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Critical fields and critical currents of superconducting disks in transverse magnetic fields

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The large nonuniform and field-dependent demagnetizing factors of superconducting disks in transverse magnetic fields complicates the determination of the lower critical field and critical current from magnetization. Correcting the applied field with a constant ellipsoidally approximated demagnetization correction D' can result in significant errors. In this study of the magnetization characteristics of lead and Nb-Ti disks with various aspect ratios a, we find an empirical relation $D'(a)$ that describes the scaling of the applied-field value H_c' (H_{c1}'), at which flux penetration occurs, with respect to the intrinsic (lower) critical field H_c (H_{c1}). A model is described for determining H_{c1} and J_c for such a geometry. The results have important implications for various magnetic measurements in high-T_c superconductors. The errors that can result in the measured values of H_{c1} and J_c, in the inferred penetration depths, and in the effective-mass anisotropies, are discussed.

Much information about the fundamental parameters of high-T_c superconductors has been obtained through various types of magnetization measurements on single crystals. A potential complication in any measurement of magnetization is the presence of a demagnetizing field. This is especially serious for fields transverse to the Cu-O planes ($H^{\perp}$) because many of the crystals are in the shape of thin platelets with the Cu-O planes parallel to the large faces. In a measurement such as that of the upper critical field H_{c2} (involving the reversible magnetization near T_c), the average susceptibility is small, making the demagnetization correction negligible. However, in measurements of the lower critical field H_{c1} and the critical current density J_c, there is a large, spatially nonuniform, and field-dependent demagnetizing field. The overall effect is that the sample experiences an average field H, which is enhanced over the applied field H_0, by a factor D'. As a result, the apparent volume $V_{\text{app}} = -4\pi(dm/dH_0)$ (the initial magnetization slope) is larger than the geometric volume V, by a factor D'_{vol}. In addition, the applied field at which flux first penetrates (H_c' or H_{c1}') is suppressed with respect to H_c (type I) or H_{c1} (type II) by a factor $(D'_{H_c})^{-1}$.

Ellipsoids are the only shapes that become homogeneously magnetized and for which the demagnetizing factor D can be readily calculated. In this case the net field experienced by the body is $H = H_0/(1+D4\pi\chi)$, where χ is the volume susceptibility. In the Meissner state of a superconductor $\chi = -1/4\pi$ so that $H/H_0 = 1/(1-D_{\text{ell}}) = D'_{\text{ell}}$, where D_{ell} is the usual demagnetizing factor for an ellipsoid (for which formulas and tables are available[1]). Henceforth all demagnetizing corrections will be described in terms of the inverted demagnetizing factors defined by $D' = 1/(1-D)$.

In the literature on high-T_c superconductors, the common practice appears to be to substitute D'_{H_c} with either D'_{vol} or D'_{ell}. It is not obvious that D'_{vol} and D'_{H_c} should be the same, and it is unclear how well either of these is approximated by D'_{ell}. Furthermore, even for an actual ellipsoidal shape, for large eccentricities it has been shown by Saif[2] that nucleation of flux lines occurs at an applied field larger than that of the corresponding demagnetization-corrected (i.e., divided by D'_{ell}) H_{c1}. In this study of the magnetization characteristics of type-I (lead) and type-II (Nb-Ti) superconducting disks, we find that D'_{H_c} and D'_{vol} are material-independent functions of the diameter-to-thickness aspect ratio a. For all aspect ratios measured $D'_{\text{ell}} > D'_{\text{vol}} > D'_{H_c}$—the inequalities increasing with a and becoming negligible for $a \sim 2$. Note that this error in the demagnetization correction will be present in the measured H_{c1} for all methods that rely on an onset of flux penetration at a given temperature and applied field such as m versus H_0 isotherms (the most common method), zero-field-cooled dc magnetization versus temperature curves,[3,4] onset of magnetic relaxation,[5] and field dependence of the rf penetration depth.[6] Furthermore, most of these methods are also susceptible to a rounding of the onset region due to premature flux penetration (of weakly superconducting regions and sharp points) and pinning (which makes gradual the deviation from initial linearity of m versus H_0). The solution to the last problem is to fit the data to some sort of model (as has been done, for example, for the second and third methods[4,5]) rather than arbitrarily picking some point as the onset of flux penetration. In this work we describe a method for fitting the m versus H_0 data to unambiguously obtain H_{c1}; additionally, the fitting also provides a good estimate of the low-field J_c, overcoming the complications caused by the demagnetizing field to be described later.

Two types of samples were used for these experiments: disks of Nb-Ti, and disks and squares of lead. The Nb-Ti disks were cut from a rod of the material with a composition of 53 at. % Nb and a T_c of 9 K. The disks were etched in a solution[7] of HF (49%), HNO_3 (70.9%) and water (3:7:15) to remove the surface layer. The lead disks and squares were cut out of sheets pressed from 99.999%-pure pellets. These were then washed in mineral acid and solvents to clean the surface. Magnetization measurements were made in a commercial superconducting-quantum-interferance-device susceptometer (SHE model 905). Temperatures were stable within 0.01 K during measurement of the isotherms. During zero-field cooling, residual fields of up to 1.5 Oe were present. The maximum error in the field at all values was of a similar magnitude.

TABLE I. Inverted demagnetizing factors ($H^{\perp}$ orientation) from apparent H_c (D'_{H_c}), apparent volume (D'_{vol}), and ellipsoidal approximation (D'_{ell}). a is the aspect ratio.

a	D'_{H_c}	D'_{vol}	D'_{ell}
	Lead discs		
1.93	1.80	2.04	2.07
2.86	1.97	2.29	2.65
5.98	2.77	3.90	4.63
9.13	3.14	5.00	6.63
22.2	5.95	11.9	14.9
46.0	9.65	19.2	30.1
80.1	12.2	33.1	51.8
	Lead squares		
2.91	2.12	2.29	2.69
10.8	3.47	5.14	7.69
20.2	5.36	8.62	13.7

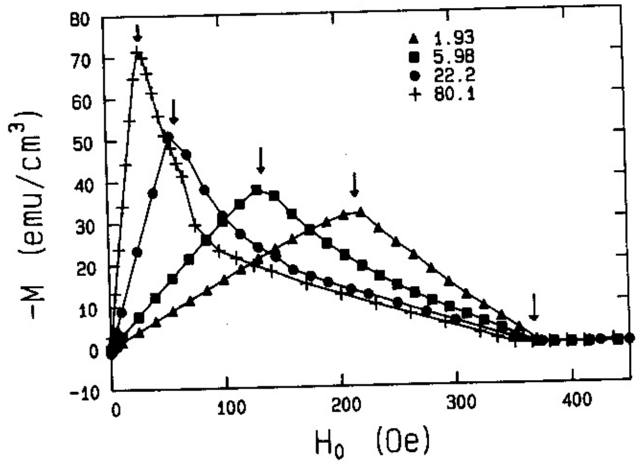

FIG. 1. Transverse-field magnetization at $T=5.5$ K of four lead disks (a's indicated in key). The arrows indicate H'_c, the field at which a sample enters the intermediate state (deviation from the initial linear behavior), and the critical field H_c (at which the magnetization extrapolates linearly to zero). The lines connect consecutive points.

Seven disks of lead were measured (at $T=5.5$ K) with aspect ratios ranging from 2 to 80. Figure 1 shows M versus H_0 for the disks with $a=1.93$, 5.98, 22.2 and 80.1; intermediate measured values of a have been omitted from the figure for clarity. Initially flux is completely excluded and the behavior is linear in H_0. From the slope we obtain the apparent-volume inverted demagnetizing factor $D'_{\text{vol}}=V_{\text{app}}/V=-4\pi(dM/dH_0)$, shown in the third column of Table I. At applied fields $H_0=H'_c$ (indicated by arrows in Fig. 1), the field at the edge of the disks exceeds the critical field; the sample enters the intermediate state of type-I superconductors, parts of it (initially a thin peripheral layer) becoming normal. The deviation from initial linearity that marks entry into the intermediate state also corresponds roughly to the peak in the M-H_0 curve—unlike the hard type-II case, where $H=H_{c1}$ is signaled by a gradual deviation in the M-H_0 curve and the peak at the higher field corresponds to complete flux penetration (H^*). As $H_0 \rightarrow H_c$ (marked by the last arrow in Fig. 1), M decreases linearly to zero. As expected, this H_c, which of course is an intrinsic property independent of shape, is about the same for all samples. The ratio H_c/H'_c equals D'_{H_c}, the inverted demagnetizing factor describing the scaling of the (lower) critical field, and is shown in column 2 of Table I. The fourth column shows for comparison the usual D'_{ell} for an ellipsoid of revolution with major-to-minor axes ratio equal to a; note that both an inscribed as well as escribed ellipsoid (with minimum volume difference) have the same a as the corresponding disk. The formula used for calculating D'_{ell} is[1]

$$D_{\text{ell}}=\frac{D'_{\text{ell}}-1}{D'_{\text{ell}}}=\frac{a^2}{(a^2-1)}\left[1-\frac{\arcsin[(a^2-1)^{1/2}/a]}{(a^2-1)^{1/2}}\right].$$

We find $D'_{\text{ell}}>D'_{\text{vol}}>D'_{H_c}$ throughout the measured range of a, the disparity increasing with a. These features can be seen more clearly in Fig. 2, which shows the three D's as functions of a. Also included in Table I (and shown in Fig. 2) are data for three lead squares. For the squares a was taken as $\sqrt{4/\pi}(l/t)$. As can be seen, the inverted demagnetizing factors of the squares behave just like those of the disks—an equivalence useful for high-T_c applications. An interpolation of the empirically found values of D'_{H_c} in Table I can now be used to find the H_{c1} and J_c of a hard type-II superconducting disk in transverse field—an application that is demonstrated below. It should be mentioned that the inequality found earlier between D'_{H_c}, D'_{vol} and D'_{ell} might be expected to be inverted for the $H^{\parallel}$ orientation (H_0 in the plane of the disk or plateletlike crystal). Some measurements made in this orientation indeed seem to support that expectation; however, this point will not be elaborated further since the magnitude of the discrepancy, and hence of its consequences, is much smaller for this field orientation.

For thin superconducting disks, Bean[8] and other critical-state models,[9,10] which describe the magnetization of a long cylinder in terms of the bulk J_c, are inaccurate unless $H_0 \gg M$. Experiments in conventional low-

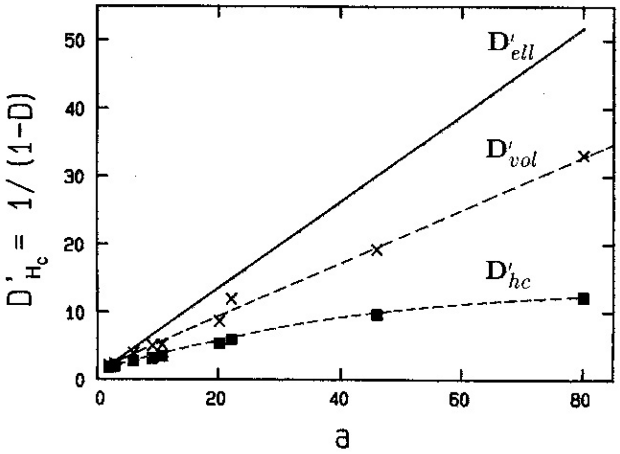

FIG. 2. Inverted demagnetizing factors of lead disks and squares. The dashed lines are guides for the eye.

T_c (Ref. 11) as well as high-T_c (Ref. 12) materials indicate that the flux front that penetrates a disk-shaped superconductor is initially cylindrical, but deviates from this geometry as it progresses into the sample. The critical state is finally reached through the faces (i.e., along the thickness) so that the field that is shielded or trapped in the center is of order $J_c t$ rather than $J_c r$, where t and r are the thickness and radius.[13] As the flux penetrates into the disk the demagnetizing factor decreases because of the decreasing average susceptibility. Matters are further complicated by the field dependence of $J_c(B)$, which is especially severe in high-T_c superconductors (see Ref. 10, and references therein). To overcome these difficulties we develop a model that describes the field dependence of the moment $m(H_0)$ for fields just above H_{c1} where only a small portion of the sample has been penetrated by the in-migrating flux front. Because most of the sample volume is still flux free in this evolving incomplete critical state, the average susceptibility (and hence D'_{H_c}) is essentially constant over the field range of interest; the field at the periphery of the disk can then be taken to be $D'_{H_c} \times H_0$. As a function of the depth x, from the surface of a long cylinder, for $x \le c(H_0 - H_{c1})/(4\pi J_c)$, the flux density typically varies as[14]

$$B(x) = H_0 - H_{c1} - 4\pi J_c x/c \ . \tag{1}$$

This expression for $B(x)$ includes the effect of H_{c1} (equilibrium magnetization), but neglects the small sharp rise in the equilibrium magnetic induction at H_{c1}.[15] Because B is small over the entire flux-density profile for the field range considered ($B \lesssim H_0 - H_{c1}$; $B \to 0$ as $H_0 \to H_{c1}$), the field dependence of J_c does not enter Eq. (1): the quantity that goes in is the low-field J_c. The moment is obtained straightforwardly by integrating $(B - H_0)$ over the sample volume. To include the effect of demagnetization in that expression we make the substitutions $H_0 \to H = D'_{Hc} H_0$ and $V \to V_{\text{app}} = D'_{\text{vol}} V$ to arrive at

$$\begin{aligned} -\frac{4\pi m}{H_0} &= V_{\text{app}} = D'_{\text{vol}} V, \quad H_0 \le \frac{H_{c1}}{D'_{H_c}} = H'_{c1} \\ -\frac{4\pi m}{H_0} &\simeq \frac{D'_{\text{vol}} V}{D'_{H_c}} \left[\left(\frac{3H_{c1} + G_\perp}{3H_0} \right) \right. \\ &\qquad \left. - \frac{(H_{c1} + G_\perp - D'_{H_c} H_0)^3}{3H_0 G_\perp^2} \right] \\ &\qquad\qquad \text{for } H_0 > \frac{H_{c1}}{D'_{H_c}} \ , \end{aligned} \tag{2}$$

where $G_\perp = 4\pi J_c r/c$. For a thin disk in parallel field the demagnetizing factor is small and, with its neglect, the corresponding expressions are

$$\begin{aligned} -\frac{4\pi m}{H_0} &= V_{\text{app}} \simeq V, \quad H_0 \le H_{c1} \ , \\ -\frac{4\pi m}{H_0} &\simeq V - V \left[\frac{(H_0 - H_{c1})^2}{H_0 G_\parallel} \right] \quad \text{for } H_0 > H_{c1} \ , \end{aligned} \tag{3}$$

where $G_\parallel = 4\pi J_c t/c$.

Figure 3 shows $-m/H_0$ plotted against H_0 for a Nb-Ti disk ($a = 8.8$) in both field orientations at $T = 7.1$ K. The solid lines are fits to Eqs. (2) and (3) with D'_{vol}, J_c, and H_{c1} as the fitting parameters. D'_{vol} affects the "height" of the initial horizontal portion. Although it was varied to optimize the fit in that region, it can also be taken from the interpolation of the lead data. In fact, the values of D'_{vol} obtained from the fits fell right on the lead-data D'_{vol} curve in Fig. 2: D'_{vol} is therefore really not an independently indeterminable fitting parameter. H_{c1} shifts the whole curve to the right or left, whereas J_c controls the slope and curvature of the flux-entry portion—allowing these independently acting parameters to be

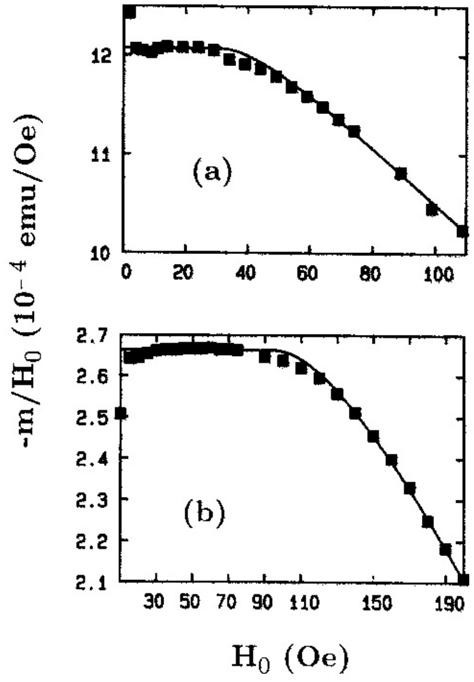

FIG. 3. $-m/H_0$ vs H_0 for a Nb-Ti disk ($a = 8.8$, $T = 7.1$ K) in (a) transverse and (b) parallel field. The solid lines are fits to Eqs. (2) and (3).

TABLE II. J_c (10^3 A/cm^2) and H_{c1} (Oe) of Nb-Ti disks in perpendicular ($H^{\perp}$) and parallel ($H^{\parallel}$) field orientations obtained from fits of the data to Eqs. (2) and (3). D'_{H_c} and D'_{ell} refer to the use of either lead-data-interpolated or ellipsoidally approximated inverted demagnetizing factors in Eq. (2).

Aspect ratio	With D'_{H_c}		With D'_{ell}	
	J_c	H_{c1}	J_c	H_{c1}
8.8 ($H^{\parallel}$)	6	94	6	94
24 ($H^{\parallel}$)	7	90	7	90
8.8 ($H^{\perp}$)	6	103	11	200
26 ($H^{\perp}$)	6	128	14	302
61 ($H^{\perp}$)	7	120	25	440

determined without ambiguity. Also the fit over an extended range of H_0 serves to reduce the ambiguity in H_{c1} due to the rounded transition region. Table II shows the results for several Nb-Ti disks (all at $T=7.1$ K). Because of its negligible demagnetization and fewer unknowns, it is well known that the $H^{\parallel}$ case is described reasonably well by critical-state models (agreement between the magnetic and transport J_c's is typically within 15%). We will therefore use the parameters determined for that orientation as "reference values." Table II shows J_c and H_{c1} (columns 2 and 3) determined directly by inserting in Eq. (2) D'_{H_c} interpolated from the lead measurements (Table I). Also shown (columns 4 and 5) are a set of J_c and H_{c1} values obtained by replacing D'_{H_c} in Eq. (2) by D'_{ell}. As can be seen, the ellipsoidal approximation results in large errors in J_c and H_{c1}, which increase with a. On the other hand, with D'_{H_c} the parameters found from fits have roughly the same values for all a. The scatter in J_c and H_{c1} may be partly due to the uncertainty in D'_{H_c} values interpolated from Table I. In addition, the values of H_{c1} will include any error in the applied field, which can be up to ±1.5 Oe. Demagnetization will magnify this error up to approximately 20 Oe. In view of these uncertainties, it is evident from Table II that Eqs. (2) and (3) provide a consistent and adequate description of the data. Note that replacing D'_{H_c} with D'_{vol} in Eq. (2) will give results that are intermediate to D'_{ell} and D'_{H_c} but still largely self-inconsistent. Figure 4 compares the value of H_{c1} measured here with published zero-temperature values (H_{c10}) for different compositions of the alloy.[16] H_{c10} was obtained from the 7.1 K value using[17] $H_{c1}=(H_c \ln\kappa)/(\kappa\sqrt{2})$ and $\kappa(t)=\kappa(1)(1.25-0.30t^2+0.05t^4)$, and assuming a parabolic temperature dependence for H_c. No published values were available for comparison with the J_c's obtained here. For both field orientations, J_c flows perpendicularly to the axis of the original rod from which disks were cut—although the field is along the rod axis for the $H^{\perp}$ case and perpendicular to the rod axis for the $H^{\parallel}$ orientation. Because of limitations on sample dimensions and resultant heating effects, the transport J_c could not be determined directly by either continuous-dc or pulsed methods.

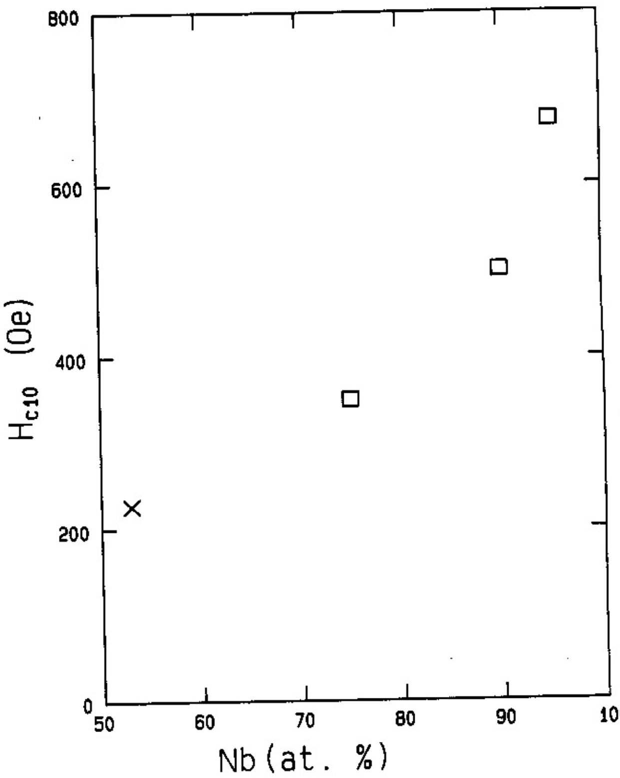

FIG. 4. Zero-temperature lower critical fields for Nb-Ti alloys as a function of the niobium content. Squares are data from Ref. 16; the cross shows the value measured here.

The results of these magnetization studies on lead and Nb-Ti disks have obvious implications for various magnetic measurements (in the $H^{\perp}$ orientation) on single crystals of high-T_c superconductors. First of all we saw that the shielding volume equals $(D'_{\mathrm{vol}})^{-1}\times 4\pi dm/dH_0$ with $D'_{\mathrm{vol}}<D'_{\mathrm{ell}}$. An incomplete "superconducting fraction" will therefore be inferred if D'_{ell} is used for the demagnetization correction. Second, estimates of low-field J_c from magnetization can now be made more accurately using the model presented above. With a simple extension a similar approach can also be used for calculating the low-field magnetic relaxation rate,[18] memory effects,[19] and other phenomena that result from flux creep. Thus it will be possible to determine the low-field flux-pinning energy $U_0^{\perp}(B\approx 0)$ with greater accuracy—a quantity used as a parameter in the comparison of different materials.[20,29] Finally, when the usual incorrect inverted-demagnetizing factors D'_{ell} or D'_{vol} are used in determining H_{c1}, the reported values will be overestimates of the intrinsic values. An error of similar magnitude will be carried over into the deduced penetration depths as well as the effective-mass anisotropy factor γ $(=\sqrt{m_c/m_{ab}})$, found, for example, from an approximate London formulation.[4,21,22] Knowing the anisotropy factor accurately is of importance in understanding the nature of the superconducting state in high-T_c materials, since different theoretical models[21,23] make different predictions about the relationship between the anisotropies in the lower and upper critical field. In Y-Ba-Cu-O, torque magne-

tometry,[24] measurements of H_{c2},[25] and those of fluctuation conductivity[26] produce $\gamma \approx 5$. The values of $H_c^{\parallel}$ and $H_{c1}^{\perp}$, and of the penetration depths $\lambda^{\parallel}$ and $\lambda^{\perp}$, show a considerable amount of scatter. Reported anisotropies in these parameters cover a range 3–10.[4,27] A recent—and perhaps the most reliable—measurement of H_{c1} by Krusin-Elbaum *et al.*[4] leads to a γ of 3.5. If their results are recalculated with the proper demagnetization correction D'_{H_c}, γ is reduced to about 1.7—significantly lower than the value obtained from H_{c2}. With some of the other high-T_c superconductors, notably Bi-Sr-Ca-Cu-O, the crystals have even larger aspect ratios and use of the proper D' is of correspondingly greater importance. In Bi-Sr-Ca-Cu-O a rather large range of H_{c1} and deduced γ values have been reported.[28–30] Our own measurements[29] originally reported an implied γ of about 35. With the new D' this would have to be revised to approximately 20. Resistive measurements of H_{c2} on single crystals[31] yield a γ of 25–60, whereas similar measurements on thin films[32] yield $\gamma \sim 15$. At present no measurements on H_{c2} from reversible dc magnetization are available. Farrell *et al.*[33] obtain $\gamma = 3000$ from torque magnetometry. Thus the scatter in the different values of γ make it difficult to draw any definite conclusions; however, as in Y-Ba-Cu-O it seems that the anisotropy factor found from H_{c1} is smaller than that obtained from H_{c2}. It will be interesting to see if this is a general property of high-T_c superconductors once additional independent and reliable measurements of the various compounds become available.

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