Extreme smallness of the transverse force on moving vortices in $Bi_2Sr_2CaCu_2O_8$

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Abstract

We report the results of direct force measurements of the longitudinal (pinning and viscous) forces and the transverse ("Magnus") force on vortices along the c direction in $Bi_2Sr_2CaCu_2O_8$ single crystals. The magnetic flux is applied locally to the center of a crystal using a micro-electromagnet, thus avoiding edge pinning and geometrical-pinning effects. The pinning and viscous forces measured by two different high-Q mechanical oscillator techniques are in good agreement, and agree with theoretical predictions. The measured transverse force on moving vortices is extremely small, in sharp contrast to recent "universal" theories, which predict the full hydrodynamic value. The data indicate that the transverse force on a moving vortex is smaller than the hydrodynamic value by a factor $\alpha \leq 0.015$.

Key words: vortex; superconductivity; Magnus; mechanical oscillator; transverse force

The form of the transverse force on a moving vortex (Magnus force) is a subject of theoretical controversy. Early theories [1] as well as recent topological calculations [2] yield the same form as the classical hydrodynamic result. This result is simply the negative of the Lorentz force; that is, in these theories, the transverse force does not distinguish between a superfluid moving past a stationary vortex and a vortex moving through a stationary superfluid. For a vortex with velocity $\mathbf{v}_v$, oriented with flux along the z direction, the predicted transverse force is

$$\mathbf{F}_{\text{transverse}} = -\frac{h}{2}\rho_s \mathbf{v}_v \times \hat{\mathbf{z}} \qquad (1)$$

where h is Planck's constant and ρ_s is the superfluid density. Other theories [3,4], which include two-fluid models, effects of rotons, phonons, impurity scattering, etc., obtain a similar form, but with an overall multiplicative constant α which can differ from unity:

$$\mathbf{F}_{\text{transverse}} = -\alpha\frac{h}{2}\rho_s \mathbf{v}_v \times \hat{\mathbf{z}} \, . \qquad (2)$$

According to various authors, transfer of momentum from quasiparticles outside the vortex can increase α, while the scattering of vortex core electrons from impurities [3,4] can decrease α. Here, we report direct force measurements on moving vortices in $Bi_2Sr_2CaCu_2O_8$ (Bi2212); our results indicate a transverse force smaller than the hydrodynamic value, supporting the latter theories.

In Fig. 1 is a schematic of our experimental setup. A small electromagnet (diameter $D = 0.5$ mm) applies flux locally to the center of a superconducting crystal, as described previously [5]; the magnet can be oscillated by a piezoelectric tube in both longitudinal and transverse directions. The directions are relative to the motion of the mechanical oscillator on which the superconducting crystal is mounted; our high-Q oscillators are the sensitive force detectors in this experiment, and have been used previously to detect vortex motion as small as 0.5 Å[6]. Applying the magnetic flux locally avoids complications due to transport currents and edge pinning.

The pinning force is given by $F = \pi B^2 D^2 A / 2\mu_o L$, where the magnetic field $B = 0.2$ T, the amplitude of motion $A = 19$ nm, and the magnet gap $L = 0.5$ mm. This gives a predicted force for $YBa_2Cu_3O_{7-\delta}$ (Y123) of $F_{\text{pin}} = (5 \pm 1) \times 10^{-7}$ N, in good agreement with the force determined from the upper resonance curves in Fig. 2, $F_{\text{pin}}^{\text{expt}} = kx_o/Q = (5.9 \pm 0.5) \times 10^{-7}$ N. For $Bi_2Sr_2CaCu_2O_8$, however, the phase of the motion has shifted by 90° (lower curves in Fig. 2), indicating that the motion has become purely viscous (force proportional to velocity instead of displacement). The size of the viscous force measured at 77 K is approximately $F_{\text{viscous}}^{\text{expt}} = 7.1 \times 10^{-8}$ N, corresponding to a viscosity per unit length per vortex of $\eta = 9.5 \times 10^{-8}$ N-s/m^2. This is close to a Bardeen-Stephen-model estimate $\eta = \Phi_0 H_{c_2}/\rho_n c^2 = 8 \times 10^{-8}$ N-s/m^2, indicating 3D vortex behavior at low fields.

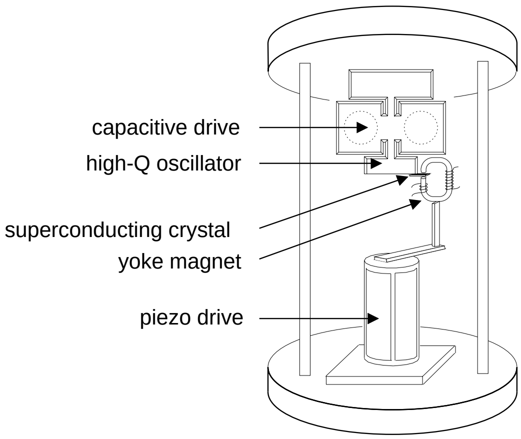

Fig. 1. Experimental setup for measuring vortex forces.

The viscous force data indicate that the vortices are in motion, but the data of Fig. 3 show that no appreciable transverse force is evident. If the transverse force parameter $\alpha = 1$, a measurable force is predicted from Eq. (1): estimating ρ_s at 77 K to be about $\rho_s \approx 5 \times 10^{26}$ /m^3, and using our crystal thickness of 61 μm and vortex velocity $v = \omega A = 7.5 \times 10^{-4}$ m/s, the expected total transverse force is about $F_{\text{transverse}}^{\alpha=1} = 1.1 \times 10^{-7}$ N. The data in Fig. 3 provide an upper bound $F_{\text{transverse}} \leq 1.6 \times 10^{-9}$ N, near our resolution limit. The data imply a suppressed transverse force with $\alpha \leq 0.015$.

In the core-electron-scattering picture [3,4], $\alpha < 0.015$ implies a dirty limit where the scattering time is less than the inverse core level spacing. Although the level spacing, if any, in $Bi_2Sr_2CaCu_2O_8$ is not known, the data are clearly a challenge to theories [2] that predict $\alpha = 1$ independent of microscopic details.

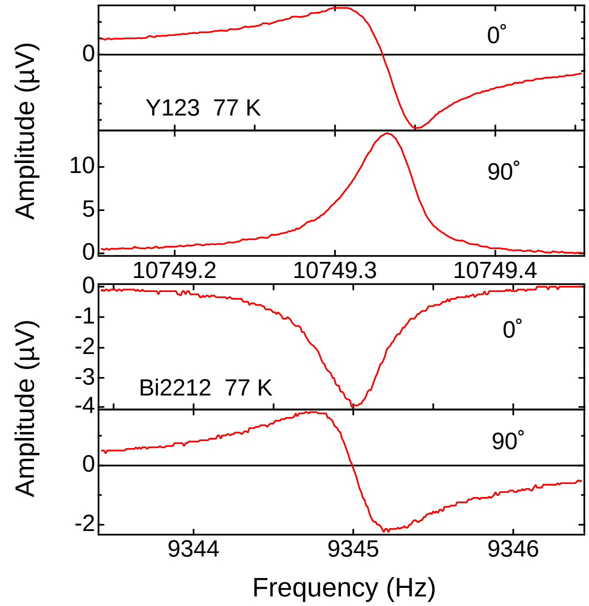

Fig. 2. Oscillator response to longitudinal force at 77 K for Y123 (top) and Bi2212 (bottom).

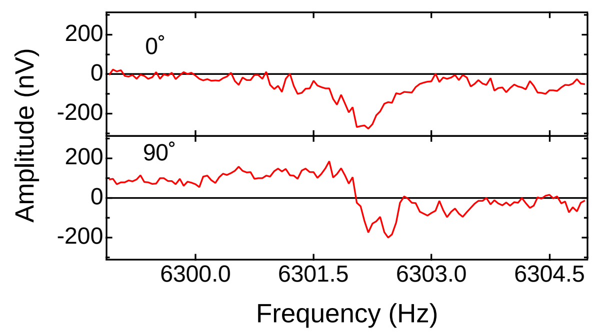

Fig. 3. Oscillator response to transverse force at 77 K for $Bi_2Sr_2CaCu_2O_8$.

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