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Flux pinning and irreversibility in $YBa_2Cu_3O_7$ superconducting crystal

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Extensive ac-magnetic-permeability studies have been carried out on the irreversible behavior and flux dynamics in superconducting $YBa_2Cu_3O_7$ crystals in external magnetic fields up to 7.5 T. From the analysis the irreversibility line $B^*(T^*)$ is found to scale as $(1-T^*/T_c)^n$, where $n \simeq 1.5$ for fields higher than 1.5 T, and $n \simeq 1$ for lower fields. The exponents are sensitive to the choice of T_c. The frequency dependence of the irreversibility temperature is carefully studied in the low-frequency region from 10 to 10^5 Hz and is found to be logarithmic in the whole frequency range. The small logarithmic slope increases with increasing external field. The analysis is done within a flux-creep picture using a single-relaxation-time form for the complex permeability, and a vortex-glass model. The peak in the imaginary part of the permeability in different dc fields is successfully fitted to the predictions of the flux-creep model. A dynamical screening length is needed to account for the observed frequency dependence of the irreversibility temperature.

An important aspect of high-T_c superconductors is their transport properties in an external magnetic field. The study of these properties has revealed unusual flux dynamics and has become a topic of central importance in current high-T_c research.[1] The so-called irreversibility line marks the boundary between reversible and irreversible regions in the B-T plane.[2] From ac-permeability measurements a point on the irreversibility line is determined from the maximum in the imaginary part of the permeability as a function of temperature for a given applied dc field and measuring frequency. Previous studies of the irreversibility line have been made by dc resistivity,[3,4] dc magnetization,[5,6] and ac-permeability[7,8] measurements. The irreversibility line has been analyzed in terms of thermally activated flux creep. In addition, the frequency dependence of the irreversibility line has been analyzed both in terms of the flux-creep model and a thermodynamic glass-to-liquid transition, both analyses leading to different vortex relaxation rates.[9] A full description of the irreversibility line within the flux-creep model requires the determination of the pinning potential as a function of temperature, magnetic field, and current, as well as parameters characterizing the escape rate of flux lines from pinning sites.

In this paper we report careful measurements of the complex ac permeability, $\mu = \mu' + i\mu''$, on a high-quality single crystal of $YBa_2Cu_3O_7$. The measurements were made with an excitation field $B_{ac} = 3\times10^{-4}$ T in the temperature range 65–95 K, employing frequencies from 10 to 10^5 Hz and external magnetic fields up to 7.5 T. Previous studies of the irreversibility line[2] have been made with higher frequencies (10^4–10^8 Hz). In our study the external magnetic field was always applied parallel to the crystallographic c axis. The irreversible behavior of the superconducting crystal is analyzed within a flux-creep model using a single-relaxation-time form of the complex permeability. To account for the frequency dependence of the irreversibility line a dynamical screening length $\delta \simeq \omega^{-1/2}$ is introduced.

The Y-Ba-Cu-O single crystal was prepared as described in Ref. 10. It has the shape of a platelet with dimensions of about $1.5\times1\times0.3$ mm^3.

In our ac-permeability measurement an adjustable ac-magnetic-excitation field generates an induced voltage in a pick-up coil wound around the sample, inside the excitation coil. The pick-up voltage is proportional to the complex permeability of the sample. Real (in phase) and imaginary (out of phase) parts are recorded separately.

The movement of flux in a type-II superconductor is determined by two main mechanisms: flow and pinning, the latter leading to flux creep[11] at finite T. Recently, a model[12] has been developed explaining the dissipation from flux dynamics, giving flow and creep in the respective limits and correctly reproducing the crossover in the resistivity.

Our ac-permeability measurements were performed employing relatively low frequencies (10–10^5 Hz), corresponding roughly to the flux-creep regime seen from resistivity measurements,[13] i.e., $\rho/\rho_0 \approx f/f_0$. In the analysis of our data we, therefore, consider flux creep but not pure flow. The excellent fit of data to the predicted equations support this approximation.

Alternatively, a thermodynamic glass-transition model[1,9] similar to spin glasses has been used to fit the observed frequency dependence of the irreversibility line. In this model the vortex relaxation time shows a power-law scaling near T_c. Expressed as a frequency one finds $f = f_0(1-T/T_g)^{z\nu}$ in the critical region implying a strongly diverging relaxation time at T_g. In glass models νz is expected to be in the range 4–8. T_g is the glass transition temperature and f_0 is a microscopic-scaling frequency.

In the flux-creep model the connection between the ac permeability and the applied ac field can be found by using the following argument: Due to the thermally activated creep, flux will penetrate the sample in a time of order $\tau = (a/Rl)$, where R is a flux-creep rate, a is a macroscopic distance describing the depth of penetration of the flux, and l is a typical distance between pinning sites. It will turn out that at least one of these quantities is frequency dependent. In the analysis of the permeability we assume homogenous magnetization of the sample in a dc-magnetic field and treat the applied field as a perturbation.[14] This gives to first order

$$\frac{dB}{dt}=(B_{\rm eq}-B)/\tau \ , \tag{1}$$

where the equilibrium field $B_{\rm eq} \simeq B_{\rm dc}+B_{\rm ac}$ is a sum of the dc field and the applied-ac-field amplitude. The resulting expression for the complex permeability is of the familiar Debye form

$$\mu'=\frac{1}{1+(\omega\tau)^2} \ , \tag{2a}$$

$$\mu''=\frac{\omega\tau}{1+(\omega\tau)^2} \ . \tag{2b}$$

The relaxation time τ is expected to be of the order

$$\tau=(a/f_0 l)\exp(U/kT) \ . \tag{3}$$

Here f_0 is an attempt frequency and k is the Boltzmann constant. The pinning potential U will be a function of T, B, and J.

The maximum in μ'' occurs when $\omega\tau=1$ and determines the irreversibility temperature, $T^*(B^*)$, for a given measuring frequency and applied field. The irreversibility line is not an intrinsic property, but will, in general, depend on imperfections like twinning, doping, precipitates of other phases, sample size, and also observation time. By applying the criterion $\omega\tau=1$, we find the following relation for the irreversibility line,

$$U/kT^*=-\ln(\omega\tau_0) \ , \tag{4}$$

where $\tau_0=(a/f_0 l)$. Here $U=\frac{1}{2}\mu_0 H_c^2(T)V_c$, where $H_c(T)$ is the thermodynamic critical field and V_c is a volume depending on the nature of pinning and on the field and current regime in which the measurement is performed. For large applied fields flux will penetrate the whole sample giving[2] $V_c \simeq a_0^2\xi(T)$, where $a_0 =1.075(\Phi_0/B)^{1/2}$ is the flux line spacing in a field B. In small applied fields we present an argument for the volume V_c, leading to another exponent in the temperature dependence of the pinning potential. This is due to a dimensional crossover in the vortex distribution. In low fields along the c direction flux will mainly end up in the relatively strongly pinning twin planes, and we find $V_c \simeq a_t\xi(T)^2$, where $a_t \simeq (\Phi_0/Bd)$ is the flux-line spacing along the twin planes and d is the distance between twin planes. From the Ginzburg-Landau theory: $\xi \sim (1-T/T_c)^{-1/2}$ and $H_c \sim (1-T/T_c)$ for large κ. This will lead to the T and B dependences of the pinning potential

$$U=A_j(1-T/T_c)^n/B \ , \tag{5}$$

with $n=1.5$ for large B, and $n=1$ for small B when twin planes are dominant pinning sites.

For the irreversibility line Eq. (4), this leads to

$$A_j(1-T^*/T_c)^n/kT^*B^*=-\ln(\omega\tau_0) \ . \tag{6}$$

Combining Eq. (2b), Eq. (3), and Eq. (5), and using $\omega\tau=1$ we find

$$\mu''=[\exp(x)+\exp(-x)]^{-1} \ , \tag{7}$$

with

$$x=\frac{A_j}{kB^*}\left[\frac{(1-T/T_c)^n}{T}-\frac{(1-T^*/T_c)^n}{T^*}\right] .$$

Equation (7) was used to fit the imaginary part of the permeability measured at fields in the range from 2 to 7 T and frequency $f=121$ Hz. This is shown in Fig. 1. The current-density dependent parameter A_j is found to be (3.3 ± 1) T for $n=1.5$. According to Eq. (2b) the maximum in the imaginary part should always be $\frac{1}{2}$. From Fig. 1 we see that the maximum in μ'' increases with increasing field. This growth with field is even stronger for lower fields. To fit the data we therefore scaled Eq. (7) with an amplitude factor. The correspondence between the predicted curve, Eq. (7), and the measured values is best near the top of the peak. The degree of asymmetry of the curves may depend on ac-field amplitude and on sample quality.[15] Possibly, the linear model is too simple, and so anharmonic effects may have to be included.

The irreversibility line in Fig. 2 is determined from the maximum in the imaginary part of the permeability in different applied fields (0–7.5 T). The curve can be fitted to the predicted formula for the irreversibility line [Eq. (6)] by rewriting this equation as

$$B^*=C(\omega)(1-T^*/T_c)^n/T^* \ , \tag{8}$$

where $C(\omega)=-(A_j/k)\ln(\omega\tau_0)$. $T_c=88.2$ K, is determined from the onset of superconductivity in μ' in zero field. This onset value of T_c will always be larger than the irreversibility temperature at $B=0$ as was used by Malozemoff *et al.*[2] in their analysis of the irreversibility line. We find the exponent for the temperature dependence $n=(1.50\pm0.05)$ at applied fields higher than 1.5 T. At lower fields we observe an almost linear decrease of the irreversibility field versus temperature, corresponding to $n=1$. However in this region we had to use $T_c=86.2$ K to fit the data. This indicates the interesting possibility of

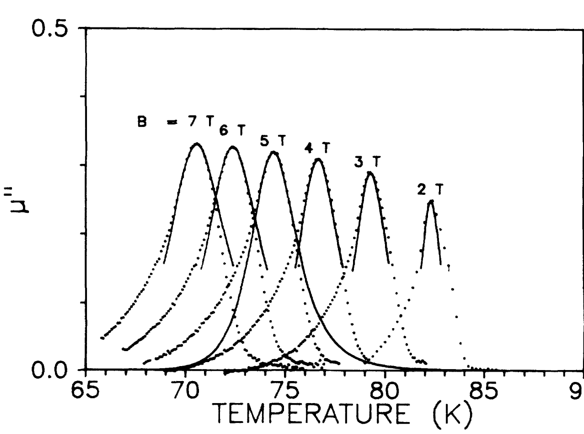

FIG. 1. The imaginary part of the complex ac magnetic permeability vs temperature in different external fields from 2 to 7 T ($\mathbf{H}\parallel c$) on an Y-Ba-Cu-O single crystal. The solid lines represent fits to these data using Eq. (7).

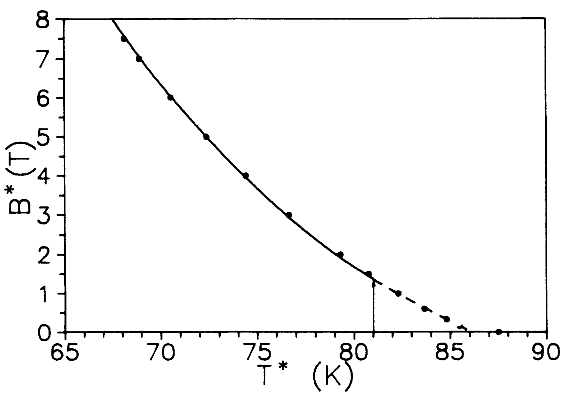

FIG. 2. The irreversibility line $B^*(T^*)$ in the field range 0 to 7.5 T ($\mathbf{H}\parallel c$) determined from ac permeability measurements on an Y-Ba-Cu-O single crystal with $f=121$ Hz and $B_{ac}=3\times10^{-4}$. The solid and dashed lines represent theoretical fits using Eq. (8), with exponents $n=1.5$ for fields higher than 1.5 T and $n=1$ for fields lower than 1.5 T.

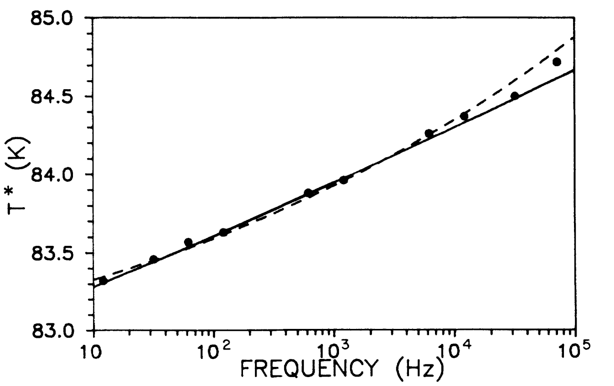

FIG. 3. The irreversibility temperature determined from the maximum in the imaginary part of the ac permeability, measured on an Y-Ba-Cu-O single crystal with $\mathbf{H}\parallel c$ as a function of frequency. Fits to flux-creep model (solid line) and glass-liquid-transition model with $T_g=82.3$ (dotted line).

a superconducting region without irreversibility at low fields in a small temperature region below T_c. The exponents, $n=1.5$ and 1 and the experimentally determined B dependence, agree with the T and B dependence of the pinning potential in the high- and low-field regions predicted in Eq. (5). It is crucial to note that a different choice of T_c equal to the irreversibility temperature in zero field, $B^*(B=0)$, gives an exponent $n\approx1.35$ instead of $n=1.5$ for the temperature dependence of the irreversibility line in fields higher than 1.5 T.

In the fit to Eq. (8) at $f=121$ Hz the parameter C(121 Hz)$=(4770\pm50)$ TK in the regime of $n=1.5$ and $C=(1850\pm70)$ TK when $n=1$. The only unknown parameter in the expression for C is τ_0, if we use the value of A_j found earlier. For $n=1.5$ we find τ_0 from the expression for C, giving $\tau_0=\omega^{-1}\exp(-A_j/kC)$, and inserting for the constants and the frequency we find τ_0(121 Hz)$=5\times10^{-7}$ s.

We have studied the frequency dependence of the irreversibility temperature T^* in the low-frequency range from 10 to 10^5 Hz and in different applied fields up to 7 T. A typical curve is shown in Fig. 3 for $B=0.6$ T. We observe a logarithmic increase in T^* with increasing frequency. The slope of the curve $dT^*/d\ln f$ is determined from the best logarithmic fit in the whole frequency range. The slope is found to increase with increasing field.

To further analyze the behavior of the irreversibility line close to T_c, let us approximate T^* by T_c in the denominator of the expression for the irreversibility line, Eq. (6). Using $n=1.5$ we obtain the relation

$$T^*\approx T_c\{1+[kT_cB^*\ln(\omega\tau_0)/A_j]^{2/3}\}\ . \tag{9}$$

We will now show that τ_0 is frequency dependent in contradiction to earlier reports where this parameter or the corresponding attempt frequency used by Malozemoff *et al.*[2] has been taken to be a constant value. Employing Eq. (9) for T^* versus frequency at $B^*=0.6$ T and using $n=\frac{3}{2}$ and $A_j=3.3$ eVT from the fit in Fig. 1 (Fig. 3, solid line), we find from the best fit $\tau_0\sim10^{-12}$ s. This value of τ_0 is an average value weighted over all frequencies and it is far less than the value found earlier at a fixed frequency $f=121$ Hz. We conclude that $\tau_0=(a/f_0l)$ is a frequency-dependent quantity. By applying Eq. (6) to all available data (Fig. 3) we find that τ_0 scales as $\omega^{-1/2}$. This observation and specifically, the frequency dependence, suggests that a dynamic screening length δ of skin-depth character is involved. In Fig. 4 we have plotted τ_0 versus frequency for $B^*=0.6$ T.

The dotted line in Fig. 3 is a fit to the glass-liquid-transition model giving a power-law scaling form of the frequency. This fit gives a glass transition temperature $T_g=82.3$ K and an exponent $z\nu=10$, which is larger than expected in glass models. Also the scaling frequency $f_0=1.1\times10^{20}$ Hz is too large to be a microscopic frequency. We conclude that the fit to the glass model gives unreasonable parameters νz and f_0 and therefore does not give an adequate description of our data.

If we substitute for the length a in the expression τ with an expression formally like the classical skin depth $\delta=(2/\mu_0\sigma\omega)^{1/2}$, we obtain for τ_0:

$$\tau_0=(\delta/f_0l)=[2\rho(T,B)/\mu_0f_0^2l^2]^{1/2}\omega^{-1/2}\ . \tag{10}$$

This formula expresses the observed frequency depen-

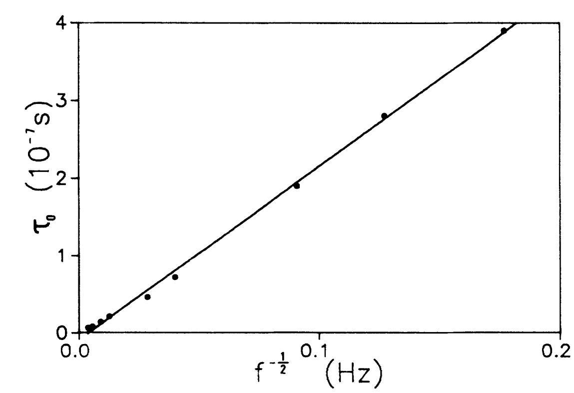

FIG. 4. τ_0 as a function of frequency found by applying Eq. (6) to all data in Fig. 3. The solid line represents a best fit and gives $\tau_0=2.2\times10^{-6}f^{-1/2}$.

dence correctly. An estimate of the attempt frequency f_0 and the flow length l can be made by inserting the observed value for $\tau_0 = 2.2\times 10^{-6}\omega^{-1/2}$ at $B=0.6$ T. This gives $f_0 l \approx 2\times 10^8 \rho(B,T)^{1/2}$. Taking the resistivity, $\rho(B,T)$, equal to 1×10^{-8} Ω m, gives $f_0 l \approx 10^3$ m s^{-1}. If we assume l to be of the order of the distance between twin planes (100 nm), we get $f_0 \sim 10^{10}$ s^{-1}.

In summary we have determined the irreversibility line in an Y-Ba-Cu-O single crystal with high accuracy and deduced two exponents for its temperature dependence, their value depending on the applied field. The logarithmic frequency dependence previously observed at high frequencies is shown to extend as far down as 10 Hz. A single-relaxation-time model gives a semiquantitative description of all $\mu(T)$ curves at all B fields using one set of parameters. It is further demonstrated that a dynamic screening length of skin-depth-type appears in the expression for the characteristic time of flux motion.

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