Magnetocaloric approach to type-II superconductors

A. Gerber,* Z. Tarnawski,† V. H. M. Duijn, and J. J. M. Franse
Van der Waals–Zeeman Laboratorium, Universiteit van Amsterdam, Valckenierstraat 65, 1018 XE Amsterdam, The Netherlands
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We propose an experimental approach to study the dynamical properties of vortices in high-temperature as well as in conventional type-II superconductors. The experimental technique is based on direct measurements of the power dissipated by vortices moving in the bulk of a superconductor. This magnetocaloric approach provides an alternative, and in a number of cases a unique, information source to a wide range of fundamental problems including vortex pinning, critical currents, surface barrier, vortex movement by quantum tunneling, magnetic instabilities, etc. Some typical results are presented for Y-Ba-Cu-O, Bi-Sr-Ca-Cu-O, and NbTi samples.

The nature of vortex pinning and associated to this, the problem of critical currents in high-temperature superconductors, has been in the center of active theoretical and experimental research during many years. Although significant progress has been made, the subject is still far from a comprehensive understanding and the interpretation of the existing experimental data remains controversial. Experimental studies of the dynamical properties of vortices in high-temperature as well as in conventional type-II superconductors are focused mainly on transport and magnetic measurements. The values of the critical-current densities in high-temperature superconductors at low temperatures are estimated to be as high as 10^6–10^7 A/cm^2. These currents are too high to be measured directly in bulk single-crystalline samples. Therefore, transport measurements at low temperatures are limited to thin films. Bulk superconductors are usually studied by measuring their magnetization curves. The fundamental problematics of this technique is that the interpretation of the measured irreversible magnetization in terms of critical currents and pinning potentials requires a certain number of assumptions, among them the functional dependence of the critical current on the local magnetic induction, as well as the dependence of the pinning potential on temperature, magnetic induction and electrical current.

A number of phenomenological critical state models is generally used, including the simplest Bean model,[1] in which the induced screening currents in the superconductor are assumed to be critical and independent of the magnetic induction and time. Different power[2,3] or exponential[4] critical-current dependencies on the magnetic induction have been proposed as well. On the other hand, the irreversible magnetization of type-II superconductors with a short coherence length (including the high-temperature superconductors) can be discussed within the framework of a fast time relaxation[5] using different current-, field-, and temperature-dependent pinning potentials. The absence of a generally recognized clear picture today originates from the fact that different theoretical models with numerous fitting parameters cannot be sorted out based on magnetization data alone. There is, therefore, a need for additional independent experimental information.

We report in this paper the development and the first results of an alternative technique, in which the power dissipated by moving vortices is directly measured. In a superconductor that is exposed to a varying applied magnetic field, screening currents are induced near the surface. Critical state models assume that the density of these screening currents are equal to the critical-current density. The magnetic induction gradient, dB/dx, is therefore determined by the local critical-current density. This relation holds for time-independent critical currents. However, the metastable critical state relaxes with time. Therefore, the effective screening current is somewhat lower than its maximum critical value.

The power p, locally dissipated by moving vortices in a hard type-II superconductor, can be estimated as $p = JdB/dt$, where J is the screening current, presumably equal to the critical current, and where B is the local magnetic induction. The time derivative of the magnetic induction, dB/dt, is determined either by the sweep rate of an applied field or by the flux creep during relaxation processes.

We measure the total power dissipated in the whole volume of the sample by monitoring the temperature of the sample kept under quasiadiabatic conditions. The experimental setup is typical for specific-heat measurements. The sample is mounted on a sapphire plate, the latter equipped with a RuO thermometer and a heater. The vacuum in the cell is about 10^{-6}–10^{-7} torr, and a thin manganin wire provides a limited thermal link to the frame. The temperature of the frame is controlled and stabilized within 1 mK at 1 K during the slow magnetic field sweeps. No temperature changes have been detected during control field sweeps with no sample mounted.

The sample's temperature T, the dissipated power P, the specific heat of the system C and K, the thermal conductance to the bath kept at temperature T_0, are connected by

$$CdT/dt = P - K(T - T_0) . \tag{1}$$

The system's specific heat C and the thermal conduction K are measured *in situ* by passing a known current pulse through the heater. Their typical values near 4 K in these experiments are $(1-10)\times10^{-3}$ mJ/K and $(1-10)\times10^{4}$ mW/K for the specific heat and the thermal conductance, respectively. The temperature of the sample is measured during a field sweep with a constant rate (of the order of a few G/sec) and the power dissipated due to the penetration of vortices is calculated using Eq. (1). A similar calorimetric technique for measuring the ac losses in thin superconducting films was proposed by Meyer, Snowden, and Sterling 22 years ago.[6]

A typical result obtained on a NbTi disk is shown in Fig. 1. The dissipation starts when the first flux has penetrated into the superconductor. The field of the dissipation onset corresponds to the field of the first penetration, which can be equal or higher than H_{c1}. When flux successively penetrates into the body of the sample, the dissipation takes place in an increasing sample volume. The measured dissipated power increases, therefore, as a function of increasing applied field. When the flux has penetrated to the center of the sample and the screening current occupy all the volume, the dissipated power reaches its maximum. For still higher applied fields, the volume in which the dissipation takes place remains constant and the local rate of the magnetic induction variation dB/dt can be assumed to be uniform and equal to $\mu_0 dH/dt$. The dissipated power is now directly proportional to the average critical-current density, and its decrease indicates a reduction of the critical current as a function of magnetic field.

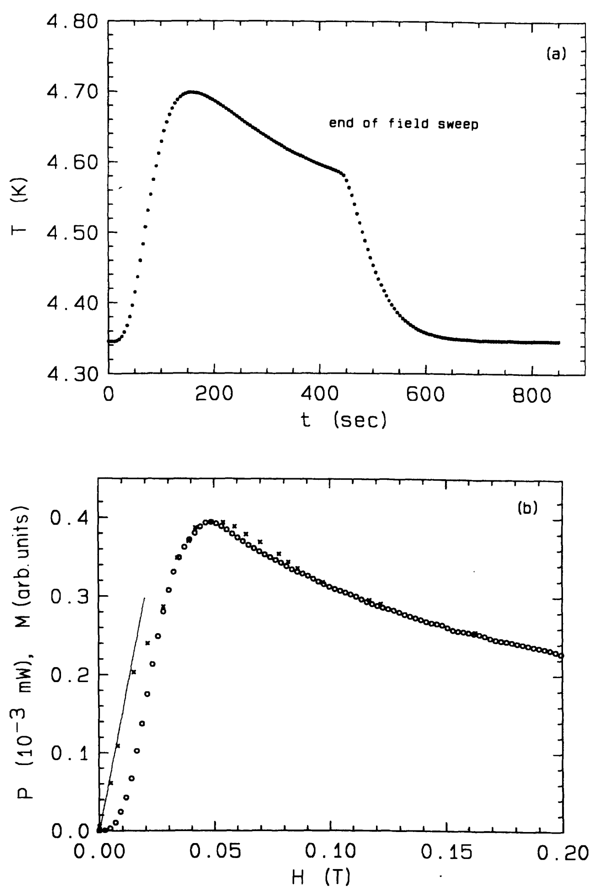

FIG. 1. (a) Temperature variation of a semiadiabatically mounted NbTi disk-shape sample during a magnetic field sweep from zero field to 0.2 T and after the field has been stabilized at 0.2 T. The sweep rate is about 4.5 G/sec. (b) The power dissipated during this sweep as a function of the applied magnetic field (○) is compared with the normalized virgin magnetization curve of the same sample (×). Magnetization was measured at the same field sweep conditions.

The results of the magnetic and magnetocaloric experiments performed at the same conditions have to be compared. Both techniques probe in different ways the same physical parameters in the sample: the screening currents and the local magnetic fields or their time derivatives. This difference is clearly demonstrated in Fig. 1(b), where the power dissipated by the penetrated magnetic flux is compared with the virgin magnetization curve of the same NbTi sample. The field sweep rate in both experiments is about 4.5 G/sec. The first flux penetration is indicated both by the deviation from the linear magnetization and by the dissipation onset around an external field of about 0.005 T. Both curves reach their maximum roughly when the screening currents flow in the entire volume of the sample. The agreement between the two techniques is satisfying. Using the simple Bean model, the critical-current densities have been calculated from both magnetocaloric and magnetization data (Fig. 2). The results coincide well at low fields but diverge strongly under high fields. A correct description of type-II superconductors in their mixed state should satisfy both sets of experimental data. The proper selection of the existing models is now under way.

The magnetocaloric approach is attractive not only as complementary to the standard magnetization measurements, but also by its own merit. It is demonstrated by a few examples in the following.

The applied magnetic field at which the first vortex penetrates inside the superconductor is traditionally looked for at the point, where the measured magnetization starts to deviate from a straight line. At high temperatures, where pinning is weak, a sharp kink defines the

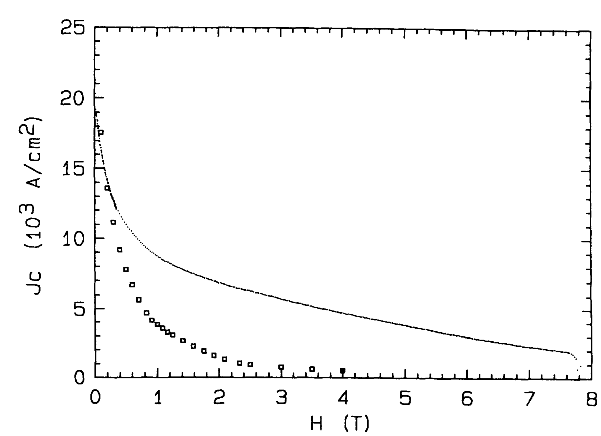

FIG. 2. Critical-current densities of the NbTi sample calculated from the magnetocaloric measurements (·) and from the irreversible magnetization curve (□) by using the Bean model.

onset of this deviation.[7] In the low-temperature region, the kink is usually smeared out by strong pinning and the onset is experimentally ill defined unless the field dependence of the measured magnetization is modeled.[8] The picture is even more complicated in granular superconductors, where the sample's screening and, therefore, magnetization is determined both by Josephson-type integranular currents and intrinsic properties. In contrast to magnetization curves, we show in Fig. 3 the temperature variation of a polycrystalline Y-Ba-Cu-O sample when the applied field has been increased from zero. The dissipated power is clearly a two-step function of the applied field. The onset of the first dissipation step indicates the penetration of vortices into the intergranular regions of the sample, where the dissipation is determined by weak intergranular currents. The onset of the second dissipation step indicates the penetration of vortices into the grains of the superconductor and its value is determined by the intragranular critical-current densities.

The existence of the Beam-Livingston surface barrier[9] in high-temperature superconductors and its influence on the magnetization and the field of penetration are widely discussed recently.[7,10] The discussion is focused on a number of characteristic features of the irreversible magnetization curves, whereas the opponents argue that at least some of these features can be described either by intrinsic granularity, by an enhanced extrinsic surface pinning, or by assuming a power-law dependence of the critical current on the magnetic induction. In terms of screening currents, the surface barrier can be viewed as a region from which vortices are strongly repulsed, i.e., a region with higher screening current near the sample's surface. At traversing this region, vortices are expected to dissipate more power than at moving deep inside the sample. This expectation is fully confirmed by our magnetocaloric measurements of a Bi-Sr-Ca-Cu-O single crystal presented in Fig. 4. The dissipation rise rate falls sharply when the applied field exceeds 600 G. A direct mapping of screening currents and surface barrier becomes, therefore, possible.

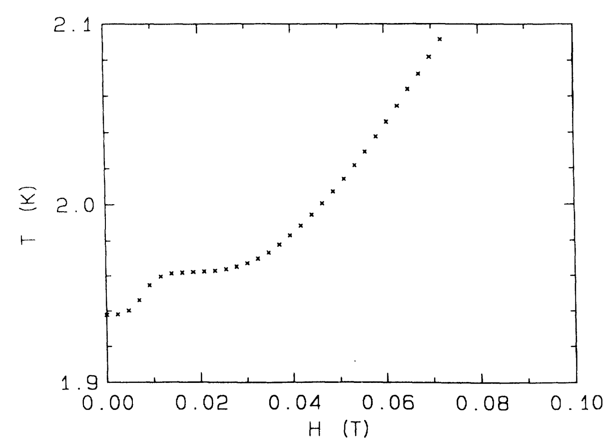

FIG. 3. The temperature variation of a semiadiabatically mounted polycrystalline Y-Ba-Cu-O sample as a function of an increasing magnetic field. The two-step dissipation process indicates an intergranular and an intragranular flux penetration, successively. The field sweep rate is about 4.5 G/sec.

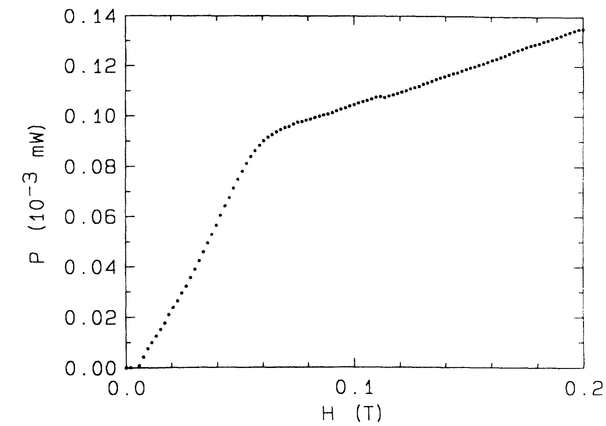

FIG. 4. The power dissipated in a single-crystalline Bi-Sr-Ca-Cu-O sample by the penetrating flux during a field sweep. The starting temperature of the sample was 1.1 K. The field sweep rate is about 0.45 G/sec. The field of full penetration of this sample is above 2 T. The reduction of the dissipation-rise rate around 600 G is the evidence for a surface barrier.

Quantum tunneling of vortices is another fundamental property recently discussed.[11] Some data clearly suggest that the magnetization relaxation rate does not show a trend towards zero at $T=0$, as expected for a thermally activated flux motion, but remains finite. This anomaly has been observed in single crystals of high-temperature superconductors,[11] heavy fermions,[12] and Chevrel-phase[13] superconductors and has been interpreted as evidence for quantum tunneling of vortices. The experimental results should, however, be treated more carefully. Relaxation of magnetization involves a redistribution of the vortex density and, as a consequence, an energy dissipation. In bulk type-II superconductors, including the high-T_c superconductors, the magnetic diffusivity can be much larger than the thermal diffusivity. Heat, generated by a moving vortex, is not conducted away, and an effective temperature of the vortex surrounding can become significantly higher than the monitored temperature of the sample's surface. This difference increases at low temperatures when both specific heat and heat conductivity of the materials are low. Magnetocaloric experiments enable us to measure directly the power release during the relaxation process. A typical result is shown in Fig. 5. Future discussions[14] of vortex movement at low temperatures should take into account this process of self-heating.

Energy dissipation released by the flux penetration is directly related to the problem of the magnetic instability in type-II superconductors. As has been mentioned above, in large-size type-II superconductors, including the high-T_c superconductors, the magnetic diffusivity, D_{mag}, can be much larger than the thermal diffusivity, D_{th}. Under conditions of appreciable flux flow, flux will be free to move and generate heat much more rapidly than the heat can be conducted away. A local increase of temperature results in a decrease of the critical current and therefore, in a deeper penetration of the flux. Under favorable conditions, the material remains superconduct-

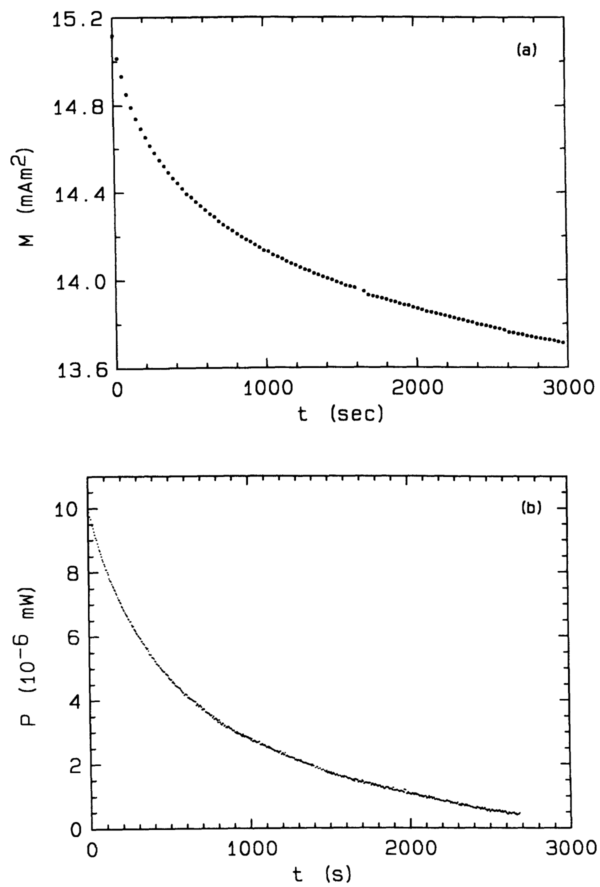

FIG. 5. (a) Relaxation of the remanent magnetization of the single-crystalline Bi-Sr-Ca-Cu-O sample and (b) corresponding power dissipation. The temperature is about 4.2 K. The time constant of the heat leak to the bath is about 10 sec.

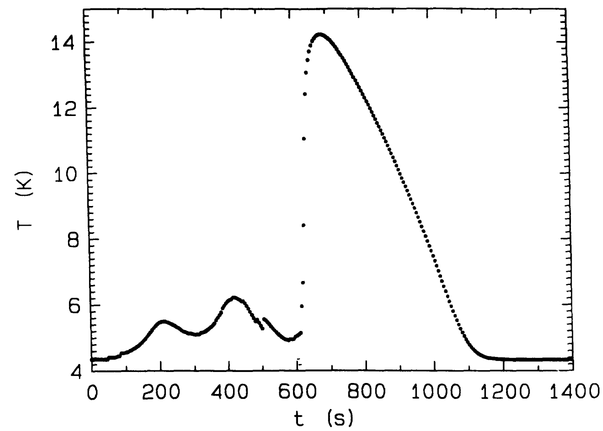

FIG. 6. Nonmonotonic temperature variation of the Bi-Sr-Ca-Cu-O sample during a field sweep with a rate of about 10 G/sec. Sharp increase in temperature at $t=600$ sec is associated with a flux jump. The field range is between 1 and 2 T.

ing, although the field distribution can hardly be expected to confirm the predictions of an isothermal theory. Under unfavorable conditions the process can lead to a thermal, and therefore, magnetic runaway. This relatively simple picture is not always followed by the experiments. The time duration of the instabilities can be orders of magnitude longer than expected, giving rise to smooth nonmonotonic temperature oscillations during the field sweep. This unexpected behavior is illustrated in Fig. 6. This is just one example of the yet unresolved problems of magnetic instabilities.[15]

The purpose of this paper is twofold. First, we wish to emphasize that no single-valued solution exists for an equation with more than one variable. In our case no unambigous selection can be done between numerous models and fitting parameters as long as it is based on the magnetization data only. Additional independent experimental data sources are necessary. We have shown that a direct measurement of the power dissipated by moving vortices is one of these independent approaches. Second, the magnetocaloric experiments provide a unique opportunity to study a wide range of fundamental properties of type-II superconductors, including the mapping of the surface barrier, thermally activated flow versus quantum tunneling of vortices, dynamics of magnetic instabilities, etc. Each of these subjects should and will be treated extensively.

*Permanent address: Sackler Institute of Condensed Matter Physics School of Physics and Astronomy, Tel Aviv University, Ramat Aviv, 69978 Tel Aviv, Israel.
†Permanent address: Solid State Physics Department, Academy of Mining and Metallurgy, al. Mickiewicza 30, 30059 Krakow, Poland.
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