Studies of pinning in high T_c superconductors

V. N. Bakradze, A. A. Iashvili, T. V. Machaidze, T. K. Nakhutsrishvili, and Dzh. G. Chigvinadze

Physics Institute, Georgian Academy of Sciences
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Vortex pinning in superconducting YBaCuO ceramics is studied by a mechanical technique. Samples rotating in a uniform magnetic field are found to acquire a torque. The latter is attributed to pinning of the vortical magnetic structure in a superconducting ceramic. A pinning force $F_p = 3 \cdot 10^{-5}$ dyne $\cdot$ cm^{-1} (in a field of 1 kOe) is found from the torque value. For high rotation velocities there is a linear relation between the torque and the sample rotation velocity. For small velocities the torque decreases drastically. The reason is that at high velocities the vortices move in a flow regime, while at small velocities they move in a creep regime. Logarithmic relaxation of the torque at liquid nitrogen temperature ($T = 77.3$ K) has also been observed. A model based upon the Anderson theory of thermally activated creep flow is suggested and accounts for these phenomena. The pinning potential U_0 is found to be ≈ 250 meV.

Soon after high-T_c superconductivity had been discovered strong relaxation effects were observed in magnetic experiments,[1] in particular, long relaxation of the trapped magnetic flux. At temperatures much lower than T_c this relaxation is linear in time and can be due to thermally activated flux creep as a result of simultaneous action of two favorable conditions: a very small coherence length ξ and relatively high characteristic temperatures.[2]

Torque relaxation was observed also, when high-T_c superconductors were studied by a torsional technique.[3–5] In the present study we suggest a model based upon Anderson's theory of thermally activated flux creep to interpret the results of the torsional experiments.

EXPERIMENT

We studied samples of $YBa_2Cu_3O_{7-x}$ ceramics made by a standard solid-phase reaction technique. The superconducting transition temperature was about 94 K. The experiments were carried out at liquid-nitrogen temperature.

The experimental setup is shown in Fig. 1. It is similar to that described in Ref. 6. A cylindrical high-T_c superconductor suspended by a thin elastic thread is placed into a transverse magnetic field **B**. The upper end of the thread is secured to a Dewar-flask cap and is rotated by an electric motor at different velocities. At a time $t=0$ the motor is turned on and both the rotation angle φ_1 of the upper head and the rotation angle φ of the sample are measured. The torque is given by the formula

$$m = f(\varphi_1 - \varphi), \tag{1}$$

where f is the elastic moment and $\varphi_1 - \varphi$ is the suspension thread twist angle.

In a zero magnetic field and for $B < B_{c1}$ the sample rotates freely together with the upper head, so that $\varphi_1 = \varphi$ and $m=0$ (Fig. 2). If $B > B_{c1}$, Abrikosov vortices build up inside the superconductor and are pinned by the crystal-lattice inhomogeneities. The external magnetic field acts on the pinned vortices and creates the torque which holds the sample. When this torque becomes so large that the force acting upon the vortices becomes larger than the pinning force, the vortices break away from the pinning centers are pinned by the neighboring ones. The torque reaches then a maximum that depends on the pinning force and the rotational velocity of the sample. Figures 2 and 3 show the measured dependences of φ and m of φ_1 for different magnetic fields.

The greatest torque m as a function of the angular velocity ω is shown in Fig. 4. It is seen that at large velocities the relation is close to linear:

$$m = m_c + m'\omega, \tag{2}$$

where m_c characterizes the pinning force and m' the viscosity of the vortex flow in the superconductor. The pinning force and viscosity are given by the formulas[3,4]

$$F_p = \frac{3\Phi_0}{4Br^3h} m_c, \tag{3}$$

$$\eta = \frac{2\Phi_0}{\pi^2 Br^4 h} m', \tag{4}$$

where r and h are the radius and height of the cylindrical sample, respectively, $\Phi_0 = 2 \cdot 10^{-7}$ G/cm^2 is the magnetic flux quantum, and F_p and η are the mean pinning force and viscosity per unit length of a vortex, respectively.

If the sample rotates slowly, i.e., $\omega \to 0$, the torque decreases drastically. Clearly, this is a manifestation of thermally activated vortex motion.

THE MODEL

Before considering the superconductor rotation in magnetic field let us recall the basic points of Anderson's theory of thermally activated flux creep.[9]

The theory of thermally activated flux creep is based on Bean's critical state model.[10] If a type-II superconduc-

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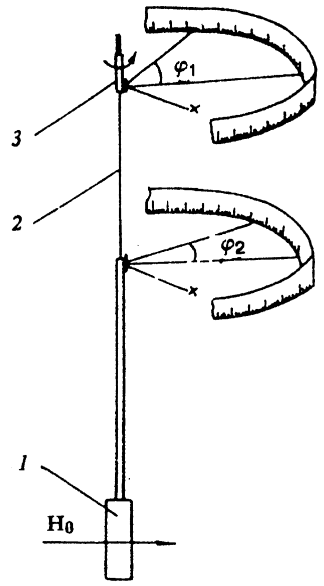

FIG. 1. Experimental setup.

tor is placed in an external magnetic field $B > B_{c1}$, the Abrikosov vortices are produced inside the superconductor in the near-surface layer. A vortex-number gradient, i.e., a magnetic-field gradient, builds up. This means that in the near-surface layer there is a macroscopic density of a current which acts on the vortices with a Lorentz force F_L. Under the action of this force and of the mutual repulsion, the vortices in an ideal single crystal are uniformly distributed inside the sample and form a triangular lattice. Crystal-lattice inhomogeneities can attract the vortices with a force F_p (pinning force), thus trapping them into "potential wells" of depth U. If the Lorentz force exceeds the local pinning force, the vortices come off the pinning centers and move inside the superconductor. Such a motion is called a stream flow. At zero temperature this motion will continue until the Lorentz force F_L becomes equal to the pinning force F_p everywhere inside the superconductor. The superconductor is said then to be in a critical state. According to Anderson's theory, at $T > 0$ the vortices can be moved by thermal activation even if $F_L < F_p$. The motion is realized by means of activated jumps of a vortex (or a group of vortices) through the potential barrier. The frequency of jumps from one pinning center to its neighbor is given by the Arrhenius formulas.

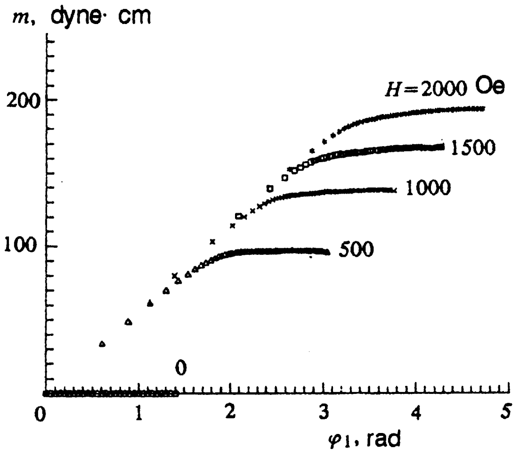

FIG. 3. Torque m versus the upper-head rotation angle φ_1 in various magnetic fields.

$$P_1 = \frac{1}{2}\nu_0 \exp\left[-\frac{1}{kT}\left(U_0 + X_0 V \frac{B\partial B}{\mu_0 \partial X}\right)\right] \tag{5}$$

$$P_2 = \frac{1}{2}\nu_0 \exp\left[-\frac{1}{kT}\left(U_0 - X_0 V \frac{B\partial B}{\mu_0 \partial X}\right)\right] \tag{6}$$

for the forward and backward directions, respectively. Here ν_0 is the attempt frequency, X_0 is the distance between the pinning centers, and V is the volume of a vortex or a group of vortices.

Such a vortex motion (thermally activated flux creep) causes a logarithmic decrease, with time, of the superconducting currents in the near-surface layer after the magnetic field is turned on, or a residual magnetization after

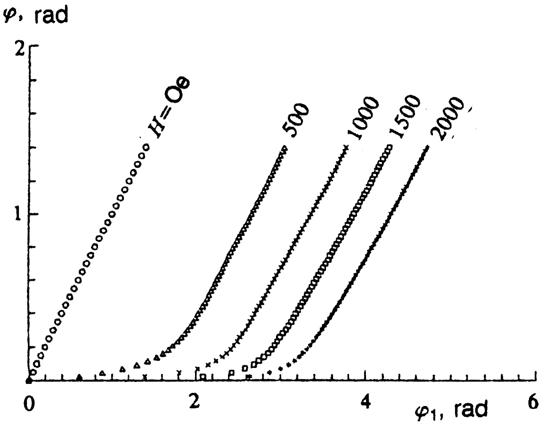

FIG. 2. The superconductor rotation angle φ versus the upper head rotation angle φ_1 in various magnetic fields.

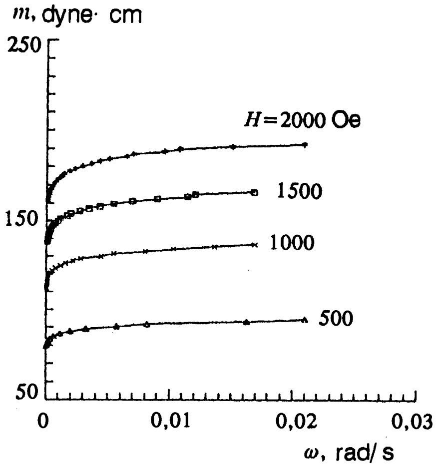

FIG. 4. Torque m versus the superconductor rotation velocity ω.

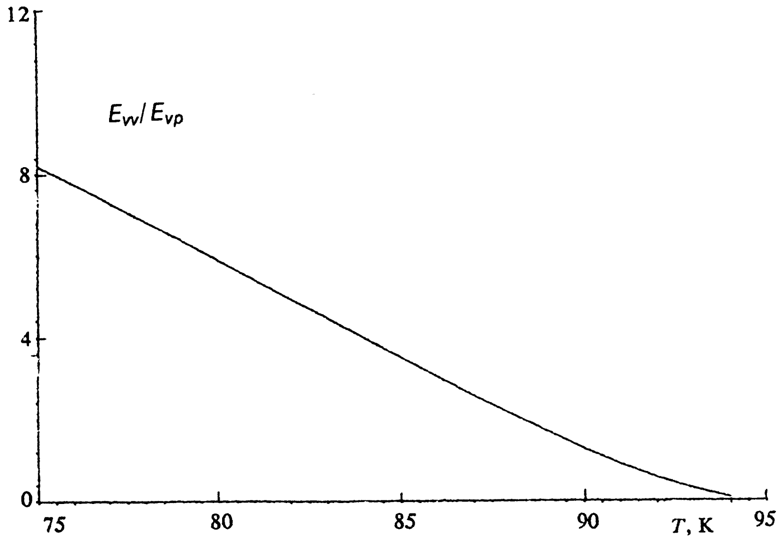

FIG. 5. The ratio E_{vv}/E_{vp} versus temperature.

the magnetic field is turned off.[11,12] By analogy with this linear vortex motion, we construct a model of rotation of a cylindrical superconductor in a transverse magnetic field.

Consider a cylindrical homogeneous and isotropic superconductor in a magnetic field $B > B_{c1}$ transverse to the cylinder axis. Let the Abrikosov vortices be uniformly distributed over the superconductor cross section. Let also the pinning centers be uniformly distributed over the superconductor volume. We can estimate the energy E_{vv} of the vortex–vortex interaction and the energy E_{vp} of the vortex–pinning center interaction.[13] For our sample (Y–Ba–Cu–O ceramic) at $T \approx 80$ K we find that $E_{vv} \gg E_{vp}$ (Fig. 5). Therefore a vortex lattice can be imagined in the form of a bundle of straight flux filaments tied into one knot and moving as an entity when the superconductor rotates. Let us replace such a vortex system by one arrow (Fig. 6) which can rotate around the center and carry a magnetic flux $\Phi = N\Phi_0$, where N is the number of vortices. The superconductor with pinning centers can be imagined in the form of a disk with sectors. The angle between the sectors is determined by the distance between the pinning centers. For the vortex lattice, each sector represents a potential well of depth U. The superconductor is driven into a critical state by suddenly turning the upper head of the suspension through a definite angle φ_1. The superconductor with the pinned vortices will turn by an angle φ which is determined from the condition that the moments applied to the sample by the twisted thread and by the magnetic field are equal:

$$f(\varphi_1 - \varphi) = \frac{\pi}{2} B\Phi_0 \sin\psi, \tag{7}$$

where ψ is the angle of vortex-lattice rotation. Since $T > 0$, the vortices, owing to thermal activation, come off the pinning centers and hop to the neighboring ones, trying to be parallel to **B**. The effective activation energy is

$$U_{\text{eff}} = U_0 \pm \frac{\pi}{2} B\Phi_0 \sin\psi. \tag{8}$$

If ψ_0 is the angle of vortex-lattice rotation for which $U_{\text{eff}} = 0$, then, by analogy with the Arrhenius formulas, we have for the frequency of hops from one sector to another

$$P_1 = \frac{1}{2}\nu_0 \exp\left[-\frac{U_0}{kT}\left(1 + \frac{\sin\psi}{\sin\psi_c}\right)\right], \tag{9}$$

and in the opposite direction

$$P_2 = \frac{1}{2}\nu_0 \exp\left[-\frac{U_0}{kT}\left(1 - \frac{\sin\psi}{\sin\psi_c}\right)\right]. \tag{10}$$

The vortex-lattice rotation velocity is

$$\frac{\partial\psi}{\partial t} = \omega - \delta\nu_0(P_1 - P_2), \tag{11}$$

where $\omega = \partial\varphi/\partial t$ is the rotation velocity of the superconductor in the laboratory frame of reference, while $\delta\nu_0(P_1 - P_2)$ is the vortex lattice rotation velocity with respect to the superconductor. If we consider processes for which $\psi > 0$, then $P_1 \ll P_2$ and

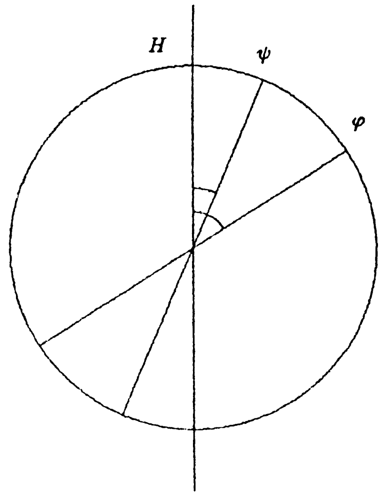

FIG. 6.

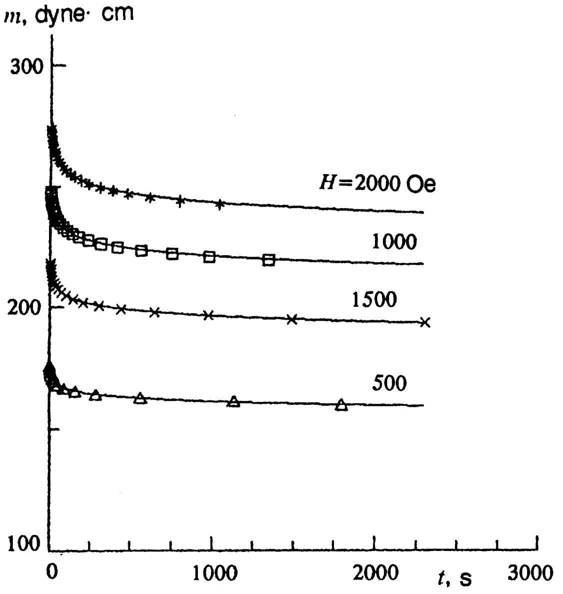

FIG. 7. Torque relaxation.

$$\frac{\partial\psi}{\partial t}=\omega-\delta\nu_0 P_2. \qquad (12)$$

If $\omega_0=\delta\nu_0$, then

$$\frac{\partial\psi}{\partial t}=\frac{\partial\varphi}{\partial t}-\omega_0\exp\left[-\frac{U_0}{kT}\left(1-\frac{\sin\psi}{\sin\psi_c}\right)\right]. \qquad (13)$$

Solving Eq. (13) with allowance for Eqs. (1) and (7) in the range $0<\psi<\psi_c$ we find at $t\gg 1$:

$$m=m(t_0)-m_c\frac{kT}{U_0}\ln\frac{t}{t_0}, \qquad (14)$$

where t_0 is an arbitrarily chosen time.

For full analogy we introduce the relaxation rate

$$R=\frac{1}{m_c}\frac{dm}{d\ln t}. \qquad (15)$$

TABLE I.

B,G	U_0,meV	m_c,dyne · cm	ψ,rad
500	273	91	0.114
1000	262	128	0.041
1500	242	158	0.022
2000	238	189	0.014

Then the pinning potential is

$$U_0=\frac{kT}{R}.$$

The relaxation rate R is found from experiment, see Fig. 7. The values of U_0 for $YBa_2Cu_3O_{7-x}$ ceramics in various magnetic fields are listed in Table I.

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