Bose-Glass behaviour in Bi$_2$Sr$_2$Ca$_{1-x}$Y$_x$Cu$_2$O$_8$ crystals with columnar defects: experimental evidence for variable-range hopping

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Abstract
We report on vortex transport in Bi$_2$Sr$_2$Ca$_{1-x}$Y$_x$Cu$_2$O$_8$ crystals irradiated at different doses of heavy ions. We show evidence of a flux-creep resistivity typical of a variable-range vortex hopping mechanism as predicted by Nelson and Vinokur.

1 Introduction

Disorder plays a crucial role in the static and dynamic properties of the mixed state of high-Tc cuprates [1]. A main feature of the diagram phase is the phase transition separating a high temperature vortex liquid-like state from a low temperature vortex solid-like state. In particular, the nature of the latter depends on the strength and the dimensionality of disorder. In the presence of an unidimensional disorder, Nelson and Vinokur predict a Bose-glass [2]. In this paper, we shall concern ourselves with the variable-range vortex hopping transport predicted in a Bose-glass.
2 Experimental method

We studied two Bi$_2$Sr$_2$Ca$_{1-x}$Y$_x$Cu$_2$O$_8$ crystals with $x = 0$ (sample A) and $x = 0.36$ (sample B) whose the zero-field critical temperature $T_c$ are 89.1K and 91K respectively. Both samples approximately had dimensions $1\times1\times0.030$ mm$^3$ and were together irradiated with 5.8 GeV Pb ions at the Grand Accélérateur National d’Ions Lourds (GANIL) at Caen, France. Irradiation doses expressed in terms of a matching field $B_\phi$ were 1.5T (sample A) and 0.75T (sample B). In both cases the incident beam was parallel to the c-axis of the crystal. The resulting damage consists of parallel columnar defects of radius $c_0 \approx 40\text{Å}$ throughout the thickness of the sample. Isothermal current-voltage (I-V) curves were recorded by using a dc four probe method with a sensitivity better than $10^{-10}$V and a temperature stability better than $5\text{mK}$. The magnetic field was aligned parallel to the columnar defects.

3 Results and discussion

We have examined in some detail the behaviour of I-V curves in magnetic fields less than $B_\phi$. A detailed discussion of data in the framework of the Bose-glass melting theory [2] will be published in a separate paper. At low temperature, we find in the limit of weak currents a non-linear thermally actived flux-creep resistivity

$$\rho = \rho_0 \exp\left(-\frac{c}{T}(J_0/J)^\mu\right)$$

where the glassy exponent $\mu$ is independent of B and takes the value $\sim 1/3$. We have determined $\mu$ as was shown in a former paper [3]. Such barrier energies at low current is indeed the very signature of variable-range vortex hopping [2]. To test the accuracy of the above view, we estimate from the theory [1,2] the energy scale and the characteristic current in Eq. (1). The energy scale $c$ is given by

$$c = 2d\sqrt{\tilde{\epsilon}_1 U}$$

with $d \approx \sqrt{\phi_0/B_\phi}$ the mean distance between columns, $\tilde{\epsilon}_1 \approx \epsilon\epsilon_0 \ln(a_0/\xi_{ab})$ the tilt modulus where $\epsilon$ is the anisotropic parameter, $\epsilon_0 = \phi_0^2/(4\pi\mu_0\lambda_{ab}^2)$ is the line tension and $a_0 \approx \sqrt{\phi_0/B}$ is the vortice-lattice constant, and $U = U_0f(T/T^*)$ where $U_0$ is the mean pinning energy, $T^* = \max(c_0, \sqrt{2}\xi_{ab})\sqrt{\epsilon_1 U_0}$ is the energy scale for the pinning and $f(x) = x^2/2 \exp(-2x^2)$ accounts for
thermal effects. In Eq. (1) \( J_0 = 1/(\phi_0 g(\tilde{\mu})d^4) \) where \( g(\tilde{\mu}) \) denotes the density of pinning energies at the chemical potential. Note that \( g(\epsilon) \) is normalized such that \( \int_{-\infty}^{+\infty} g(\epsilon) \, d\epsilon = 1/d^2 \). Although a form of \( g(\epsilon) \) is not yet available, an estimate of \( g(\tilde{\mu}) \) can be done in terms of \( \gamma \) the energy dispersion of pinning energies. Such an intrinsic dispersion originates from the intervortex repulsion and the presence of disorder. The field independent value of the glass exponent \( \mu \approx 1/3 \) suggests that \( \gamma \) is dominated by the disorder effect, and thus we can consider \( g(\epsilon) \) as a smooth function near \( \tilde{\mu} \) [4]. Then, \( g(\tilde{\mu}) = 1/(d^2\gamma) \), wherefrom we obtain

\[
J_0 \approx \gamma/(\phi_0 d).
\] (3)

In this case, one expects \( \gamma \) to be given by the combination of the energy dispersion arising from the structural disorder and the one, \( \gamma_i \), which results from some on-site disorder [1],

\[
\gamma \approx \gamma_i + t_d.
\] (4)

An estimate for the energy dispersion due to the structural disorder, i.e., the randomness in the distance between the irradiation tracks, has been made in terms of the hopping matrix element connecting sites separated by the typical distance \( d \) [2],

\[
t_d \approx 2\sqrt{2/\pi} \frac{U}{\sqrt{c'/T}} \exp\left(-\frac{c'}{T}\right)
\] (5)

where \( c' = c/\sqrt{\sigma} \). On the other hand, assuming the variations in the defect diameters induced by the dispersion of the ion beam as the first cause for random on-site energies, we approximate \( \gamma_i \) to the width of the distribution of pinning energies

\[
\tilde{P}(U_k) = P(c_k) \frac{dc_k}{dU_k}
\] (6)

where the pinning energies \( U_k \) and the defect radius \( c_k \) are related to one another through the formula [2]

\[
U_k = \frac{\epsilon_0}{2} \ln \left[ 1 + \left( \frac{c_k}{\sqrt{2}\xi_{ab}} \right)^2 \right]
\] (7)

and \( P(c_k) \) define a distribution of defects, such that \( N(c_k) = \int_0^{c_k} P(c'_k) dc'_k \) is the number of columns per unit area with radius less than \( c_k \) and \( P(c_k) \) is normalized such that \( N(+\infty) = 1/d^2 \).
The solid lines shown in Fig. 1 are a fit of $\frac{c}{T} J_0^{1/3}$ to data. The exponent 1/3 accounts for the value of the glassy exponent $\mu$. We have used the temperature dependence as predicted in the two-fluid model for the in-plane penetration depth i.e., $\lambda_{ab}(T) = \lambda_0 \left[1 - \left(\frac{T}{T_c}\right)^4\right]^{-1/2}$, and we have chosen a Gaussian distribution for $P(c_k)$ centered at $c_0$, with a width $w$. Indeed, Fig. 1 shows that the theoretical curves and experimental data quantitatively agree. It should be noted that the model fits above $B_\phi/2$ fail. Such a fit results in realistic values for fitting parameters as shown on the table 1 where $\xi_0$ denotes the in-plane coherence length at $T = 0$.

| Sample | $c_0$ (Å) | $w/c_0$ (%) | $1/\epsilon$ | $\lambda_0$ (Å) | $\xi_0$ (Å) |
|--------|-----------|-------------|--------------|-----------------|-------------|
| A      | 45 ± 2    | 17.5 ± 2.5  | 50 ± 2       | 1790 ± 20       | 17 ± 2      |
| B      | 45 ± 2    | 16 ± 2.5    | 52 ± 2       | 1910 ± 20       | 15 ± 2      |

Table 1 shows two significant points. First, the mean value of defect diameters $2c_0 \approx 90$ Å with a dispersion of $w/c_0 \approx 17.5\%$ is typical of damage track diameters produced in Bi-based compounds with 5.8 Gev Pb ions [5]. Second, the only superconducting parameter variable is the penetration depth $\lambda_0$. If one assumes that $\lambda_0$ is independent of $B_\phi$, it clearly appears that $\lambda_0$ increases with $x$ as expected for an underdoped sample [6,7]. Finally, we make a comparison between $\gamma_i$ and $t_d$. We obtain temperature dependent ratios of $\gamma_i$ to $t_d$ of order 100. According to the Eq. 4, this means that the energy dispersion mainly arises from the on-site disorder.
4 Conclusion

We find striking evidence (for $B < B_\phi/2$) for a variable-range vortex hopping mechanism originating in the random pinning energies induced by the energy dispersion of the ion beam.

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References

[1] G. Blatter, M. V. Feigel’man, V. B. Geshkenbein, A.I. Larkin and V. M. Vinokur, Rev. Mod. Phys. 66, 1125 (1994).

[2] D. R. Nelson and V. M. Vinokur, Phys. Rev. B48, 13 060 (1993).

[3] V. Ta Phuoc, A. Ruyter, L. Ammor, A. Wahl, J. C. Soret and Ch. Simon, Phys. Rev. B56, 122 (1997).

[4] U. C. Täuber and D. R. Nelson, Phys. Rev. B52, 16 106 (1995).

[5] S. Hebert, V. Hardy, M. Hervieu, G. Villard, Ch. Simon and J. Provost, to be published in Nucl. Instr. and Meth. B.

[6] G. Villard, D. Pelloquin, A. Maignan and A. Wahl, Physica C278, 11 (1997).

[7] G. Villard, D. Pelloquin and A. Maignan, to be published in Phys. Rev. B58.