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Temperature dependence of the magnetic hysteresis of a $YBa_2Cu_3O_{7-\delta}$ single crystal.

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Magnetic hysteresis loops (MHL) have been measured on a single crystal of $YBa_2Cu_3O_{7-\delta}$ using a QD MPMS SQUID magnetometer. The MHLs were recorded in the temperature range 4.4 to 70 K in magnetic fields up to ± 5 T. A 'fishtail' shape of the MHL was observed at temperatures between 10 and 65 K. Position of the fishtail maximum scales well with $(1 - T/T_c)^{1.78}$ but the corresponding magnetic moment value does not scale to a single temperature function. The MHL size drops much more rapidly with increasing temperature at $T < 20$ K than in the intermediate range (20 to 50 K) where the decrease is proportional to $\exp(-T/13\mathrm{K})$. At $T > 55$ K the character of MHL changes strongly and it seems to become controlled by surface barrier effects. *

A detailed study of the shape of the magnetic hysteresis loop (MHL) and its development with temperature has been performed on the $YBa_2Cu_3O_{7-\delta}$ single crystal by means of a QD MPMS SQUID magnetometer. The sample of the dimensions $a \times b \times c = 1 \times 1 \times 0.015$ mm^3 was prepared by the slow-cooling method described in Ref. [1]. Zero-field-cooled magnetisation curve measured at the applied field $B_e = 0.5$ mT indicated the onset of superconductivity at 84.0 K. This value was taken as T_c in calculations. Figure 1 shows the temperature scan of the irreversible magnetic moment calculated as a half of the MHL size. From this plot several remarkable features follow. The fishtail character of the MHL is clearly evident for practically all the investigated temperature range. Only at the lowest temperature, 4.45 K, there is only a slight kink evident on the curve instead of the fishtail minimum. The depth of the fishtail minimum first increases with rising temperature but at about $T \approx 50$ K it starts to decrease again and above 70 K it disappears at all and the MHL transforms into a plateau. The dash line in fig. 1 indicates the field of full flux penetration approximated as $B_{\mathrm{pen}} \approx 3\mu_0 M_{\mathrm{pen}}/|\chi_0|$ where M_{pen} is the magnetic moment at the penetration field and χ_0 is the differential susceptibility. The fishtail minimum lies consistently close to but outside the region delimited by B_{pen}.

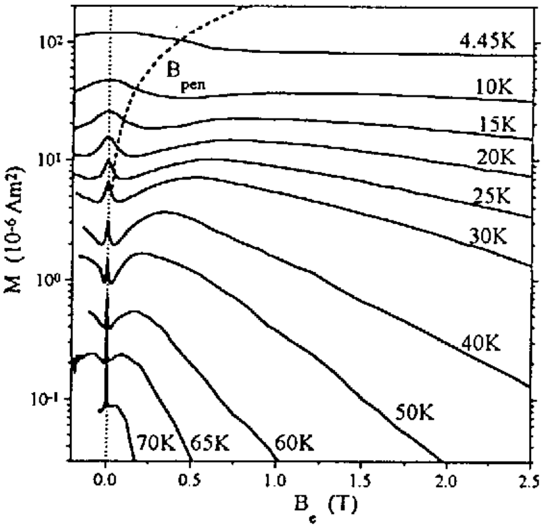

Figure 1: Temperature scan of the irreversible magnetic moment M obtained as a half of the MHL height.

We tried to find the scaling law for the fishtail maximum. Plots of the position and the corresponding magnetic moment value as a function of temperature [2] are shown in figure 2. Whereas the position of the fishtail maximum scales in a wide

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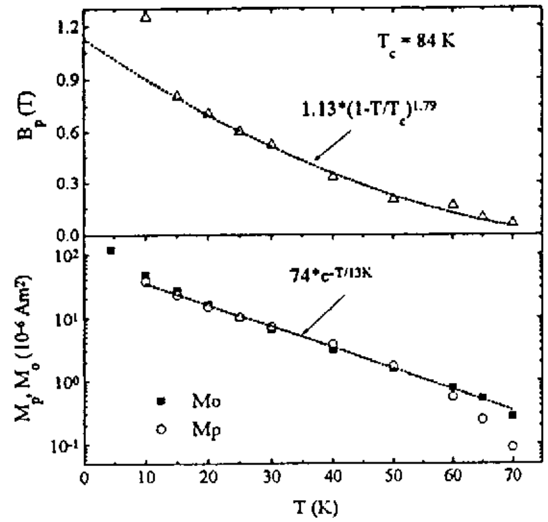

Figure 2: Temperature dependence of the position B_p (a) and the height M_p (b) of the fishtail peak. The $M_p(T)$ dependence is compared with $M_0(T)$, the height of the central peak.

temperature range (except the lowest temperatures) with $(1 - T/T_c)^{1.78}$, fig. 2(a), magnetic moment at the fishtail maximum M_p decays exponentially with increasing temperature as $\exp(-T/13\mathrm{K})$, fig. 2(b). Again, at high temperatures (above 60 K) magnetic moment departs strongly from this dependence. It is interesting to note that the same temperature dependence as that exhibited by height of the fishtail maximum is also obeyed by the central peak height denoted in fig. 2(b) as M_0.

The as measured data of the magnetic hysteresis loops recorded at different temperatures were normalized with respect to the fishtail peak coordinates (B_p, M_p) to test quality of the scaling. The MHL for 4.45 K which does not exhibit fishtail maximum explicitly, was normalized using the values of B_p and M_p) extrapolated from higher temperatures. The results are shown in fig. 3. It is evident that the scaling is quite good in the intermediate temperature range but fails both at low and high temperatures. Also the high-field parts of the curves do not fit the same universal curve well. The explanation of this inconsistency lies mostly in the experimental conditions. Reading of each experimental point recorded with the SQUID magnetometer starts after some 2 minutes after the stop of the field sweep. It depends on the rate of relaxation (which is both field- and temperature dependent) in how much relaxed state the measurement is done. It explains the rather strong departure of M at low temperatures from the scaling law obtained at intermediate temperatures. The relaxation rate increases considerably at fields above the fishtail maximum [3, 4]. Due to this the $M(B_e)$ curves obtained by SQUID magnetometer (fig. 1) do not run in parallel as they do when the relaxation rate is constant [4] but they spread into a fan.

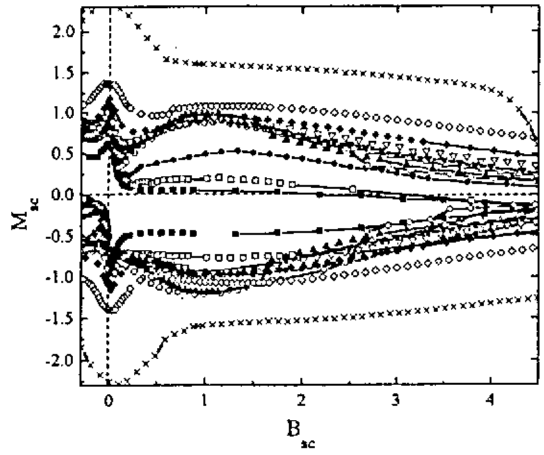

Figure 3: Magnetic hysteresis loops normalized with respect to the position and height of the fishtail peak, $B_{sc} = B_e/B_p$ and $M_{sc} = M/M_p$. Temperatures are the same as in fig. 1.

At high temperatures character of the MHL changes completely and cannot be explained only by the change of the relaxation rate. The sensitive SQUID measurements enable to detect details of the slight signal at these temperatures and show that the fishtail-like MHL converts into the shape typical for the flux motion governed by the surface barrier effects [5, 6, 7]. It represents a link to the arrow-head shape of MHL observed on the compounds like $YBa_2Cu_4O_8$ [5] or $Bi_2Sr_2CaCu_2O_8$ [8]. In both cases the narrow neck of the MHL occurs at rather high temperatures where vortices probably transform from the 3D threads into separate, relatively free pancakes which can easily exit the sample if the applied field is being reduced.

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