

Observation of quantum effects of vortices in MgB₂ superconductors

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Abstract

Irreversibility lines and magnetic relaxation of MgB₂ are studied. The Large separation between irreversibility line and upper critical magnetic field for $T \rightarrow 0$ is explained by quantum fluctuations of vortices. Theoretical fits are in good agreement with experimental data. Magnetic relaxation rates of MgB₂ are studied. A quantum correction of the relaxation rate is proposed, leading to a simple evaluation of the energy barrier: $U_0(T, H) \sim U_{th}(T)U_H(H) \propto (1 - T/T_c)^\alpha(\mu_0 H)^\beta$ with $\alpha \sim 1.5$ and $\beta \sim -2.0$.

Key words: Quantum effects; vortex matter; MgB₂

Recent studies of vortex dynamics of MgB₂ superconductor suggest that quantum effects may play an important role in this material [1]. According to Blatter and Ivlev [2,3], a melting line has two contributions, corresponding to thermal contribution and quantum contribution respectively. From their theory, the melting (or irreversibility) line can be expressed as:

$$H^* \approx 4\theta^2 H_{c2}(0)/(1 + \sqrt{1 + 4S\theta/t})^2, \quad (1)$$

where $\theta = c_L^2(\beta_{th}/G)^{1/2}(1/t - 1)$ is the temperature variable, $t = T/T_c$ the reduced temperature, $\beta_{th} \approx 2.5$, c_L the Lindemann criterion, G the Ginzburg number characterizing thermal fluctuations, and $S = q + c_L^2(\beta_{th}/G)^{1/2}$ the suppression parameter. In the theory,

$$q = 2\tau_r c Q \sqrt{\beta_{th}/G}/\pi^3 \lambda \approx 2\nu \sqrt{\beta_{th}/G}/\pi^3 K_F \xi, \quad (2)$$

where $Q = e^2 \rho_N / \hbar d$ is the quantum sheet resistance, $\rho_N = m/e^2 n \tau_r$, d the layer spacing, m the effective mass, τ_r the relaxation time, n the carrier density, λ the penetration depth, ν the free parameter, and K_F

the Fermi wavenumber nearly constant at low temperature. Using a temperature dependence of the coherence length, $\xi \approx \xi(0)/(1 - t)^{1/2}$, we have: $q(t) \approx 2\nu \sqrt{\beta_{th}/G}/\pi^3 K_F \xi \approx q_0(1 - t)^{1/2}$ with q_0 the quantum parameter at 0 K. As can be expected from the change of the magnetic structure along the irreversibility line (where Q is temperature dependent, and λ may not precisely follow the $\xi \approx \xi(0)/(1 - t)^{1/2}$ relation in reality), affected by the crystallographic structure, we use the following expression for an effective quantum parameter $q(t)$:

$$q(t) = q_0(1 - t)^p, \quad (3)$$

where p is an adjustable free parameter. Figure 1 represents fits of irreversibility lines (here, $H^* = H_{irr}$) of several MgB₂ samples [one thin film ($T_c \approx 38$ K) and two MgB₂ bulk materials ($T_c \approx 39$ K)] using a vibrating sample magnetometer (VSM) [1], in good agreement with the experimental data. The inset table presents the corresponding fitting parameters. The following differences have to be considered when comparing the data as their crystallographic structures and defects are rather different. The thin film, having relatively large p value when comparing with bulk samples, is mainly *c*-axis oriented with textured structures. The

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Fig. 2. Magnetic field dependence of U_0 at $T = 0$. Inset: $U_{th} = U_0(\mu_0 H)^2$ scaling results.

0.30 and $\beta = -2.0 \pm 0.1$, is found for $p = 0$. Therefore, we determine the simple approach $U_0(T, H) \approx U_{th}(T)U_H(H) \propto (1 - T/T_c)^\alpha(\mu_0 H)^\beta$.

In conclusion, we propose the effective quantum parameter $q(t)$ under the framework of quantum fluctuations. The relative contributions of quantum and thermal effects are evaluated for different irreversibility lines [1]. Theoretical fits are in good agreement with experimental data. Furthermore, we have measured the temperature dependence of the magnetic relaxation rates of a MgB₂ superconductor in three magnetic fields. By extrapolating each relaxation rate R to $T = 0$ K, we find that the extrapolation does not reach zero, revealing that the quantum tunneling of vortices plays an important role in this superconductor. A quantum correction of the relaxation rate is proposed for properly evaluating the energy barriers. We find that the correction leads to the energy barrier monotonically increases with decreasing temperature. Both the analyses suggest that the quantum effects of the vortex matter exist in MgB₂ superconductors.

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