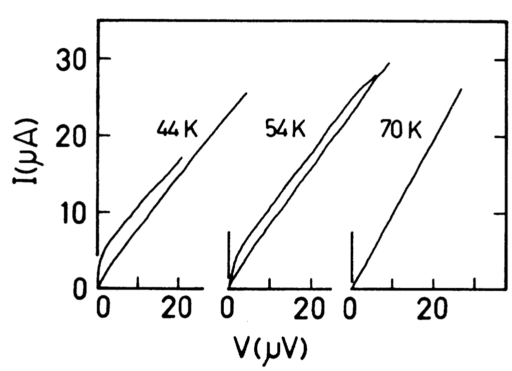

FIG. 4. The extremes of the I-V characteristics (obtained by varying B) at several different temperatures. Between 50 and 66 K there is no zero-voltage part, but the voltage at constant current still oscillates with the magnetic field. Above 66 K the I-V curves are straight lines and V is independent of the magnetic field within our present experimental accuracy.

value of I_m decreased with temperature. Some examples of sets of I-V curves are given in Fig. 4. The zero-voltage part of the I-V characteristics disappeared around 50 K, but the I-V relationships remained nonlinear and B dependent. Voltage oscillations could be seen at temperatures up to 66 K. Above this temperature the oscillations were buried in the noise (0.2 μV).

The temperature dependence of the I-V characteristics is caused by a combined effect of the T dependence of I_m, in the absence of noise, and the rounding of the I-V curves due to thermal noise.[7] The effect of the latter is determined by the parameter $\gamma = I_m(T)h/(2\pi e k_B T)$. When $\gamma < 5$ the I-V characteristics have no zero-voltage part. With $I_m = 5$ μA the value of $\gamma = 5$ is reached at $T = 50$ K, in agreement with the experimental results.

All attempts to make a point contact with a nonzero critical current at liquid-nitrogen temperatures have been unsuccessful so far. The I-V dependences were linear. With $\gamma > 5$ one finds that I_m should be larger than 9 μA in order to show clear interference phenomena at 78 K.

In conclusion, we first observed clear evidence of macroscopic quantum interference phenomena in Sn-$YBa_2Cu_3O_{9-y}$ and $YBa_2Cu_3O_{9-y}$-$YBa_2Cu_3O_{9-y}$ junctions. This result is encouraging for the application of high-T_c materials in sensitive detectors such as ac and dc superconducting quantum interference devices, in superconducting computers, etc., although thermal noise may constitute a severe problem.

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