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# Flux pinning regimes in Hg-1201

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ABSTRACT

We report on measurements of the time dependent irreversible magnetization due to flux creep in the high-$T_c$ superconductor $HgBa_2CuO_4$ (Hg-1201). Close attention is paid to the low-field and low-temperature region of the mixed state where the flux dynamics differs significantly from that found at higher temperature and field strength. Due to low-vortex density and only small thermal perturbations flux creep in this pinning regime is dominated by the motion of individually pinned flux lines. The observed time dependent decay of the magnetization departs clearly from a simple logarithmic time law. As is commonly accepted, the deviation results from dependence of the mean activation energy upon current density which is nonlinear and takes into account that during creep relaxation the effective pinning barrier depends on the actual distribution of vortices. We analyzed the relaxational behavior in Hg-1201 in order to specify the nonlinear relationship between activation energy and current density. Our experimental findings fit in best with predictions given by the collective pinning theory, i.e. the current dependent activation barrier follows a power-law behavior. On going to higher temperatures, this behavior first changes only moderately and in a continuous manner. In the vicinity of a characteristic temperature $T^*$, however, a uniform description is basically questioned by strong changes in vortex dynamics, which are associated with a crossover between pinning regimes of different type.



## 1. Introduction

The mercury based high-$T_c$ cuprate $HgBa_2CuO_4$ (Hg-1201) exhibits tetragonal symmetry with one single CuO-layer per unit cell and becomes superconducting at about 94 K. It is the relatively simple crystal structure and the fact that samples of high phase purity can be prepared, which favors Hg-1201 to be accepted as model system [1].

With regard to technical applications one of the most important properties of type-II superconductors refers to their ability of flux pinning in the mixed state. Profound knowledge about flux mobility and pinning properties is therefore of high practical interest. Over the last years extensive dc and ac magnetization studies revealed a complex vortex dynamics in the mixed state of Hg-1201 [2]. There it turned out that the pure phase shows a high vortex mobility over large parts of the superconducting phase diagram.

Only when cooling towards temperatures well below the melting transition, thermally assisted flux diffusion slows down and strong flux pinning can be observed. As is well-known, also in that regime a slow redistribution of flux lines takes place in the interior of the sample and gives rise to gradual changes of the total superconducting dipole moment. This so-called magnetic creep relaxation can be detected with high accuracy by use of sensitive measuring devices like e.g. SQUIDs. Long-term observation of the magnetic moment then provides valuable informations on creep dynamics of the vortex-system and pinning mechanism involved.

## 2. Experimental

Single-phase $HgBa_2CuO_{4-}$ was synthesized following the procedure described in Ref. [3]. Samples of ceramic Hg-1201 of some 100 mg have been prepared and their dc magnetization investigated by use of a commercial SQUID magnetometer (MPMS, Quantum Design).

## 3. Results and discussion

Investigating the mixed state of superconducting Hg-1201 below the irreversibility line revealed regions of quite different flux mobility of the vortex lattice as sketched in the $B$–$T$ phase diagram of Fig. 1. This became obvious when analyzing the flux dynamics by means of ac magnetization and creep relaxation measurements which allow inspection of the dynamic behavior on very different

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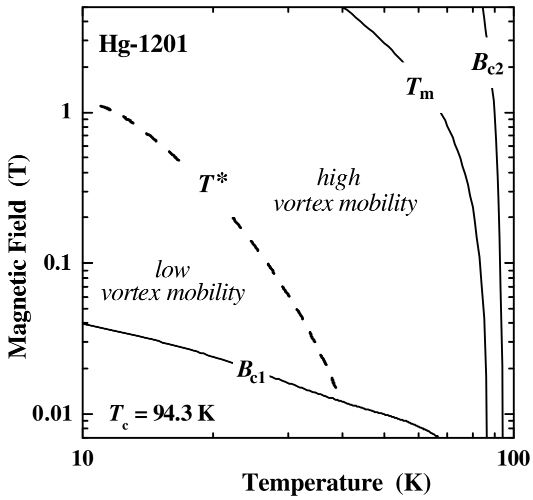


**Fig. 1.** Vortex phase diagram of Hg-1201 distinguishing pinning regimes with high- and low-vortex mobility in the solid flux state.

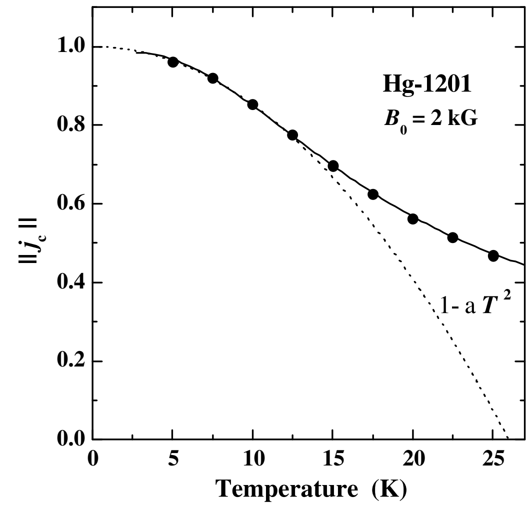


**Fig. 2.** Temperature dependence of the critical current density normalized to the magnitude at zero temperature obtained by aid of the quadratic fit $1 - aT^2$ shown. Quite remarkable, the fit also agrees fairly well with the ansatz $1 - (T/T^*)^2$.

time scales. Indeed, changes in magnetization due to rapid flux diffusion can be properly studied using ac methods, whereas those connected with flux creep have to be investigated by means of long-term relaxation measurements, which are the main subject of this paper.

Somehow confusing, within the solid flux phase an unusually strong decrease of vortex mobility has been found on cooling but well below $T_m$ where, flux lattice melting occurs. More precisely, only for temperatures and magnetic field strength below a characteristic line, named $T^*$ in the diagram of Fig. 1, thermally assisted flux diffusion slows down considerably and enables recording of magnetic hysteresis loops as well as creep relaxation measurements. Experimentally, $T^*(B)$ can be easily defined by a pronounced step-like anomaly in the temperature dependence of the dc magnetization which appear in both ceramics and single-crystalline samples [4].

It is just the abrupt change in vortex mobility around $T^*$ deep within the solid vortex phase of pure Hg-1201 that catches our attention and gives motivation to investigate the flux creep behavior in more detail. Preliminary results of early relaxation experiments performed at temperatures $T < 30$ K and magnetic field strength $B < 3$ kG were presented recently [5]. These studies indicate systematic changes in flux dynamics which occur when approaching $T^*$ from below. It turned out that the general behavior can be well described within the scope of the collective pinning theory [7]. Most remarkable, the variation of the given functional form with temperature can be attributed mainly to changes of one single parameter, namely the exponent $\mu$, which represents a characteristic quantity specifying the pinning properties. Meanwhile, we improved both experiment and data evaluation in order to check this behavior with much higher reliability.

For the nonlinear dependence of the mean activation energy $U$ upon supercurrent density $j$ collective pinning theory generally predicts a power-law of the form $U \propto \{(j/j_c)^{-\mu}-1\}$. Here, $\mu$ is a critical exponent depending on dimensionality and effective bundle size of the vortex assembly, which is a function of temperature and magnetic field. Furthermore, $j_c$ denotes the critical current density and is temperature dependent as well. Indeed, the rapid decrease of the magnetic hysteresis for $T \rightarrow T^*$ reflects a strong temperature dependence of $j_c$, which has to be taken into account and is depicted in Fig. 2.

For the low-temperature and low-field region it is expected that flux creep is dominated by the motion of individually pinned flux lines. Above a certain temperature or field strength, however, the interaction between the vortices cannot be neglected any longer and will modify the creep process significantly, because pinning now involves collectively pinned vortex bundles. Thus, temperature and dc magnetic field have a certain effect. On the other hand, in any case the observed relaxational behavior departs from a simple logarithmic time law. The deviation results from the nonlinear dependence of $U(j)$ above mentioned. Unfortunately, this becomes clearly visible only at larger time scales, i.e. in order to determine the actual relaxation law accurately from experiment, quite long observation times are usually needed.

An alternative procedure frequently used in literature and originally proposed by Maley et al. [6] is based on the rate equation $dM/dt \propto \exp\{-U/kT\}$ leading to $U = kT(c - \ln|dM/dt|)$. Here c is assumed to be constant and used as fitting parameter yielding a smooth dependence of $U$ vs $M$ (see e.g. [5]). Since, $M \propto j$ and $j/j_c$, respectively, the functional form of $U(j/j_c)$ can be determined this way. In accordance with previous findings, the evaluation of our late experimental data again yields a power-law behavior and confirms the correctness of the collective pinning theory [7].

However, when assuming a fixed power-law, the experimental data matches with the expected behavior only for restricted ranges in temperature. Consequently, when enlarging the temperature interval, the agreement becomes less accurate and the given ansatz describes the actual behavior of $U(j)$ only approximately. This is due to the fact that the exponent itself is actually temperature dependent due to changes in the delicate balance between pinning and inter-vortex interaction. At lower temperatures the fit is remarkable good as becomes evident from Fig. 3 and we obtain $\mu = 0.15$ for $T \leqslant 10$ K. In particular, the magnitude of $\mu$ is in excellent agreement with theoretical predictions. Indeed, for the low-temperature, low-field region where it is assumed that individual flux lines dominate the creep behavior collective pinning theory leads to $\mu = 1/7$ in the three-dimensional case.

In result of a careful data evaluation, the obtained exponent $\mu$ is small at low-temperature but becomes rapidly larger on warming above about 10 K as depicted in Fig. 4. The pronounced increase of $\mu$ for increasing temperature now suggests that single-vortex pinning becomes considerably affected by thermal fluctuations and interaction between vortices has to be taken into account. The evolution of $\mu(T)$ reflects mean-field behavior and according to theory it seems likely to conclude that we find here experimental evi-

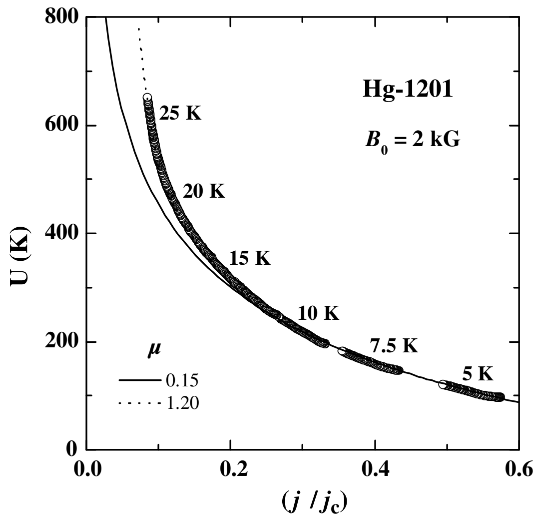


**Fig. 3.** Mean activation energy as function of supercurrent density normalized to the critical current density referring to the different temperatures chosen. A field strength of 2 kG has been applied after cooling the sample in zero field.

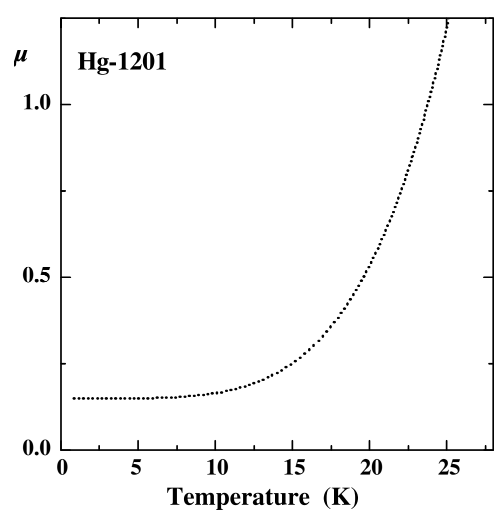


**Fig. 4.** Temperature dependence of the critical exponent as it has been determined from the analysis of the creep relaxation data by means of the collective pinning theory.

dence for a crossover from the regime of single-vortex to vortex-bundle pinning.

The steady increase of $\mu(T)$ suggests gradual changes of a more or less homogenous vortex phase. Nevertheless, this idea must be strongly questioned in view of various experimental hints, which indicate that the crossover between the different pinning regimes is not as continuous as it looks like from this mean-field behavior. Instead and what has been discussed earlier in more detail [5], the crossover is most probably associated with a temporary coexistence of both pinning regimes over a certain temperature interval, i.e. in a figurative sense the transitional behavior is reminiscent more of the 1st than the 2nd order phase transition. It can be therefore expected that around $T^*$ the different pinning regimes refer to locally separated regions, the relaxation rates of which differ much. In consequence, the detected creep rate represents an average of both a slower and a faster process weighted by the respective volume part.

Above $T^*$ the occurrence of magnetic relaxation due to fast flux diffusion in Hg-1201 is now well established by experiment [2]. As mentioned, fast relaxation taking place in parts of the mixed phase cannot detected properly by creep measurements as performed here but requires the use of ac-methods. Accordingly, fast magnetic relaxation was extensively studied by investigating the frequency dependent response of the ac magnetization which enabled the identification of fast diffusion-like processes in Hg-1201 for $T > T^*$.

It seems likely to assume that the crossover region around $T^*$ separates pinning regimes of different type. This also becomes obvious when regarding the field dependent behavior of the relaxation rate. In the low-temperature region the magnetic field dependence of the creep rate turns out to be rather weak. This again indicates an activation energy being only marginally influenced, i.e. roughly holds $U(B) \approx$ const.. This, however, is characteristic for single-vortex pinning where interaction between vortices is almost irrelevant. In contrast, for $T > T^*$ the mean activation energy attributed to fast magnetic relaxation in Hg-1201 was found to be strongly dependent on the magnetic field. Since, the latter fact confirms the important role of vortex–vortex interaction, the flux dynamics in that temperature region is highly indicative of the regime of vortex-bundle pinning.

## 4. Conclusions

In summary, with regard to earlier experiments, our present creep studies give additional support for a scenario where a transition between pinning regimes associated with different types of vortex pinning may result in strong changes in the flux dynamics of a superconductor. In a low-magnetic field of 2 kG, these changes are detectable in the relaxational behavior only at elevated temperatures, i.e. above about 10 K, but they increase dramatically on further heating towards $T^*$. It therefore seems likely to conclude that the crossover from single-vortex to vortex-bundle pinning increases strongly the flux mobility in Hg-1201 for temperatures around $T^*$ and also gives rise to the pronounced decrease of diamagnetic shielding observed.

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