Pinning and lower critical field in $Tl_2Ba_2CaCu_2O_x$ single crystals

A. V. Bezryadin, V. N. Kopylov, V. M. Krasnov, V. A. Larkin, V. V. Ryazanov, T. G. Togonidze,[1] and I. F. Shchegolev

Institute of Solid State Physics, Academy of Sciences of the USSR;[1] Physics Faculty, Tiflis State University

(Submitted 29 December 1989)
Pis'ma Zh. Eksp. Teor. Fiz. **51**, No. 3, 147–150 (10 February 1990)

The magnetic characteristics of $Tl_2Ba_2CaCu_2O_x$ superconducting single crystals have been measured by two different methods. The anomalous temperature dependence of the penetration magnetic field is linked with a sharp change in the pinning of magnetic flux at temperatures near 40 K.

Two series of measurements of the magnetic moment M in a field $H \perp ab$ have been carried out in order to determine the lower critical field H_{c1} of $Tl_2Ba_2CaCu_2O_x$ single crystals with $T_c = 115$ K. In one series of measurements, a vibration magnetometer was used to measure the dependence $M(H)$ at $T =$ const as the field was swept from 0 to 33 kG and back over a time on the order of 30–40 min. In the other series of measurements, a SQUID magnetometer measured the dependence $M(T)$ at $H =$ const during the heating of samples cooled beforehand to 100 K in a zero field.

Figure 1 shows examples of the dependence $M(H)$ for one of the single crystals. The irreversible behavior of the magnetization, expressed as a hysteresis and a remanent pinned flux, is generally observed at all temperatures. Above 40–50 K, however the irreversibility is slight, noticeable only at weak magnetic fields. On the forward paths of the $M(H)$ curves there are some clearly expressed minima, associated with the onset of the penetration of magnetic flux into the sample. Below 40 K the shape of the $M(H)$ curves is evidence of strong pinning. Figure 2 shows curves of $M(T)$ for another sample of the same lot. As the field is increased, the transition initially becomes noticeably broader, and its low-temperature edge shifts to a much lower temperature. In fields $H \geqslant 600$ G, however, these changes essentially stop.

Determining the field ($H_{\rm pen}$) at which flux begins to penetrate into the sample at a given temperature (or determining the temperature at which flux begins to penetrate in a given field, $T_{\rm pen}$) is complicated by the fact that the onset of the transition is blurred by imperfections in the shape and quality of the samples. Under these conditions the point at which penetration begins can be seen far more clearly on the curves of $\sqrt{B}$ versus H than on the curves of $M(H)$ or $B(H)$. Figure 1 shows some illustrative curves, along with the curves of $H_{\rm pen}(T)$ obtained in this manner. The latter curves incorporate the demagnetizing factor of the sample, $D = 0.8$ (Fig. 3).

At $T \geqslant$ K the values of $H_{\rm pen}$ agree within $\pm 5\%$ with the positions of the minima on the curves of $M(H)$, and they agree within $\pm 10\%$ with the values found in one way or another from the $M(T)$ curves.[1] Since the behavior of the magnetization is

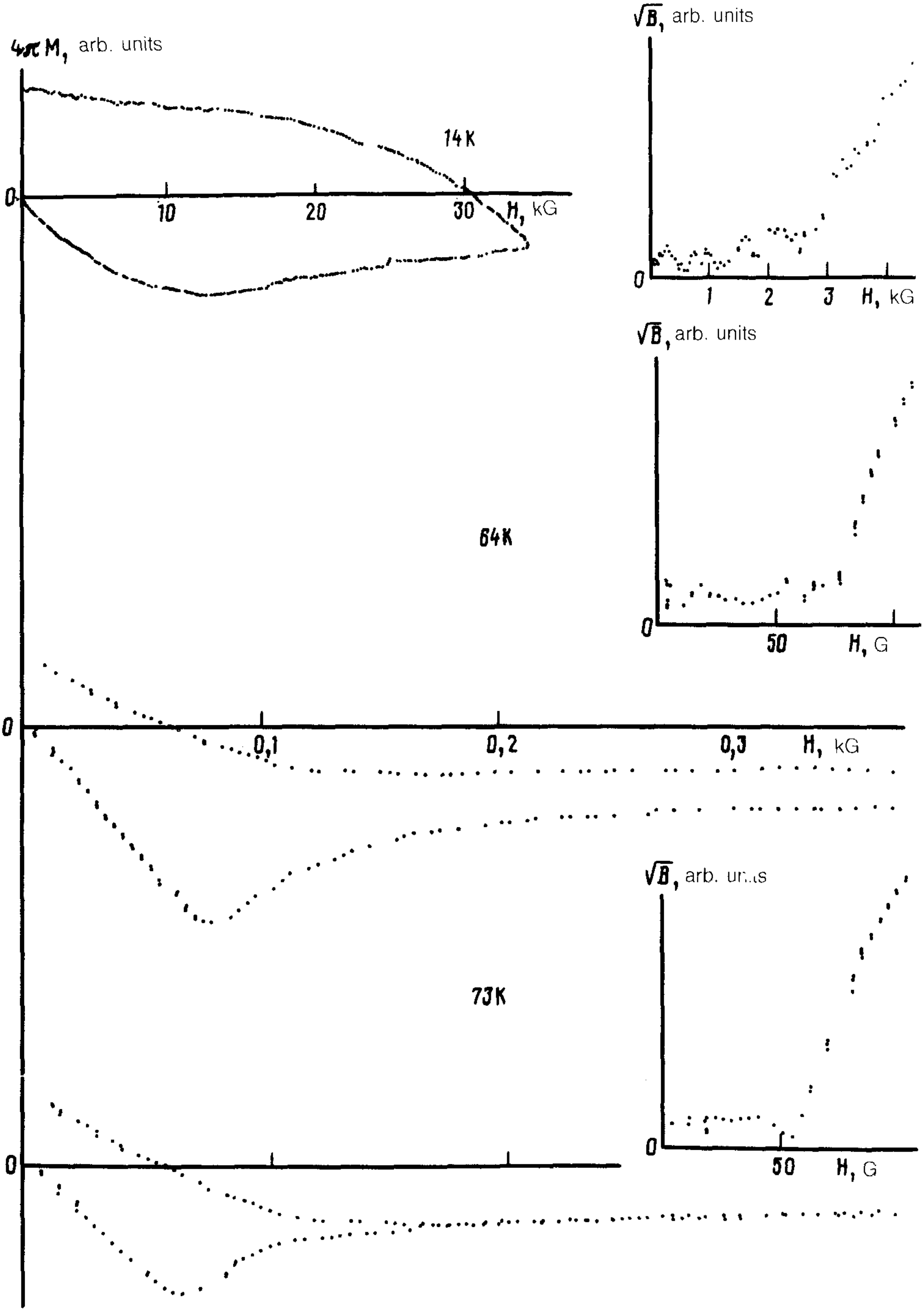
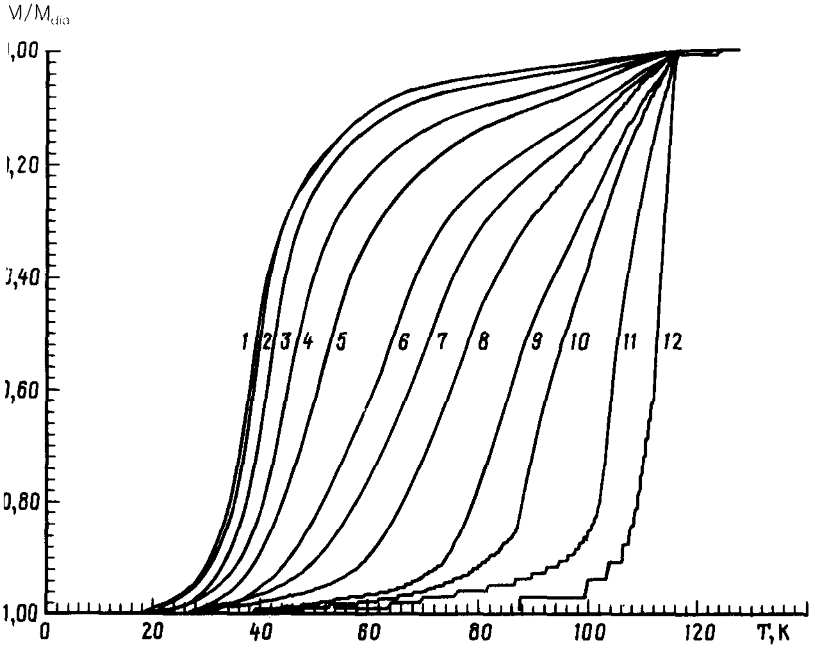


FIG. 1. The magnetic moment and $\sqrt{B}$ (in the insets) of a $Tl_2Ba_2CaCu_3O_x$ single crystal ($1\times1\times0.14$ mm) versus the external magnetic field at the specified temperatures ($H\|c$).



G. 2. Temperature dependence of the magnetic moment of a $Tl_2Ba_2CaCu_3O_x$ single crystal .14×0.52×0.14 mm) in various external fields. 1—766; 2—692; 3—572; 4—409; 5—269; 6—209; 7—3; 8—125; 9—94; 10—73; 11—39; 12—13 G.

early reversible at these temperatures, we can take these values of H_{pen} to be the alues of the lower critical field, $H_{c\,1}$.

Below 40–50 K, the value of H_{pen} begins to increase rapidly with decreasing emperature (see the inset in Fig. 3). This behavior can also be seen in a qualitative vay from the $M(T)$ curves in Fig. 2, which undergo almost no shift with increasing ield at low temperatures. The most likely reason for this sharp increase is a significant ncrease in the pinning; it would hardly reflect the temperature dependence of the field $_{c\,1}$. The same factor is apparently responsible for the rapid increase in the field H_{pen} vhich has been observed[2] in $YBa_2Cu_3O_7$ single crystals below 30 K.

Above 50 K the curves of $H_{c\,1}(T)$ are linear. This result agrees with the results of neasurements for other high-temperature[1,2] and low-temperature[3] layered supercon-luctors, while it is in poor agreement with the predictions of the BCS theory (the lashed line in Fig. 3). An extrapolation to $T=0$ yields values of $H_{c\,1}(0)$ from 0.5 kG o 0.8 kG and the corresponding values $\lambda = 0.08\text{-}0.1\ \mu m$. Clear evidence of a sharp lecrease in the pinning of a vortex lattice with increasing T in $Bi_2Sr_2CaCu_2O_x$ and $YBa_2Cu_3O_x$ single crystals was seen experimentally in Ref. 4 in measurements of the factor and frequency shift of a mechanical resonator near 30 K and 80 K, respective-y. Gammel *et al.*[4] also mentioned observing a "melting" of the vortex lattice in thal-

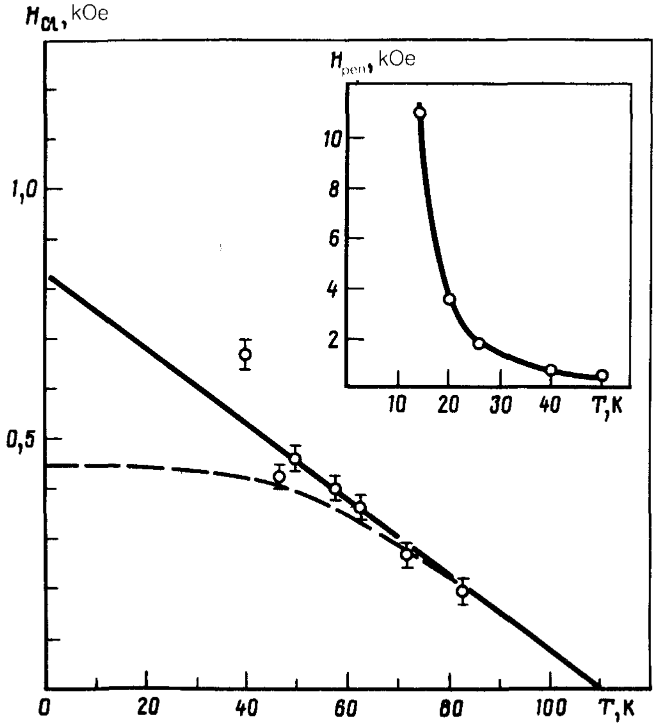


FIG. 3. The field at which flux penetration begins versus the temperature (the results of vibration measurements). The dashed line shows $H_{c1}(T)$ according to the BCS theory in the clean limit.

lium single crystals at a temperature near 40 K. This temperature agrees well with the temperatures (~40–50 K) at which we observed the sharp change in the pinning force.

The experimental data show that the existence of a fairly definite depinning temperature is apparently a general property of all high-temperature superconductors. Possible reasons for this effect are discussed in Refs. 5–7, but the choice of specific depinning mechanisms will require further experiments.

We wish to thank B. I. Ivlev for a useful discussion.

[1] M. V. Kartsovnik *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 595 (1988) [JETP Lett. **47**, 691 (1988)].
[2] T. Ishii and T. Yamada, Physica C **159**, 483 (1989).
[3] A. V. Pal'nichenko, *Candidate's Dissertation*, Chernogolovka, 1989.
[4] P. L. Gammel *et al.*, Phys. Rev. Lett. **61**, 1666 (1988).
[5] D. R. Nelson and H. S. Seung, Phys. Rev. B **39**, 9174 (1989).
[6] E. H. Brandt, Phys. Rev. Lett. **63**, 1106 (1989).
[7] M. V. Feigel'man and V. M. Vinokur, Preprint. Submitted to Phys. Rev. B. 1990.

Translated by Dave Parsons