LT 21 Proceedings of the 21st International Conference on Low Temperature Physics
Prague, August 8-14, 1996
Part S3 - Superconductivity 2: HTS - Vortices (experiment)

Angular anisotropy of the irreversibility line in thin $YBa_2Cu_3O_{7-\delta}$ films: pinning in vortex liquid

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We report on measurements of the angular dependence of the irreversibility temperature $T_{irr}(\theta)$ in $YBa_2Cu_3O_{7-\delta}$ films. We find that neither depinning nor melting are responsible for the appearance of magnetic reversibility. Instead, we find evidences that T_{irr} is determined by a crossover from pinned to unpinned vortex liquid.

1. INTRODUCTION

The origin of the irreversibility line (IRL) in high-temperature superconductors (HTS) is an intriguing and still a widely discussed topic [1-5]. Large fluctuations and weak pinning enrich the field-temperature (H-T) plane by a number of dynamic and static transitions, which can account for the appearance of irreversibility. Models, proposed to identify the origin of IRL for HTS, include depinning by thermal activation [2-5], melting [6-8], a vortex fluid to vortex glass transition [9,10] and pinning of vortex liquid above the melting line [3,11-13].

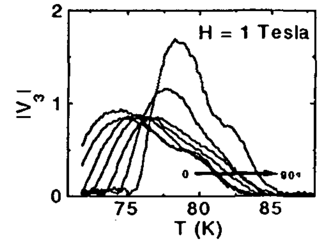

Fig. 1 Amplitude of the third harmonic of the AC response as a function of temperature at different angles θ between 0 and 90°.

2. RESULTS

A 1500 Å, 100×500 μm^2 c-oriented laser ablated $YBa_2Cu_3O_{7-\delta}$ film is measured. $T_c \approx 89$ K was determined as the onset of diamagnetic expulsion in a DC field of 5 G. The irreversibility temperature $T_{irr}(\theta)$ was measured as the onset of the third harmonic signal during field-cooling from temperature above T_c. The AC response was probed by a 80×80 μm^2 InSb Hall-probe, positioned at the center of the sample. The 1 G AC magnetic field, at frequency of 134 Hz, was always parallel to the c-axis, whereas a DC magnetic field, up to H=1.5 Tesla, could be applied at any direction θ with respect to the c-axis.

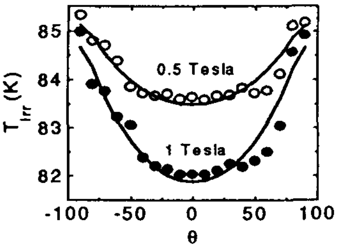

Fig. 2 T_{irr} as a function of the angle θ for H=0.5 and 1 Tesla. The solid lines are fits to Eq. 6

In Fig. 1 we show typical data for the third harmonic amplitude V_3 as a function of temperature for angles between 0 and 90°. There is a clear difference between the curves: the larger the angle is, the narrower is the curve and its onset is shifted to higher temperatures. We determined the onset temperature using a 20 A/cm² criterion. In Fig. 2 we plot this irreversibility temperature as a function of the angle for two values of the external field: 0.5 and 1 Tesla. Note that T_{irr} increases in approaching $\theta=\pm 90°$.

Finally we plot in Fig. 3 the frequency dependence of T_{irr} for DC fields of 0.5 and 1 Tesla. Apparently, the slope $dT_{irr}/d\ln(f)$ is larger for 1 Tesla.

3. DISCUSSION

In our analysis we use the approach, suggested by Blatter et al. [14], for scaling of physical quantities in the case of intrinsic anisotropy, i.e., we replace $T \rightarrow \varepsilon T$ and $B \rightarrow \varepsilon_\theta B$, where $\varepsilon_\theta = \sqrt{\cos^2(\theta)+\varepsilon^2\sin^2(\theta)}$ and $\varepsilon \approx 1/7$ is the anisotropy parameter for YBCO. The most common mechanisms for the onset of irreversibility are depinning and melting. Using the scaling approach, the explicit expressions for those temperatures are derived in [14].

$$T_{dp}(\theta) = 4\varepsilon\varepsilon_0\xi^2\left(\varepsilon_\theta B/\Phi_0\right)^{1/2} \qquad (1)$$

and

$$T_m(\theta) = 4\varepsilon\varepsilon_0 c_L^2\left(\Phi_0/\varepsilon_\theta B\right)^{1/2} \qquad (2)$$

However, we could not satisfactory fit our data to neither of these expressions.

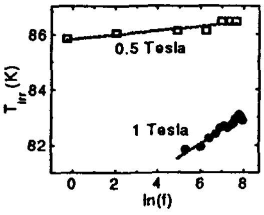

Fig. 3 Frequency dependence of T_{irr} at $\theta=0$ for $H=0.5$ and 1 Tesla. The solid lines are fits to Eq. 6

Yet, another approach is to consider possible pinning in the vortex liquid phase (see for discussion Ch. VI in [3] and Refs. therein). Any fluctuation in the vortex structure has to be averaged over the characteristic time scale for pinning t_{pin}. Usually, in the liquid state there is no pinning because the time scale for thermal fluctuations, t_{th}, is always smaller than t_{pin}. However, if the viscosity of the liquid is large enough, then there is a possibility for plastic deformations with a characteristic time scale t_{pl} larger than t_{pin}. Then, such a liquid is pinned. As shown in Ref. [3], the magnitude of t_{pl} increases with increase of viscosity of vortex liquid, which can be characterised by barriers for **plastic** motion of vortices:

$$U_{pl} \propto \left(T_c - T\right)/\sqrt{B}\,. \qquad (3)$$

The characteristic time is given by

$$t_{pl} \approx t_{th}\exp\left(U_{pl}/T\right) \qquad (4)$$

The crossover between pinned and unpinned liquids occurs at the temperature T_k where the characteristic relaxation time for pinning t_{pin} becomes comparable with that for a plastic motion t_{pl}. Thus, we can estimate T_k using Eqs.3 & 4 as:

$$T_k = T_c/\left(1 + A\ln\left(t_{pin}/t_{th}\right)\sqrt{B}\right) \qquad (5)$$

where A is some constant. Using the anisotropic scaling as discussed above and noting that in our case of AC experiment we can replace t_{pin} by $1/f$, where f is the experimental frequency, we obtain for the crossover temperature T_k:

$$T_k = T_c/\left(1 + A\ln\left(f_{th}/f\right)\sqrt{\varepsilon_\theta B}\right) \qquad (6)$$

where we defined $f_{th}=1/t_{th}$. This equation has clear predictions for the angular variation of T_{irr} and its frequency dependence. The fits (solid lines) in Fig. 2 are in a good agreement with Eq.6. For both fields we get $A\ln(f_{th}/f)\approx 0.05 << 1$ (B is in Tesla). Using this, we may approximate Eq. (6) at not too large fields as:

$$T_{irr} = T_c\left(1 - A\ln\left(f_{th}/f\right)\sqrt{B}\right) \qquad (7)$$

which results in a linear dependence of T_{irr} upon ln(f) and a slope dTirr/dln(f) which increases with B. This equation describes correctly our data on the frequency dependence, as is demonstrated by the solid lines in Fig. 3. We note that the approximated expression, Eq. 7, is valid in the whole experimental regime since Eq. 6 predicts a maximum in the slope dTirr/dln(f) at $B=(A\ln(f_{th}/f))^{-2}\approx 400$ Tesla for the experimental parameters. This value is, of course, beyond experimental limits.

In conclusion, by measuring the angular and the frequency dependence of the irreversibility temperature, we demonstrate that in YBCO thin films T_{irr} is well described as a crossover temperature between pinned and unpinned vortex liquid.

Acknowledgements: This research was supported in part by the Israeli Science Foundation administered by the Israeli Academy of Science and Humanities and the Heinrich Hertz Minerva Center for High Temperature Superconductivity, and in part by the DG XII, Commission of the European Communities and the Israeli Ministry of Science and the Arts. A. S. and R. P. acknowledge a support from the Israeli-France co-operation program AFIRST. R. P. acknowledges the hospitality of SESI at Ecole Polytechnique during part of this research.

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