

FLUX CREEP AND RELATED PHENOMENA IN HIGH TEMPERATURE SUPERCONDUCTORS

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Irreversible features, which dominate the magnetic data in high temperature superconductors, are reviewed. Special attention is given to two phenomena: (i) The temperature and field dependence of the relaxation rate and its implication on measurement of critical fields. (ii) The field dependence of the magnetization which exhibits scaling features below the irreversibility line. The discrepancy in the barrier heights from magnetic relaxation and from resistivity measurements is discussed.

1. INTRODUCTION

Most type-II superconductors, including high-temperature superconductors (HTSC), exhibit irreversible magnetic features.¹ Thus, for example, the field-cooled (fc) magnetization is less diamagnetic than the zero-field-cooled (zfc) branch of the magnetization. The temperature T_{irr} where the zfc and the fc branches coincide is, for most conventional superconductors, practically identical with the superconducting transition temperature T_c . For HTSC, however, $T_{irr} < T_c$ and $T_{irr}(H)$ divides the field-temperature (H-T) phase diagram into reversible and irreversible regimes.^{2,3} The irreversible regime is characterized by pinning of magnetic flux. The magnetization in this regime is usually described by the Bean model.⁴ At high enough temperatures, magnetic vortices can undergo depinning due to thermal fluctuations. This phenomenon, known as flux creep, has been treated by the Anderson-Kim model.⁵

The flux creep in HTSC is unusually large.³ We can account for the observed giant flux creep and related irreversible features^{3,6-10} by extending the Anderson-Kim and the Bean models to include the fingerprints of HTSC, (i.e. high temperatures and unusually small pinning energies). This approach not only explains irreversible data but also points to possible serious effects on future applications of HTSC and to the intrinsic difficulties in identifying thermodynamic properties, in particular upper critical fields.^{6,11,12} The onset of the observable flux creep, however, allows a determination of the lower critical fields,⁸ thus bypassing the difficulties of the conventional techniques.

In this paper we briefly review flux creep data for HTSC and focus on the temperature and field dependence of the relaxation rate $dM/d\ln t$. We analyze

the data in the framework of the Bean model and pursue our analysis to predict scaling features of the magnetization curves. Our new results for HTSC as well as for conventional superconductors support this prediction. We also discuss the discrepancy of activation barriers determined from the low temperature magnetic relaxation and from resistivity and ac susceptibility measurements nearer to T_c .

2. FLUX CREEP

In Refs. 7-9 we presented data of magnetic isotherms as a function of time for YBaCuO and for BiSrCaCuO crystals. The relative changes of the magnetization are enormous. For example, for YBaCuO at 70 K we observe $\approx 30\%$ change in M during the first hour. For BiSrCaCuO the effect is even more dramatic; we observe $\approx 70\%$ change already at 20 K.

At low temperatures the magnetic data are logarithmic in time, but more complex non-logarithmic decays are observed in the high temperature limit. Recent works treat explicitly this complex behavior in terms of thermally activated flux flow¹³ and distribution of pinning energies.^{10,14} Here we focus on the low temperature behavior where the time-logarithmic description is an excellent approximation of the data. In this limit we have studied the field dependence of the relaxation rate $dM/d\ln t$. We have found that above a threshold field, which we identify as the lower critical field H_{c1} , the relaxation rate increases as a power of the field, see Fig. 1.

These results are explained in Ref. 8 in the framework of the Bean and Anderson-Kim models.^{4,5} It is useful to review the basic derivation in view of recent

controversy about the size of the energy barrier, to be discussed further below. In its simplest form, Anderson-Kim flux creep predicts that flux is thermally activated over a barrier of height $U = U_0(1 - J/J_{c0})$ at a rate

$$f = f_0 \exp [-U_0(1 - J/J_{c0})/kT] , \quad (1)$$

where U_0 is the barrier height in the absence of a current density J , which exerts a driving force on the vortices, where J_{c0} is the (possibly temperature-dependent) critical current density in the absence of flux creep, and where f_0 is an attempt frequency. Inverting Eq. 1 gives

$$J = J_{c0}[1 - (kT/U_0) \ln(f_0/f)] . \quad (2)$$

In a critical state, as described for example by the Bean model, the current density J is given by the critical current density J_c and is directly related to the irreversible magnetization of the superconductor. Since J in Eq. 2 is directly related to $\ln(f_0/f)$ or equivalently $\ln(t/t_0)$, the irreversible magnetization is predicted to relax according to $\ln(t)$ as observed in experiment. It is important to note, for our discussion below, that from the coefficient of the $\ln(t)$ dependence, one can extract directly U_0 , the **zero-current-density** barrier height.

In its simple version the Bean model assumes that the critical current J_c is field-independent leading to a linear dependence of h on x . A more realistic model takes $J_c = J_{c1}h^{-n}$, where J_{c1} is the maximum critical current at a given temperature and n is a phenomenological power, typically 0.5-1 in experiments. Such a recent extension of the Bean model yields⁸ for a slab of thickness D ,

$$H + 4\pi M = \frac{2}{CD} \frac{n+1}{n+2} [H^{n+2} - H_{c1}^{n+2}] , \quad H_{c1} \leq H \leq H^* , \quad (3)$$

$$H + 4\pi M = \frac{2}{CD} \frac{n+1}{n+2} [H^{n+2} - (H^{n+1} - \frac{CD}{2})^{(n+2)/(n+1)}] , \quad H \geq H^* , \quad (4)$$

where $C \equiv 0.4\pi(n+1)J_{c1}H_{c1}^n$ and $H^* \equiv (CD/2 + H_{c1}^{n+1})^{1/(n+1)}$ is the lowest field for which currents flow through the entire volume of the sample. Note that for $n=0$, the original Bean equations⁴ are recovered.

The calculation of the relaxation rate $dM/d\ln t$ from Eqs. 1 and 2 is straightforward (provided one can ignore the flux continuity equation,¹³ which is reasonable at low temperatures). It is apparent from these equations that $dM/d\ln t$ is determined by two parameters, namely H_{c1} and U_0 . (U_0 is derived from the expression to C ; J_c depends explicitly on U_0 . The value of J_c is derived from the remanent magnetization⁴). Following this procedure we are able to determine the lower critical fields⁸ - see Fig. 1 - thus bypassing the difficulties in conventional determination of H_{c1} from $M(H)$ data.

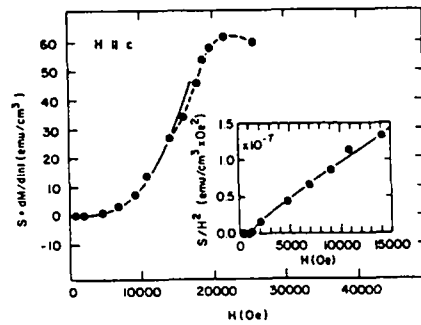


FIGURE 1
Relaxation rate of the zero-field-cooled magnetization as a function of field (corrected for demagnetization) for fields parallel to the orthorhombic c-axis of an YBaCuO crystal. Inset: Relaxation rate $S = dM/d\ln t$ normalized by H^2 as a function of field. Solid lines are fit to $dM/d\ln t$ derived from Eq. 3. (See Ref. 8). Broken line is a guide for the eye.

The barrier height, U_0 , is found to be of order 10-50 meV for YBaCuO crystals and a factor of 2-3 smaller for BiSrCaCuO crystals.⁹ The unusually low values found in relaxation measurements were confirmed by many groups. However, recent analysis of resistivity data^{15,16} as well as ac susceptibility data⁶ has led to a determination of a barrier height U of the form

$$U = A_J [1 - (T/T_c)^2]^{3/2} / H , \quad (5)$$

where A_J is a current-density-dependent coefficient determined¹⁷ to lie in the range of 10-60 eV/kG. (This form differs from that originally proposed in Ref. 3 in using $1 - (T/T_c)^2$ rather than $1 - (T/T_c)$ to allow extension to low temperatures.) We postulate^{3,6} that the field-dependent form of Eq. 5 crosses over to a field-independent form at low fields.

Considering that typical low temperature magnetization measurements are done in the range of 1 kG applied field, we can estimate the size of the activation energy which we would expect at low temperatures from Eq. 5. According to the numbers quoted above, we find values of 10's of eV, almost three orders of magnitude larger than the values from low temperature magnetic relaxation. This has been a serious problem for the flux creep interpretation.

It is tempting to attribute this discrepancy to the fact that the magnetic measurements are done in the critical state, with $J \approx J_c$, so the the total barrier

$U = U_0(1 - J/J_{c0})$ is close to zero, while the resistivity and ac-susceptibility measurements probe much lower current densities. However, as pointed out above, the magnetic relaxation measurement differs in a fundamental way from the resistivity and ac susceptibility measurements; it determines U_0 rather than U . Therefore, this interpretation of the discrepancy is unacceptable.

An interesting alternative for reconciling these results has emerged from the work of Zeldov et al.¹⁶ on YBaCuO films, who found that U in Eq. 5 (or equivalently the coefficient A_2) depends **logarithmically** on J according to the phenomenological relation $\ln J_0/J$. Here J_0 is an effective critical current density of order 10^6 A/cm² in these films. (Since electric field is proportional to frequency in Eq. 1, such a logarithmic dependence implies that the IV curves are power laws rather than exponentials.) While, as we have shown earlier, a linear J -dependence of the barrier cannot account for the discrepancy in the different measurements, the nonlinear dependence can give an effect. Although the barrier J -dependence has not been explicitly determined yet in crystals, we take the J_0 value determined in the films and can then estimate an increase in apparent $U(J)$ over that of the magnetization measurements by a factor of $\ln(J_0/J)$. This is a factor of about 14 when comparing to results of resistivity measurements at 1 A/cm². This goes a long way towards resolving the discrepancy but is still quantitatively insufficient. Alternatives involve distributions of pinning barriers^{10,14} or conceptually new models like vortex glass freezing,¹⁸ which introduce collective pinning effects in a novel way.

3. SCALING OF MAGNETIZATION CURVES

The field H^* , defined above as the first field at which flux fronts from the edges meet at the center, has another physical meaning: It defines a new field-scale for which the magnetization curves 'collapse' onto a single curve. For fields $H \gg H_{c1}$ the scaling field is $H^* \approx (CD/2)^{1/(n+1)}$. By scaling both sides of Eqs. 1 and 2 by H^* , we find

$$\frac{4\pi M}{H^*} = -\left(\frac{H}{H^*}\right) + \frac{n+1}{n+2} \left(\frac{H}{H^*}\right)^{n+2} \tag{6}$$

$$\frac{4\pi M}{H^*} = -\left(\frac{H}{H^*}\right) + \frac{n+1}{n+2} \left[\left(\frac{H}{H^*}\right)^{n+2} - \left\{\left(\frac{H}{H^*}\right)^{n+1} - 1\right\}^{(n-2)/(n+1)}\right] \tag{7}$$

Eqs. 3 and 4 can be summarized as

$$4\pi M = H^* f_{\pm}(H/H^*), \tag{8}$$

where f_- and f_+ are the scaling functions for $H \leq H^*$ and for $H \geq H^*$ respectively. Thus, a one parameter scaling is an intrinsic feature of the extended Bean model provided that H_{c1} in Eqs. 1 and 2 might be neglected. It is important to note that the Bean model describes the magnetic data in the irreversible regime only. We thus expect the scaling features to vanish above the irreversibility line. Moreover, the analysis

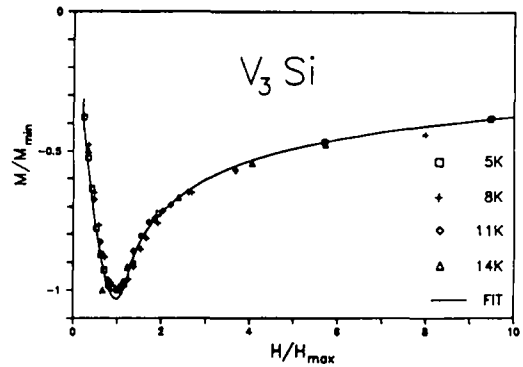


FIGURE 2
Scaled magnetization curves for V_3Si ($H/H_m \leq 10$) for the indicated isotherms. Solid line is a fit to Eqs. 6 and 7 with $n=0.4$

described here is general; we thus expect that the scaling features to be found in conventional as well as in HTSC.

In recent articles¹⁹ we have demonstrated the success of the extended Bean model by presenting scaled magnetic data for ceramic samples of YBaCuO, BiSrCaCuO and TlBaCaCuO. Furthermore, we were able to show¹⁹ that deviations from scaling start at the irreversibility line. The experimental scaling parameter is H_m , the field for which the magnetization reaches its maximum absolute value. (In the Bean model $H_m \propto H^*$). The location of the maximum and the quality of the scaling are independent of the geometrical length scale of the ceramic sample. We therefore conclude that the scaling features are determined by the average length scale of the grains. A fit of the scaled data to Eqs. 6 and 7 yields values between 0.4 and 0.45 for the exponent n for the above three HTSC systems. This "universal" behavior implies that J_c of HTSC grains follows approximately a $h^{-1/2}$ behavior, in agreement with recent transport measurements²⁰ of critical currents in single grains.

Here we present new data for a conventional superconductor, a powder of V_3Si particles immersed in a stycast matrix. For this sample $T_c = 16.2$ K. Details of sample preparation are described in Ref. 21. Magnetic measurements will be described elsewhere. A summary of the magnetization curves for the V_3Si samples at various isotherms is shown in Fig. 2. The scaling features of the magnetic data are apparent in this figure. The solid line is a fit of the scaled data to Eqs. 6 and 7 with $n=0.4$. Thus we conclude that the observed scaling features are general to type-II superconductors, as predicted by the Bean model.

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