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High vortex mobility in Hg-1201

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Abstract
We report on detailed investigations of the mixed state in the mercury based high-$T_c$ superconductor HgBa$_2$CuO$_4$ (Hg-1201) by means of ac and dc magnetization measurements. Over large parts of the superconducting phase diagram the vortex mobility turned out to be remarkably high. From knowledge of the phase boundaries and the irreversibility line also determined, it became clear that in Hg-1201 thermal activation strongly supports the flux diffusion in both liquid and solid vortex phases. Thermally assisted flux diffusion widely stops here only for temperatures well below the melting line. In particular, the strong decrease of vortex mobility within the solid phase suggests a transition between different regimes originating from a different nature of vortex pinning, i.e. collective or single, and indicates a weak to strong pinning crossover of vortex matter in pure Hg-1201. A phenomenological description of the flux dynamics based on the classic diffusion formalism has been performed.

Keywords: Hg-based high-$T_c$ superconductors, phase diagram, vortex dynamics

1. Introduction
The cuprate HgBa$_2$CuO$_4$ (Hg-1201) belongs to the family of mercury based high-$T_c$ superconductors which exhibit transition temperatures of up to 135 K [1]. With only one single CuO$_2$ layer per unit cell Hg-1201 is the most simple representative of this class and can be produced with high phase purity. The experimental investigations derive much benefit from this fact concerning significance and reliability of the data obtained.

A prominent reason limiting technical applications of the pure material arises from its insufficient ability to pin magnetic flux when it becomes superconducting. Apart from the determination of the $B$-$T$ phase diagram to get knowledge about flux mobility and pinning properties is therefore of high practical interest. Time or frequency dependent measurements of the magnetization may serve here as an efficient tool to investigate the flux dynamics experimentally. Accordingly, the mixed state of superconducting Hg-1201 has been studied in detail by means of extensive ac magnetization measurements.

2. Experimental
Single-phase HgBa$_2$CuO$_{4+δ}$ was synthesized from a mixture of Ba$_2$CuO$_{3+δ}$ and HgO following the procedure described in Ref.2. From the base material then samples of ceramic Hg-1201 of some 100 mg have been prepared. One specimen has been investigated here by means of ac and dc susceptibility measurements (MPMS and PPMS, Quantum Design).

3. Results and discussion
3.1 Magnetization
The superconducting transition occurs in Hg-1201 at about 94 K. What is disillusioning from a practical point of view, even if cooled well below the transition temperature in both ceramic and single-crystalline samples only a relatively low magnetic remanence can be induced by
means of external dc magnetic fields [3]. This, however, indicates that magnetic flux in Hg-1201 is only weakly pinned at these temperatures. Indeed, as measurements of the dc magnetization clearly show, the regime of strong flux pinning which gives rise to the familiar hysteresis loops of the Bean type is reached in pure Hg-1201 only for temperatures lower than about 20 K [4]. These findings thus point to a high flux mobility which affects the mixed state over a wide range and refer to the important role of flux dynamics in this system.

The competition of elastic and pinning energy of the vortices and the energy of thermal fluctuations gives rise to the rather complex behavior of the vortex system as it is generally found in high-$T_c$ materials [5]. Melting of the flux lattice, for instance, is now well established in the literature and has been detected particularly in Hg-1201 also by NMR [6]. On the other hand, information about the dynamics of vortices can be received most directly from their response to externally applied alternating magnetic fields. Consequently, we investigated the ac magnetization of the mixed state in superconducting Hg-1201.

The temperature dependence of the off-phase component $M''(T)$ is shown in Fig.1. Here it becomes apparent that flux lattice melting leads to a quite sharp feature, named peak 1, which is almost independent on the excitation frequency used. In contrast, the additional peak below the melting transition, denoted peak 2 in the figure, turns out to be strongly frequency dependent, which is characteristic of diffusion phenomena. Since the magnetic response depends almost linearly on the excitation field $b$, the dynamic behavior can be theoretically treated in a simple manner by use of the ordinary diffusion equation [7]. Hence, we assume

$$\frac{\partial b}{\partial t} = D \Delta b$$

where $D$ denotes the magnetic diffusivity being closely linked with the mean mobility of the vortices. In general, the coefficient $D$ depends on both temperature and external dc magnetic field, i.e. $D = D(T,B)$. Experimentally, this becomes evident from Fig.2, where the frequency dependence of the ac magnetization is shown at fixed temperature and which poses a counterpart to Fig.1 where, in contrast, the dc magnetic field is held constant. In many cases the transport can be satisfactorily described by the thermally activated form

$$U \approx U_0 \left[1 + B / B_0 \right]^{-1}$$

where $B_0$ is an auxiliary parameter. The comparison presented in Fig.3 confirms that our experimental findings are in fair agreement with the given theoretical expectation. Obviously, increase of the external dc magnetic field strongly favors the mobility of vortices in the sample.

### 3.2 Phase diagram

In order to get a comprehensive view of the whole situation in superconducting Hg-1201, the phase diagram is presented in Fig.4. Apart from the phase boundaries here is also inserted a collection of lines which depict symbolically the diffusion behavior of the vortex system. The lines show the temperature and field dependence of peak 2 in the ac magnetization at different frequencies. For this purpose all peak positions in the diagram obtained at a certain frequency are connected by a common line. In Fig.4 this has been done for a selection of frequencies chosen in experiment. The peak in $M''(T)$ reflects the maximum response of the vortex system which is assumed to be diffusion controlled in our case. Thus, each line of the collection
represents a line of constant magnetic diffusivity synonymous with one of constant vortex mobility. As is to be expected, and can be easily seen from the diagram, flux diffusion in Hg-1201 slows down quickly on decreasing temperature and magnetic field strength but well below the melting line.

The magnitude of loss peak 2 depends on the mean vortex density. The latter, however, is roughly proportional to the externally applied dc magnetic field. Decrease of the field strength, therefore, results in a lower mean vortex density in the sample. In consequence, the detected peak magnitude of $M''(T)$ becomes smaller and finally vanishes when approaching the lower critical field. Here $B_{c1}$ is approximated by the diamagnetic "peak field" which can be directly obtained from the virgin magnetization curve. It is defined by the magnetization maximum which has to be attributed to the beginning of flux penetration.

The vortex phase forming above this boundary is restricted by the melting line. As NMR investigations clearly showed, the flux mobility decreases strongly on entering the solid from the liquid vortex phase [6]. Nevertheless, though becoming lower the flux mobility remains remarkably high also in the crystalline phase. Only for temperatures considerably lower than $T_m$ vortex pinning becomes fully effective and leads to hysteresis loops of the Bean type.

4. Conclusion

Our investigations reveal a high vortex mobility in superconducting Hg-1201 for large parts of its phase diagram. Evidently, thermal activation strongly affects flux pinning and leads to a weakly remanent mixed state over a broad temperature range. The latter also includes the melting transition, which separates here a weakly pinned solid phase (quasi-ordered Bragg glass) from a vortex liquid. Thermally assisted flux diffusion widely stops only for temperatures well below the melting line. It is particularly the strong decrease of the mean flux mobility within the solid phase which suggests a transition between different regimes originating from a different nature of vortex pinning, i.e. collective or single. This scenario is quite reminiscent of a weak to strong pinning crossover of vortex matter as treated e.g. in [9]. A detailed analysis of the transitional behavior found here in Hg-1201 is therefore of special interest but beyond the phenomenological treatment used above.

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Figures

Fig. 1  Off-phase ac magnetization at different frequencies at fixed external dc magnetic field using an ac field amplitude of 0.5 G

Fig. 2  Off-phase ac magnetization at different frequencies at fixed temperature using an ac field amplitude of 0.5 G
Fig. 3  Field dependence of the activation energy

Fit: $\propto [1 + B/B_0]^{-1}$

$B_0 = 0.67 \text{ T}$

Fig. 4  Superconducting phase diagram

$T_c = 94.3 \text{ K}$