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Quantum interference and critical currents in polycrystalline high-T_c samples

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We report clear and systematic evidence of quantum interference effects on Y-based high-T_c polycrystalline superconductors. Reliable direct measurements of the critical transport current, at different temperatures and fixed low magnetic fields, stepwisely increased, exhibit on top of the smeared Fraunhofer-like gross structure, a pattern of almost regular oscillations of $J_c(B)$.

Despite the inability of polycrystalline high-T_c superconductors to carry high amounts of electrical currents and its limitations to show clear signs of the fundamental high-T_c superconductivity mechanism, the granular high-temperature superconductors constitute interesting and highly complex systems. The critical transport current density J_c through granular superconductor subject to a magnetic field, reflects the particular confluence of fundamental tunneling effects and a number of structural and sample-dependent characteristics.

The gross features of J_c as a function of the magnetic field and temperature have, to a great extent, been explained by considering these systems as percolative networks of Josephson weak links of random orientations and sizes.[1-3] The almost constant values of J_c at very low fields, as well as its rapid and monotonic decrease for H between 10–30 Oe, depending on the sample, have been well fitted[3,4] by assuming that the current through each junction is defined by its own Fraunhofer diffraction pattern whose oscillations are smeared out after averaging in the junction lengths and relative orientations with respect to the external magnetic field.[4-6] It has also been observed[7] that the decrease of the critical current, with the magnetic field, reaches a minimum similar to the one observed by Neerink *et al.*[8] for artificially layered Ge/Pb superconductors, which is then followed by an increase to a plateau, of moderate and almost constant values, which extends up to the critical field H_{c2}. This so-called peak-effect behavior at the mixed-state region has been accounted for by Nikulov and Remisov[9] by extending the model of Josephson-junction systems to include an averaging of the phase differences calculated by summing, in the continuous limit, contributions of the Abrikosov vortices, parallel to the junction planes.

It is known that, due in part to heating of the current contacts and leads, the direct measurement of critical transport currents, represent and extremely difficult experimental problem. The temperature fluctuations force the averaging of experimental outcomes with the undesirable consequence of possible loss of subtle details. It is then clear that the experimental data reflect at least two averaging procedures: the intrinsic coherent and incoherent sum of microscopic properties to produce a macroscopic behavior, dependent on the size, homogeneity, etc., of the system, and the extra averaging of the experiment results to get rid of the measurement procedure uncertainties. These kinds of reported results, are described by the previously mentioned statistical models.

It is well known that the washing out of the detailed behavior of some quantities leaving only the relevant gross properties, is a common feature in complex and many-body problems, and has often been described by constructing appropriate ensembles of equivalent systems and averaging then across the ensemble. In a given bulk superconducting sample, the broad distribution of grain sizes and shapes, making contact with each other at different points, justifies in principle the statistical description of the measured quantities. Since a statistical description is better justified for larger systems of Josephson junctions, we decided to search experimental conditions where the continuous limit is not fully applicable, i.e., small but still macroscopic samples, as well as experimental procedures chosen to reduce the measurement uncertainties. We took samples with cross sections of the order of 0.3 mm^2 and lengths of 3–4 mm, with grains between 10–50 μm. Despite the size effect[11] on the magnitude of the current density and the reduction of the self-field,[12] the number of percolative paths is substantially reduced and easily decoupled by low intergranular magnetic fields. As expected and shown here, this sort of mesoscopic network of Josephson junctions will be less able to wash out quantum coherence details.

The purpose of this article is to report reliable direct measurements of the critical transport current at different temperatures and fixed low magnetic fields, almost regularly increased, on small but still macroscopic polycrystalline high-T_c superconductors which, because of the participation of an unknown but finite number of paths and loops, exhibit, on top of the smeared Fraunhofer-like gross structure, a pattern of almost regular oscillations of $J_c(H)$. Our focus of interest is on these evidences of macroscopic quantum interference effects, rather than on the also interesting gross structure of $J_c(H)$.

We present data on critical transport current measurements on polycrystalline Y-based samples which clearly show that, besides the quantum diffraction effects on the Josephson junctions described by the well-known function

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$$j_{cj}=j_0\frac{\sin(\phi_j/\phi_0)}{\phi_j/\phi_0}\ , \tag{1}$$

where $\phi_j=Ba_j$ is the flux through the Josephson junction with $B\sim B_{\rm ext}$, a network of paths manifest quantum interference effects originated on the various loops of Josephson junctions, that give rise to transport currents described by

$$j_{cl}=j_{cm}\cos\left[\delta^l+\frac{\pi\phi_l}{\phi_0}\right]. \tag{2}$$

Here $\phi_l=Ba_l$ is the flux thread by the loop of surface a_l and, j_{cm} is the minimum critical current on the Josephson junctions of the loop. In a mesoscopic network of Josephson junctions, the total transport current through the few superconducting paths and loops of the sample must be obtained by summing, rather than integrating, on the finite number of random contributions. According to the experimental evidence, reported here, part of the washing out of the detailed behavior of critical transport currents is certainly done by the measurements procedure. As mentioned before, even at low-energy dissipation, it is rather difficult and practically impossible to keep the temperature absolutely constant when the transport current is being changed to reach a transition point at fixed magnetic fields. Direct and natural consequences of this limitation are uncertainties and fluctuations in the measured temperature and critical current values. The mandatory averaging of the various experimental measurements masks any subtle phenomena. The procedure we followed, allows accurate measurement of all the critical parameters: J_c, $B_{\rm ext}$, and T_c. By slowly increasing the temperature, at fixed current and magnetic field, we reach the transition point. To avoid hysteretic effects,[13,14] the different magnetic-field values have been increasingly fixed. The various J_c vs T_c curves, at these magnetic fields, are (see Figs. 1 and 2) reasonably well fitted by the function[3]

$$J_c=J_0\left[1-\frac{T}{T_c}\right]^\alpha \tag{3}$$

with the experimental values of α lying between 0.7 and 0.8 (see Fig. 3), which, as is well known, depends on the sample, the magnetic field, and the conduction properties of the material in the barrier. The most interesting features of these curves are

(1) a sort of swinging, around a fixed point, of the whole $J_c(B_{\rm ext})$ curve as a function of the magnetic field. As mentioned before, it can be seen that for small uncertainties of the temperature, say $\delta T\sim 1$ K at $T=70$ K, it is not possible to distinguish the current at $B_{\rm ext}=3.6$ mT from that at $B_{\rm ext}=5.6$ mT. This is enough to wash out any subtle oscillation.

(2) a curvature characteristic of a parameter α in the interval (0.5,1), with different values on different regions of $(1-T/T_c)$.

(3) large error bars around the well-known critical fields H_c^J and H_{c1}.

The values of the parameter α larger than the typical critical exponent for a superconductor-insulator-superconductor junction (i.e., $\alpha\sim 0.5$), but lower than that for a superconductor–normal-metal–superconductor junction (i.e., $\alpha\sim 1.5$), correspond clearly to a mixture of some percentages of these junctions and to the presence of the expected semiconducting and dissipative barriers. The parameters α obtained from the $J_c(T)$ curves, partially shown in Figs. 1 and 2, are plotted in Fig. 3 as a function of the magnetic field. For fields above the weak-junctions-decoupling field, an increase in the critical exponent is observed and, is related to a lowering of the barrier height, i.e., a better conducting quality of the remaining coupled Josephson junctions. The dependence of the current on the magnetic field, indicates clearly that it is an intrinsic property of the tunneling process and reflects the influence of the quantum diffraction and interference phenomena at the macro-

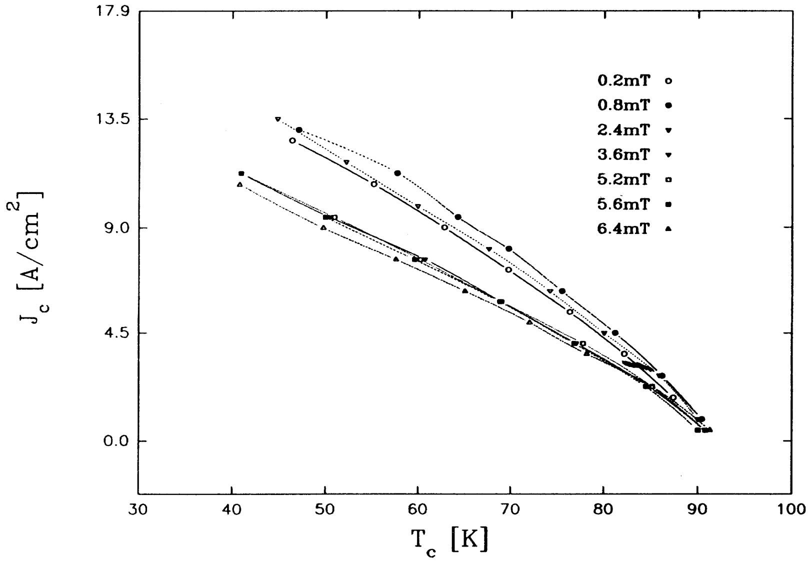

FIG. 1. The transport critical current for different magnetic fields as a function of the temperature (sample 1).

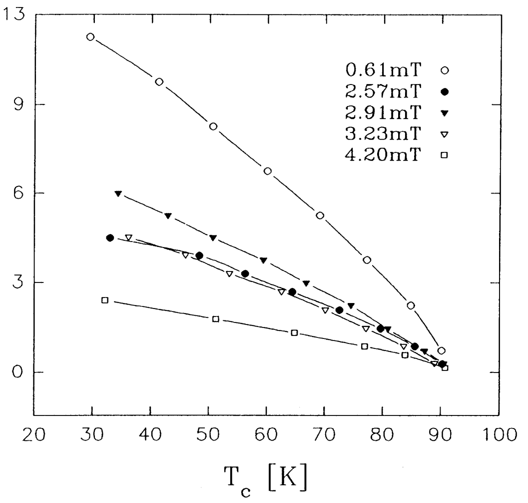

FIG. 2. The transport critical current for different magnetic fields as a function of the temperature (sample 2).

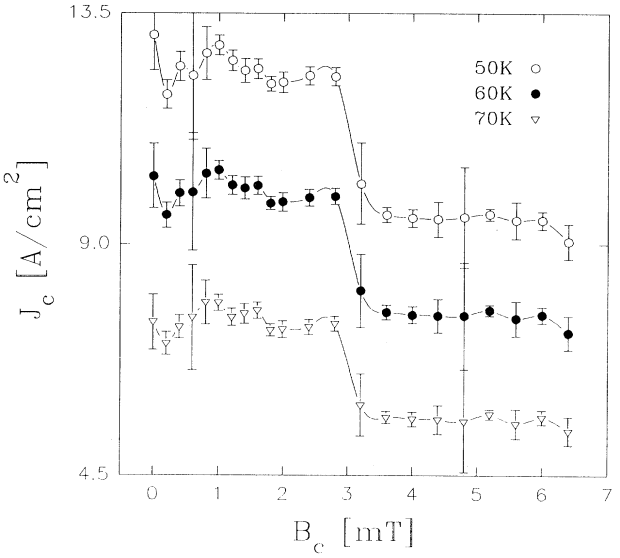

FIG. 4. The transport critical current as a function of the magnetic field for a $YBa_2Cu_3O_{7-\delta}$ sample with 5 h of annealing in an oxygen environment (sample 1). These curves were deduced from $J_c(T)$ curves which are partially shown in Fig. 3.

scopic level. From the $J_c(T)$ curves, for different values of the magnetic field and samples, we deduce the magnetic-field dependence of the critical transport current. In Figs. 4 and 5, the $J_c(B_{\rm ext})$ curves are plotted for two $YBa_2Cu_3O_{7-\delta}$ samples which differ only on the final annealing time process. The oscillating behavior of J_c has been consistently observed for other Y- and Gd-based samples. We attribute it to quantum interference effects. Obviously, these are sample-dependent oscillations whose frequency is of the order of 1 mT. Being the argument $\phi_l/\phi_0 \sim 2\pi n$ with $\phi_l = B_l a_l$ and $\phi_0 = 2\times 10^{-15}$ Wb, we have, for $n=1$, $a_l \sim 2\pi\phi_0/B_l \sim 4\pi\times 10^{-12}$ m^2, which corresponds to loops with radio of the order of 2 μm. This is also of the order of grain contacts cross sections as well as of the Josephson penetration length λ_J. By assuming that the percolation network contains paths with and without quantum interference loops, the total transport current will have contributions of the form defined by Eqs. (1) and (2) with a_j and a_l random variables, i.e.,

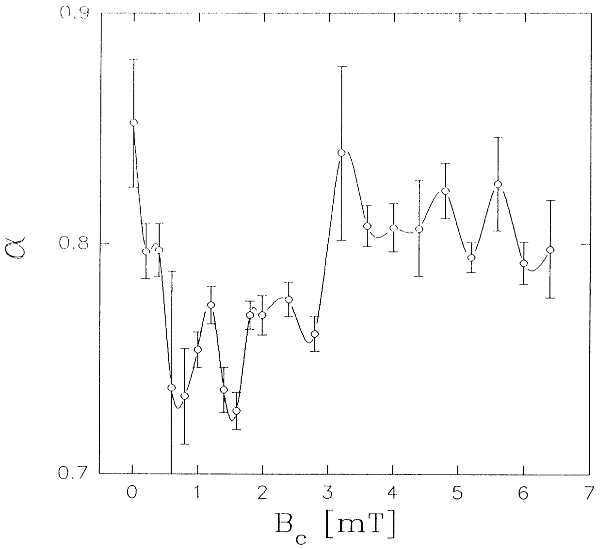

FIG. 3. The critical exponent α when the experimental currents of Fig. 3 are fitted by $(1-T/T_c)^{\alpha}$.

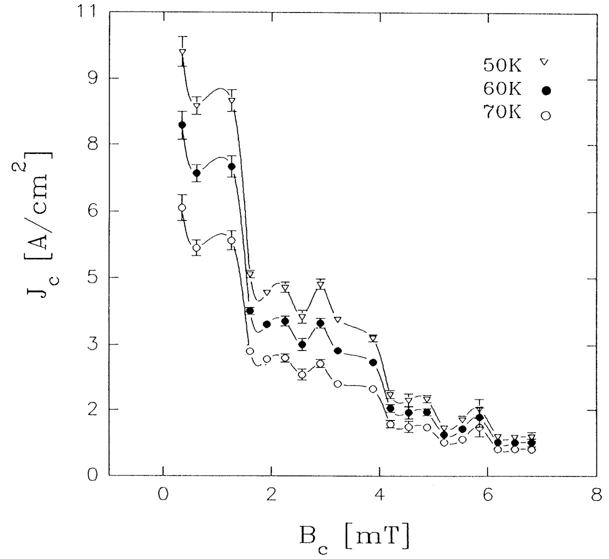

FIG. 5. The transport critical current as a function of the magnetic field for a $YBa_2Cu_3O_{7-\delta}$ sample with 50 h of annealing in an oxygen environment (sample 2). These curves were deduced from $J_c(T)$ curves which are partially shown in Fig. 4.

$$J_c(B_{\text{ext}})=\sum_{j=1}^{N_j} j_{0j}\frac{\sin(\pi\phi_j/\phi_0)}{\phi_j/\phi_0}+\left[\sum_{l=1}^{N_l} j_{0l}\frac{\sin(\pi\phi_{jl}/\phi_0)}{\phi_{jl}/\phi_0}\right]\cos\left[\delta_l+\frac{\pi\phi_l}{\phi_0}\right]. \quad (4)$$

For the orders of magnitude observed in our samples, i.e., $a_j \sim 1$ μm and $a_l \sim 5$ μm, with small fluctuations for highly homogeneous samples, we obtain a curve like the one shown in Fig. 6. In the limit of large N_j and N_l or in the limit of high randomness of the parameters a_j and a_l, the $J_c(B)$ curve with oscillating structures, described by Eq. (4), changes into a curve with the well-known gross structure.

We have shown here that by fixing the magnetic field and the current and, slowly changing the temperatures, we obtain reliable and accurate critical parameters capable of exhibiting subtle and well defined field-dependent critical transport current oscillations. The associated $J_c(T)$ curves, fitted by the function $(1-T/T_c)^\alpha$, produce a field- and sample-dependent parameter α with values between 0.7 and 0.8. A careful analysis of these exponents is in progress. The quantum coherence observed at macroscopic systems (mesoscopic networks) recalls analogous coherence effects observed in mesoscopic disordered conductors. We expect clear and regular oscillations on small but macroscopic rings of polycrystalline samples. These experiments are in progress also.

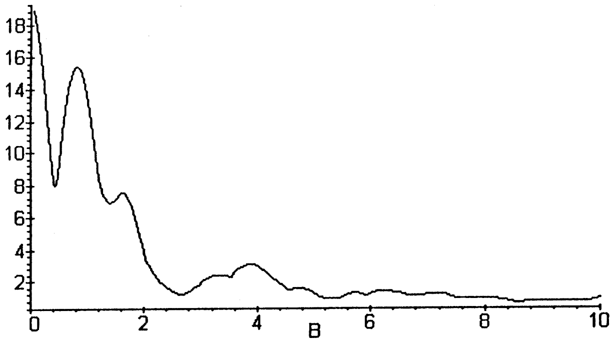

FIG. 6. The critical transport current (in A/cm^2) as a function of the magnetic field (in mT) for a particular set of stochastic parameters a_j and a_l in Eq. (4) and $N_j=6, N_l=11$.

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