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Flux Dynamics in Rb_3C_{60} Crystals†

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We report the results of ac susceptibility measurements on Rb_3C_{60} fullerene superconductor prepared with C_{60} crystals. The temperature, T_{irr}, of the maximum in χ'' shifts to high temperature with increasing ac magnetic-field frequency *f. We* fit the irreversibility line (IL) $T_{irr}(H_{dc})$ with the scaling relation $H_{dC}=H_{irr}(0)(1-T_{irr}/T_o)^n$ and obtain n = 1.5 and $T_0=$ 30.3 K for the 10 kHz IL near T_c. We find a roughly linear dependence on logarithmic f for $1/T_{irr}$. By comparing the results to the expected frequency responses for flux pinning and flux flow, the observed frequency dependence of T_{irr} is interpreted by thermally activated flux creep in the fullerene.

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Fullerene superconductors have the highest transition temperature T_c in organic superconductors. Experiments have revealed many interesting properties in this new superconductor system; however, one important property of superconductivity - irreversibility - remained relatively unexplored. In this paper we use ac susceptibility techniques to study the irreversibility behavior in Rb_3C_{60} crystals. The experimental results are analyzed with the flux flow model and flux pinning model.

Growth of C_{60} single crystals is reported elsewhere [1]. X-ray diffraction analysis on the gronn crystals shows pure C_{60} single phase. The single crystals are plate-shaped and have a typical length of 0.3 mm. 25 mg of C_{60} crystals were mixed with a stoichiometric quantity of elemental Rb in a sealed Pyrex ampoule. The conditions for synthesizing Rb_3C_{60} are similar to those reported earlier [2]. ac susceptibility measurements were carried out on the synthesized Rb_3C_{60} with a Lakeshore 7221 ac Susceptometer. The time varying magnetic field is in the form of $H_a=H_{dc}+h_{ac}\cos(2\pi ft)$, where H_{dc} and h_{ac} correspond to dc and ac magnetic field amplitudes, respectively, and f is the frequency of ac magnetic field. In our measurements, $H_{dc}\gg h_{ac}$.

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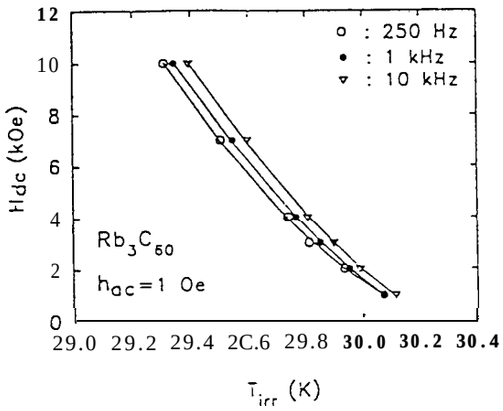
T_c of the Rb_3C_{60} sample, determined from the onset of X' at low h_{ac} and $H_{dc}=0$ Oe, is 30.8 K. The imaginary part X" shows a narrow peak near T_c (intragranular) and a broad peak at low temperature (intergranular). We will focus our discussion only on the intragranular peak hereafter. By assigning the temperature of the maximum of χ'' to be the irreversibility temperature T_{irr} [3], ILs at three different frequencies and $h_{ac}=1$ Oe are shown in Fig. 1. T_{irr} decreases with increasing H_{dc}; however, the effect is relatively weak. For instance, at the largest applied $H_{dc}(1T)$, T_{irr} lowers than $T_{irr}(H_{dc}=0)$ only by 0.8 K. The ILs in Fig. 1 also exhibit a dependence on frequency; IL shifts to high temperature with increasing f. The $T_{irr}(H_{dc})$ curves in Fig. 1 are fitted with the scaling relationship $H_{dc}=H_{irr}(0)(1-T_{irr}/T_0)^n$ with $H_{irr}(0)$, T_0 and n as fitting parameters. For the curve of $f=10$ kHz, the fit yi' elds n = 1.5, T_0 = 30.3 K, and $H_{irr}(0)$ = 188 T. The fit for the 1 kHz curve yields practically identical values for three parameters. However, for the 250 Hz curve, we obtain $H_{irr}(0)$ = 360 T, T_0 = 30.3 K, and n = 1.74. These fits yield T_0 lower than T_c and unphysically large $H_{irr}(0)$. Because ac susceptibility techniques normally probe the superconductivity behavior very near T_c parameters like $H_{irr}(0)$, that obtained from fitting the data of a very limited temperature range then extrapolated to 0 K, can have very large errors. Hence we emphasize that the fitted parameters n and T_0 are probably only meaningful near T_c. We also found that if T_0 is set to T_c, the quality of fit is not as good as that shown in Fig. 1.

As depicted in Fig. 1, at a given H_{dc}, T_{irr} shifts to higher temperature as f is increased. Our experiment shows that the effect is enhanced as H_{dc} or h_{ac} is increased. As f increases from 1 kHz to 10 kHz, the amount of shift in T_{irr}. is about 40 mK. This f-dependence of T_{irr} is shown in Fig. 2, where lnf is plotted against $1/T_{irr}$ for different H_{dc}; lnf exhibits roughly a linear dependence on $1/T_{irr}$. The right y-axis in Fig. 2 is plotted on linear f scale; the dependence of $1/T_{irr}$ on f is clearly nonlinear.

The imaginary part X" corresponds to the power losses of a superconductor in an ac magnetic field. X" could originates from either flux-flow or flux pinning. Flux-flow losses arises from the viscous motion of flux lines driven by the ac field. Clem has shown that for this case [4], X" maximizes when $a\sqrt{2/\delta_f}=2.5$, here δ_f is the skin depth and is proportional to $(\rho_f/f)^{1/2}$, where ρ_f is the flux-flow resistivity. Thus T_{irr} depends strongly on f through the f-dependence of ρ_f. Chen obtained the expression, $1-T_{irr}/T_c=[H/H_{c2}(0)](f_0/f)$, for flux flow T_{irr} [5], where f_0 is a characteristic frequency. The relation predicts a linear dependence on $1/f$ for T_{irr}.

In the case of flux-pinning, X" maximizes when h_{ac} just the center of a superconductor. At $T > 0$ K, the pinned flux lines can move via thermally activated flux creep (TAFC). The effect of TAFC on ac susceptibility has been calculated by Müller for high-temperature superconductors (HTS) [6]. He shows that T_{irr} shifts to higher temperature with increasing f; further, lnf depends linearly on $1/T_{irr}$. This is a much weaker f-dependence than the 1/f-dependence expected for flux flow. The result in Fig. 2 is consistent with Müller's prediction. Moreover, similar dependence has been observed on HTS by several groups and the results were interpreted by the TAFC effect in the samples [3,6]. Consequently the linear relation in Fig. 2 is interpreted by a TAFC effect in the Rb_3C_{60} sample.

The temperature associated with χ''-peak for the Rb_3C_{60} crystals exhibits a dependence on frequency. The results are attributed to thermally activated flux creep in the



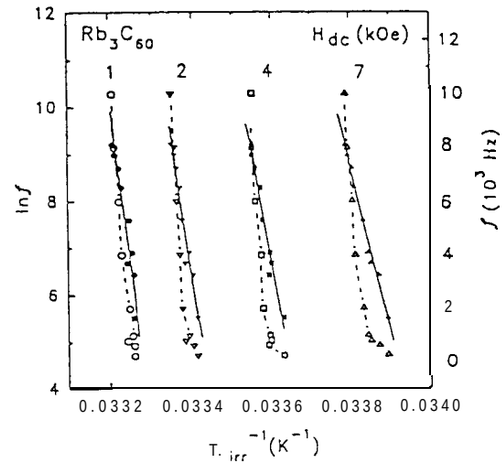


FIG. 1. Irreversibility line $T_{irr}(H_{dc})$ for Rb_3C_{60} crystals at three ac driving frequencies. T_{irr} was determined from the temperature of the maximum in χ''.

FIG. 2. Inverse irreversibility temperature $1/T_{irr}$ vs. logarithmic f (solid symbols), and f (empty symbols) at various static magnetic field H_{dc}. Here h_{ac} = 1 Oe.

fullerene.

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References

[1] J. B. Shi, M.M. Lee (unpublished).
[2] M. W. Lee, M. F. Tai, S. C. Luo, and J. B. Shi, Physica C245, 6 (1995).
[3] A. P. Malozemoff. T. K. Worthington, Y. Yeshrun, F. Holtzberg, and P. H. Kes, Phys. Rev. B38, 7203 (19%).
[4] J. R. Clem, in *Magnetic Susceptibility of Superconductors and Other Spin Systems*, edited by R. A. Hein, T. L. Francavilla, and D. H. Liebenberg, (Plenum, New York, 1992), p. 177.
[5] Q. Y. Chen, in ref. 4, p. 81.
[6] K. H. Müller, Physica C168, 585 (1990).
[7] There are many papers on this subject. Here we can only refer to some of the earlier ones-: N. Nikolo and R. B. Goldfarb, Phys. Rev. 39, 6615 (1990).