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Flux-pinning potential and its measurement from magnetization decay

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We present calculations of the magnetization decay for a zero-field-cooled sample subject to a field H. The calculations are within the framework of the critical-state model and assume that the current density decays exponentially with the field. The results provide a possible explanation for the reported anomalous increase of the pinning potential with field and temperature.

Measurements of the time decay of magnetization are being extensively used to infer[1-8] the pinning potential U_0 for high-temperature superconductors (HTSC). The well-established explanation of this magnetization decay is provided by Anderson's idea[9] of the thermal excitation of flux bundles, over an effective pinning potential, in the direction of the flux gradient. If one assumes that the effective potential is $U_e = U_0 - \alpha JB$, then one obtains (see Xu *et al.*,[4] and references therein)

$$M(t) = M_0[1 - (kT/U_0)\ln(1 + t/\tau)] , \quad (1)$$

where $\tau (\sim 10^{-6}$–10^{-12} s) is the characteristic relaxation time of a flux bundle. For $t \gg \tau$, one then obtains

$$U_0 = -(kTM_0)/(dM/d\ln t) , \quad (2)$$

and Eq. (2) has been used to extract U_0.

Magnetization-decay measurements at various temperatures (T) and applied fields (H) have, however, yielded[3,4,7] the unphysical results that U_0 rises as T rises, and also as H rises. Hagen and Griessen[3] first emphasized that the inferred U_0 rises with T in HTSC, and that this manifests itself in the experimental data as a peak in $|(1/M)(dM/d\ln t)|$. They have explained this T dependence by requiring that there be a distribution of U_0 in any sample; others[4,6,8] have invoked the idea of Beasley, Labusch, and Webb[10] that U_e is actually a nonlinear function of J. In this paper we shall pursue our earlier suggestion[11] that Eq. (1) is not valid in most experimental situations; that the critical-state model must be invoked, and that the field dependence of J_c can explain why $-(kTM_0)/(dM/d\ln t)$ rises with increasing T and H.

Magnetization-decay measurements have been reported, in both conventional superconductors and in HTSC, for samples cooled in zero field (ZFC) to a temperature T, subjected to a field H, and then H is either (i) maintained at constant value along with the temperature;[2,4-7,12-15] (ii) increased after a time t;[16-18] (iii) reduced to zero and only then measurements begin;[12,13,19] or (iv) held fixed and the decay is studied after cooling the sample to a lower temperature.[8,20] In addition, the magnetization decay has been studied in field-cooled samples, held at constant T, after the field is switched off.[21] It has generally been found that the magnetization decays logarithmically with time in all these cases, though careful measurements do show some deviations from this behavior.[6,15]

In all the experimental situations mentioned in the previous paragraph, the sample is subjected to an isothermal field variation, and shielding currents are set up in accordance with the critical-state model. The large values of J_c imply that $B(\mathbf{r})$ varies sharply within the sample, and this flux profile will also vary as the shielding currents decay. The critical-state model was first invoked, to explain the details of magnetization decay in HTSC, by Yeshrun *et al.*[2] They basically assumed constant-B shells in the sample, where the shielding current at each shell decays because of flux creep as

$$J_c(t) = J_{c0}[1 - (kT/U_0)\ln(t/\tau)] . \quad (3)$$

This results, to first order in kT/U_0, in the magnetization decaying as

$$M(t) = M_0[1 - (kT/U_0)A(H)\ln(t/\tau)] . \quad (4)$$

In this scheme $A(H)$ does not depend on the absolute value of H but on the ratio H/H^*, where $H^* = J_c(T)D/2$ is Bean's parametric field for a sample of transverse dimension D. Bean had assumed that J_c is independent of field, and it is then easily shown[2,5,22] that $A(H)$ increases with H for $H \leq H^*$, and is constant for $H \geq H^*$. In actual practice J_c for HTSC decreases sharply with increasing field, and magnetization measurements indicate that this decrease is exponential.[23,24] The decay rate can be characterized by another parametric field H_0. $M(t)$ is then obtained[2,22] in the form of Eq. (4) where $A(H) = A[H, H^*(T), H_0(T)]$ has an implicit temperature dependence through $J_c(T)$ and $H_0(T)$. It has been our contention[11] that the T and H dependences attributed by the use of Eq. (2) to U_0, actually may have a major contribution from $A[H, H^*(T), H_0(T)]$. Equation (2) should thus be replaced by

$$U_0 = kTA[H, H^*(T), H_0(T)][-M_0/(dM/d\ln t)] . \quad (5)$$

If the actual U_0 is independent of T and H, and we use Eq. (2) to infer the pinning potential (which is denoted by U^*), then since

$$U^* = U_0/A[H, H^*(T), H_0(T)] ,$$

the inferred T and H dependences of U^* are actually the T and H dependences of A. Similarly, the peak[3] in $[(-1/M_0)dM/d\ln t]$ is then attributed[11] to a peak in kTA. In this paper we present calculations to substantiate this contention.

Before presenting our calculation we must stress that

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Eq. (5) has been successfully used, with a constant value for U_0, to explain[2,5,22] the field dependence of $dM/d\ln t$ at small H for ZFC samples in the field-on case, the sample-size dependence of the decay rate in this case, and also[22] the smaller decay rate (by a factor of 3–4) observed[12] for ZFC samples in the field-off case. Kunchur, Poon, and Subramanian[18] have used this equation to explain the memory effect[16–18] seen in magnetization decay.

We have earlier[22] calculated $A(H,H^*,H_0)$ for a sample in the shape of an infinite slab, with the assumption that J_c decays exponentially with H as

$$J_c(T,H)=J_c(T,0)\exp[-|H|/H_0(T)]\,. \tag{6}$$

For a ZFC sample exposed to a field $H<H_l$, where $H_l=H_0\ln(1+H^*/H_0)$ is the minimum field for full penetration, we have

$$A(H,H^*,H_0)=\left[\frac{(H^*H/H_0^2)\exp(-H/H_0)}{(H/H_0)-1+\exp(-H/H_0)}-1\right]^{-1}. \tag{7}$$

For $H>H_l$, we have

$$A(H,H^*,H_0)=\left[\frac{(H^*/H_0)\ln[1-(H^*/H_0)\exp(-H/H_0)]}{(H^*/H_0)+\exp(H/H_0)\ln[1-(H^*/H_0)\exp(-H/H_0)]}-1\right]^{-1}. \tag{8}$$

For incorporating the T dependence, we provide as an experimental input the data of Hampshire, Chan, and Larbalestier.[25] For epitaxial thin films of $YBa_2Cu_3O_7$, they found that for fields along the c axis and transport currents in the ab plane, an exponential law holds over large ranges of H and T. For 20 K $<T<$ 70 K, they fit their data to Eq. (6) with $J_c(T,0)=5.2\times10^5[1-(T/75)^2]$ amp/cm^2 and $\mu_0H_0(T)=1250/T^2$ tesla. Using these experimental temperature dependences, we have calculated $A[H,H^*(T),H_0(T)]$ for various sample dimensions. In Fig. 1 we show typical results for $kTA(H,H^*,H_0)$, which would be the observed $[-(1/M_0)dM/d\ln t]$ for a constant U_0. Our calculations show a peak in $A(H,H^*,H_0)$ at $H=H_l$, and the plots of kTA in Fig. 1 mimic some of the temperature dependences reported for $|(1/M_0)dM/d\ln t|$ (see Fig. 1 of Ref. 3). We note that the peak shifts to lower temperature as H is increased. In Figs. 2 and 3 we note that $U^*=U_0/A(H,H^*,H_0)$ increases with increasing H, and also with increasing T, for $H>H_l$. The use of Eq. (2) instead of Eq. (5) for obtaining U_0 from experimental $(1/M_0)dM/d\ln t$ would shift the T and H dependence of A to the inferred U^*.

While we have chosen the transport measurements of Hampshire, Chan, and Larbalestier[25] for our analysis, we note that the details of $J_c(T,H)$ may vary from sample to sample because of weak links, twinning, microstructure, etc. We wish to point out that a different T dependence of H^* (Fig. 4), or a different set of values for H_0 (Fig. 5), do reproduce (and, in fact, enhance) the peak in kTA [and thus in $(-1/M_0)dM/d\ln t$] as a function of temperature. Calculations of $A(H,H^*,H_0)$ are available for samples in the shape of a cylinder,[26] and the peak in kTA would still

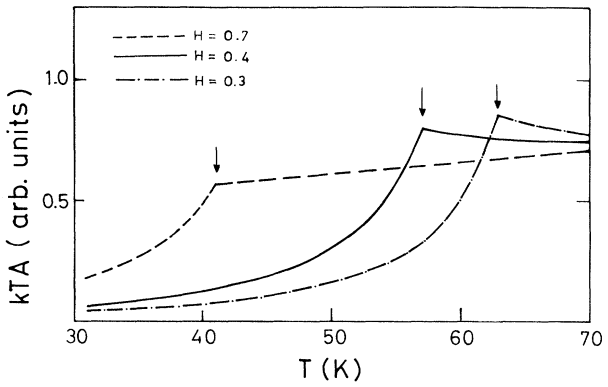

FIG. 1. We plot the temperature dependence of $kTA(H,H^*,H_0)$ for different values of H (indicated in tesla). $H^*(T)$ and $H_0(T)$ follow Ref. 25. For a constant U_0, this is the calculated T dependence of $(-1/M_0)dM/d\ln t$. The sample is assumed to have $D=0.5$ mm, and the arrows indicate the temperature at which the applied $H=H_l(T)$.

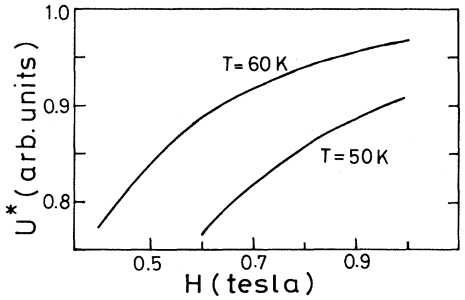

FIG. 2. Following the calculations shown in Fig. 1, we plot $U^*(H)$ at two temperatures. $H>H_l$ throughout, and U_0 is assumed to be constant.

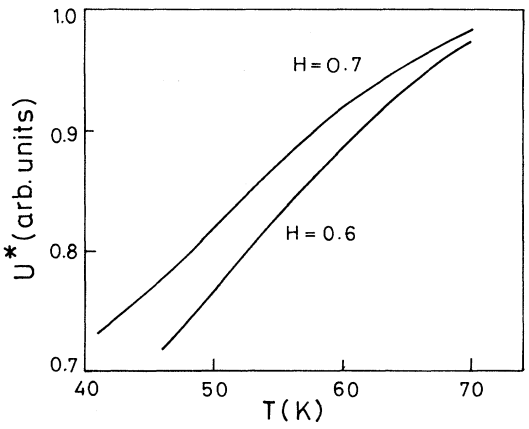

FIG. 3. For a constant U_0, we plot $U^*(T)$ at two fields (indicated in tesla). $H>H_l$ throughout, and A is calculated as in Fig. 1.

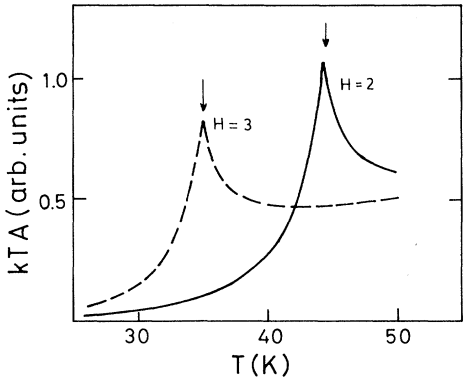

FIG. 4. Same as Fig. 1 except that $H^*(T)$ is assumed to vary as $1/T$. We assume that $H^*(20\ \mathrm{K}) = 31.5$ tesla.

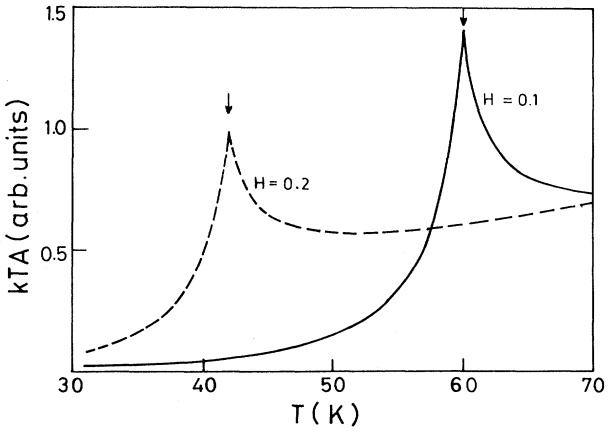

FIG. 5. Same as Fig. 1 except that $H_0(T)$ is smaller throughout by a factor of 10.

be seen at the temperature T_0 where $H_l(T_0) = H$. Similarly, the fact that A decreases with increasing H for $H > H_l$ is common to the three forms[27] of $J_c(H)$ in current usage.

The pinning potential U_0 is, in general, a function of both T and H; its estimation from an experimentally measured $(d\ln M/d\ln t)$ requires the use of Eq. (5), with $A[H,H^*(T),H_0(T)]$ determined using Eqs. (7) or (8). The full penetration field $H_l(T) = H_0(T)\ln[1 + H^*(T)/H_0(T)]$ is easily determined experimentally from the isothermal-magnetization data (at T) as the field at which the ZFC virgin magnetization and the forward hysteresis curves merge.[28] $H_l(T)$ is also the field at which $dM/d\ln t$ shows a peak [provided $U_0(T,H)$ is a smooth function of H]. The hysteresis curve can also yield H_0 and thus H^*, with the provision that one uses the curve in the region $H > H_l(T)$.[28] H^* and H_0 can also be determined directly by transport measurements of $J_c(T,H)$—except that these are not possible for the grain-aligned powders used in some studies.[4,7]

To conclude, we have argued that the critical-state model must be incorporated when determining U_0 from the magnetization decay measured on samples subjected to isothermal-field variations. Most of the anomalous T and H dependences[4,7] predicted for U_0 may be attributable to the use of Eq. (2) instead of the more appropriate Eq. (5).

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