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WEAK QUANTUM FLUX CREEP AND STRONG PINNING IN THE NEW SUPERCONDUCTOR MgB_2*

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The newly discovered superconductor MgB_2 has a transition temperature T_c of about 40 K, which is touching the upper line of that predicted by the phonon-mediated Bardeen–Cooper–Schrieffer (BCS) theory. It is interesting to investigate the flux creep in MgB_2 and compare it with other superconductors. We have measured the magnetization relaxation of MgB_2 sintered at high temperature and high pressure. It is found that the quantum tunnelling and the thermally activated flux creep are very weak, implying a strong pinning in this material.

Keywords: MgB_2, flux creep, pinning
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I. INTRODUCTION

Flux creep in the mixed state of type-II superconductors has been well studied. It is the main cause for the magnetization relaxation and the superconducting current decay. The two physical processes leading to the magnetic relaxation are the thermally activated hopping[1] of vortices and their quantum tunnelling[2,3] between the pinning centres. Therefore, investigations of the flux creep of superconductors can attain much important information about vortex motion and pinning, which will ultimately influence the high-power application. Recently, a new superconductor[4] MgB_2 has been found with a transition temperature T_c of about 40 K, which lies between the conventional superconductors and the high-T_c superconductors. Therefore, it is interesting to investigate the flux dynamics in MgB_2 and compare it with other superconductors.

In this paper, we report on the magnetization relaxation measurement of MgB_2 sintered at high temperature and high pressure. It is found that the quantum tunnelling and the thermally activated creep are very weak, implying a strong flux pinning in the material.

II. EXPERIMENTAL DETAILS

The sample used was prepared at high pressure and high temperature (P=6GPa, T=950°C) for 0.5h which was described clearly in a recent publication.[5] X-ray diffraction (XRD) analysis showed that it is of single phase, with the second phase less than 1wt%. Magnetic measurements were carried out with a superconducting quantum interference device (SQUID, Quantum Design MPMS 5.5T).

III. RESULTS AND DISCUSSION

In Fig.1, we present the temperature dependence of magnetization measured in the ZFC (zero-field cooled) process. In the ZFC process the data were obtained in the warming-up process at a field $H=1\times10^{-3}$T, after the temperature was lowered from above T_c to about 5K at zero field. The magnetization data were collected versus time after the field was increased to a certain value. The diamagnetic transition is very sharp at about 40K and the transition width is about 3K. The ZFC signal describes the internal magnetic flux profile that is related to the flux motion.

In Fig.2, the time dependence of the magnetization M is shown from 2K to 32K at 0.5T. It is clear that the data can be fitted linearly in a double logarithmic scale.

From the thermally activated flux motion model, the magnetization relaxation can be described by

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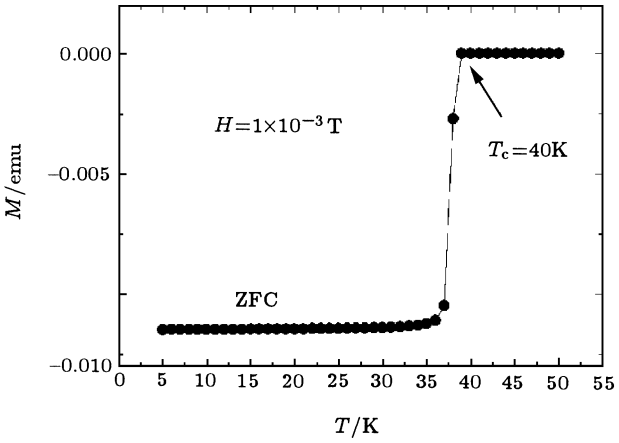


Fig.1. Temperature dependence of the ZFC magnetization measured at H=1×10^{-3} T. The diamagnetic transition is very sharp at about 40 K and the transition width is about 3 K.

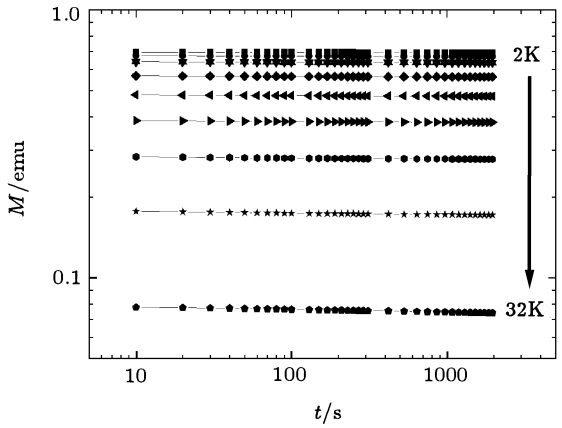


Fig.2. Time dependence of the magnetization $M(t)$ in logarithmic scale at temperatures of 2K, 4K, 6K, 8K, 10K, 14K, 18K, 22K, 26K, 30K and 32K. It is clear that, in a double logarithmic scale, the data can be fitted linearly very well.

$$\mathrm{d}M/\mathrm{d}t \propto \exp(-U_e/k_BT), \quad U_e(j,T) = U_0 - w, \quad (1)$$

where U_0 is the intrinsic pinning energy, w is the work done by the Lorentz force on the vortex when it moves from one pinning point to another, and U_e is the effective pinning energy. Since the current is proportional to magnetization, the superconducting current decay also obeys the same relation.

In the Anderson–Kim model, a linear relation $U_e(j,T) = U_c(1 - j/j_c)$ is proposed, where U_c is a temperature-dependent function. Using this relation, one can obtain the solution of Eq.(1)

$$M(t) = M_0\{1 - (k_BT/U_c)\ln(t/t_0)\}. \quad (2)$$

The normalized relaxation rate is defined as $S(T)$=-d$\ln M$/d$\ln t$, and the model predicts that S is proportional to temperature.

The Anderson–Kim model is valid only when j, which is proportional to M, does not drop too much from the corresponding critical value j_c. Generally, at low temperatures, the decay rate S is small and the Anderson–Kim model is preferred.

However, at high temperatures, the decay rate S is large, and $U_e(j,T)$ has a more complicated current and temperature nonlinear dependent relation which is predicted by the collective pinning theory[6] and the vortex glass theory.[7] So the relation of $S(T)$ deviates from the linear behaviour. Also, when the temperature approaches the irreversible line where flux flows freely, the relaxation rate S rises to 100%.

When the temperature decreases towards 0K, according to the thermally activated flux, the decay rate S hopping should drop linearly to zero. However, because the flux can move through quantum tunnelling, the relaxation rate S of magnetization does not reach zero and arrives at some finite value. The residue relaxation rate S at 0K is a strong evidence of the flux quantum tunnelling.

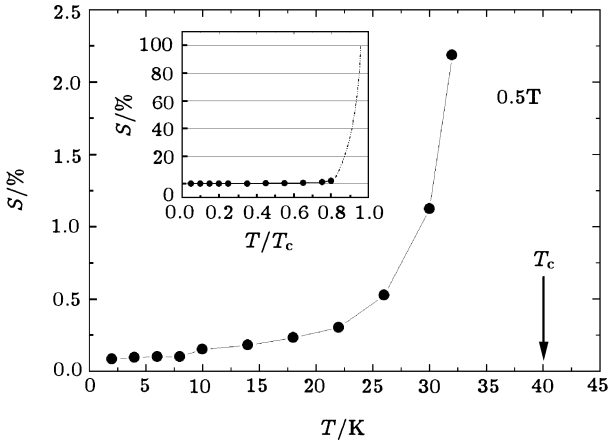


Fig.3. Relaxation rate $S(T)$ of the magnetization at H=0.5T from 2K to 32K. The relaxation rate S cannot be extrapolated to zero at 0K. It is about 0.1%. In the inset, the same data are plotted with normalized temperature T/T_c, where T_c ~40K. The dash-dot line is a guide to the eye.

Figure 3 shows the decay rate S of our MgB_2 sample at H=0.5T from 2K to 32K. The relaxation rate S cannot be extrapolated to zero. Therefore, the quantum creep of flux turns out to exist in MgB_2. However, it is found that the quantum creep rate $S(0)$ at 0K of our sample is only about 0.1%, one order of magnitude smaller than that in high-T_c superconductors. So we conclude that the newly discovered superconductor,

MgB_2, has a very small quantum creep rate at 0K, which is similar to conventional superconductors.

From the work of Blatter *et al.*[8] one obtains that, in the dissipative limit, the normalized relaxation rate $S(0)$ of magnetization or superconducting current in the quantum region at 0K is given by

$$S(0) \approx e^2 \rho_n(0)/2\hbar L_c(0) \qquad (3)$$

where $\rho_n(0)$ is the normal state resistivity at 0K and $L_c(0)$ is the length of the tunnelling vortex segment, which decreases with increasing anisotropy ε and the Ginzburg–Landau (GL) parameter κ.

In the case of the new superconductor MgB_2, the normal state resistivity $\rho_n(0)$ is about $1\mu\Omega/\mathrm{cm}$[9,11] and the GL parameter $\kappa \sim 26$,[9] which are small compared to the high-T_c superconductors. Also, the MgB_2 has an almost isotropic structure[10]. All the above parameters cause the quantum relaxation rate of MgB_2 to be small.

In Fig.3, another phenomenon one can easily see is that the decay rate $S(T)$ rises rather slowly when the temperature increases. A plateau extends from 2K to about 20K which is almost half way to $T_c \sim 40$K. And, with the temperature approaching the irreversible line, about 37K at $\mu_0 H = 0.5$T, the decay rate $S(T)$ can be supposed to take a sharp rise to 100%. In the inset we show the drastic rising, where the dashed line is a guide to the eye.

The rather stable relaxation rate as the temperature rises indicates that the thermally activated flux creep is also very weak. Together with the high superconducting critical current density of the material, e.g. $j_c = 1 \times 10^5 \mathrm{A/cm}^2$ [11] at 15K and 1T, we can conclude that the pinning energy is very high.

IV. SUMMARY

In summary, we have measured the magnetization relaxation $M(t)$ of the newly discovered superconductor MgB_2 at a field of 0.5T. The temperature dependence of the relaxation rate has been derived. It is found that the quantum flux creep is very weak compared with high-temperature superconductors and similar to conventional superconductors. We also found some evidence of strong flux pinning in MgB_2 that efficiently suppresses the thermally activated flux creep.

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