'Flux Waves' in $Bi_2Sr_2CaCu_2O_{8+\delta}$

B. Kalisky[1], A. Shaulov[1], B. Ya. Shapiro[1], T. Tamegai[2] and Y. Yeshurun[1]

1. Department of Physics, Institute of Superconductivity, Bar-Ilan University, Ramat-Gan 52900, Israel
2. Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Abstract. We observed a new behavior of vortex instabilities in $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals, namely a quasi-periodic motion of the flux front separating the unstable vortex state from the thermodynamic vortex phase. These "flux waves" were shown to be a direct result of a unique defect pattern that characterizes $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals grown by the floating zone method.

Keywords: $Bi_2Sr_2CaCu_2O_{8+\delta}$, Vortex phase transition, Magnetic relaxation.
PACS: 74.25.Qt 74.62.Dh 76.60.Es

Local measurements of magnetic relaxation in high temperature superconductors have shown unusual phenomena such as negative relaxation near the edge of the sample and zero relaxation at the 'neutral line'[1,2]. Also, accelerated magnetic relaxation was observed and attributed to the annealing process of metastable disordered states coexisting with the quasi-ordered thermodynamic phase near the vortex order-disorder transition line[3].

Here we report on a remarkable phenomenon of oscillating magnetic relaxation. Time resolved magneto-optical imaging of the spatial distribution of magnetic induction across the sample, revealed a quasi-periodic motion of the flux front separating the unstable vortex state from the thermodynamic vortex phase. In this paper we demonstrate these 'flux waves' and suggest an explanation to this unique phenomenon.

Measurements were performed on a 1.4×8×0.05 mm³ $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal (T_C = 92 K). The crystal was grown using the floating zone method[4]. The external magnetic field, H, was raised abruptly to a target value between 140 and 840 Oe with rise-time < 50 ms. Immediately after reaching the target field, magneto optical (MO) snapshots of the induction distribution across the sample surface were recorded at time intervals of 40 ms for 5.5 seconds, using iron-garnet MO indicator with in-plane anisotropy[5] and a high speed Charge Coupled Device (CCD) camera. This procedure was conducted at several temperatures between 20 and 25 K. In a different type of experiment, a sequence of MO images was taken during a sweep of the temperature in the presence of a constant external magnetic field, which was applied for long enough time so that the system is relaxed. The spatial resolution of the presented MO data is 4 μm/pixel.

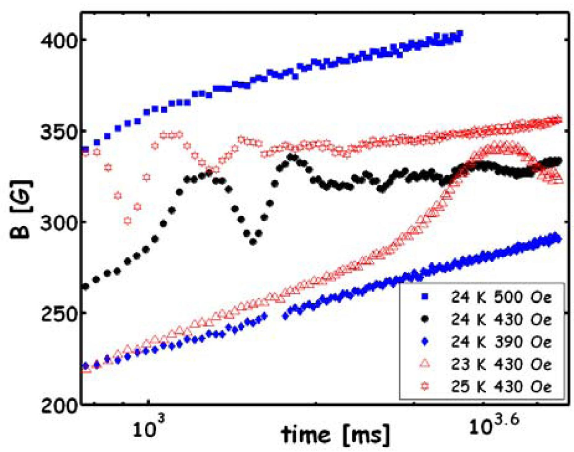

FIGURE 1. Time dependence of local induction B measured at 240 μm from the sample edge, after abrupt application of external magnetic field at constant temperature.

Figure 1 shows the time evolution of the local induction B at a certain location in the sample (240 μm from the left edge) after application of an external magnetic field. At 24 K, the expected behavior of B is observed after application of 500 or 390 Oe (square and diamond symbols, respectively), B increases logarithmically with time. However, when an intermediate field is applied, e.g. 430 Oe, marked by full circles, a unique behavior is observed, namely an oscillatory behavior of B with decaying amplitude. This phenomenon, limited to a certain field range, is also limited by the temperature: Data for 23 and 25 K (triangles and stars, respectively) demonstrates that at

CP850, *Low Temperature Physics: 24th International Conference on Low Temperature Physics;*
edited by Y. Takano, S. P. Hershfield, S. O. Hill, P. J. Hirschfeld, and A. M. Goldman

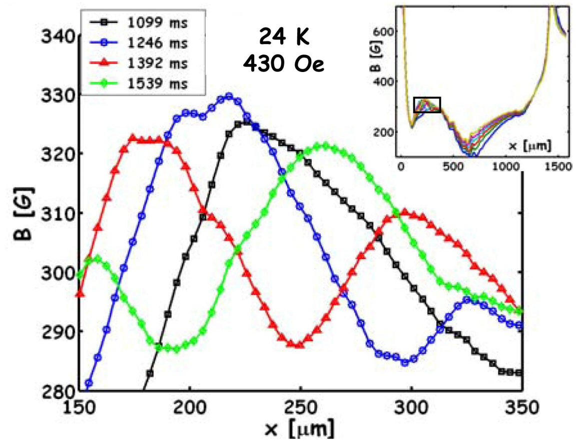

FIGURE 2. Local induction B at the indicated times after application of 430 Oe at 24 K, plotted as a function of the location across the sample (x=0 is the left edge of the sample). In the inset B(x) is plotted across the entire sample width. The small square marks the region which is enlarged in the main figure.

high temperatures the phenomenon is too fast to be measured (we see only its 'tail' at 25 K) and at low temperatures it is very slow (we observe only the first oscillation at 23 K).

The inset to Figure 2 shows the induction profile across the sample at different times after application of 430 Oe at 24 K. The main panel of the figure is focusing on the region marked by a square. The time evolution of induction profiles demonstrates 'flux waves', i.e. induction oscillations in both time and space. We note that the 'waves' move in the opposite direction to the incoming flux from the edge of the sample due to relaxation in the presence of the applied field.

These 'flux waves', observed when the magnetic field was changed at a constant temperature, were also observed when the temperature was changed at a constant applied field.

In the following we suggest an explanation to the observed 'flux waves'. Our explanation is based on the dynamic behavior of transient disordered vortex states (TDVS)[6], which exist below the order disorder transition induction, B_{od}. This dynamics is determined by the difference between the local induction B and B_{od}. We also noticed that all our $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples are characterized by pronounced defect patterns that were already described in the literature[7] and attributed to the inevitable local oxygen disorder[8]. Presumably, such defect patterns cause a spatial distribution of the vortex order-disorder transition induction, B_{od} [9].

When the magnetic field is raised abruptly, the sample is filled with TDVS. After a certain time the ordered phase nucleates at a point where $B-B_{od}$ is minimal (for uniform B_{od} this point is the sample center). The annealing process is revealed by the appearance of a break (change of the local slope) in the profile. This break separates between the ordered phase at the center of the sample and the TDVS, which are characterized by a higher persistent current. With time the annealing process of TDVS continues. The annealing is revealed by the movement of the break towards the sample edge.

In our sample, due to the spatial distribution of B_{od}, TDVS in certain parts of the sample are less stable than in other parts of the sample because they are found at inductions that are further away from B_{od}. This results in nucleation and front propagation of the thermodynamic vortex phase at different parts of the sample at different times. The collective movement of several fronts towards the sample edge creates the impression of flux waves.

In summary, 'flux waves' are observed in a limited field and temperature region near the vortex order-disorder phase transition. Spatial variation of B_{od} across the sample and a relatively flat profile are essential conditions for observation of this phenomenon.

We acknowledge support from the German-Israel Foundation (GIF). Y.Y. acknowledges support from the Wolfson Foundation. This research is supported by the ISF Center of Excellence Program (Grant No. 8003/02) and the Heinrich Hertz Minerva Center for High Temperature Superconductivity.

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