Measurement of the Nonlinear Meissner Effect in Superconducting Nb Films Using a Resonant Microwave Cavity: A Probe of Unconventional Pairing Symmetries

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We report the first observation of the nonlinear Meissner effect (NLME) as a function of an applied magnetic field, phenomena which observation has been previously reported as highly improbable to be measured due to vortex dissipation. In our experiments, we have used thin Nb films and measured the resonance frequency of a planar superconducting cavity as a function of the magnitude and the orientation of a parallel magnetic field. Use of low power rf probing in films thinner than the London penetration depth, significantly increases the field for the vortex penetration onset and enables NLME detection under true equilibrium conditions. The data agree very well with calculations based on the Usadel equations.

In a s-wave superconductor, it can be shown that the NLME changes the penetration depth by a small amount which depends quadratically on a planar magnetic field [1]. Therefore, the kinetic inductance of the central piece of the resonator (see Fig. 1 left) changes its kinetic inductance, and a change in resonator total inductance is measurable as a change in resonance frequency. The main experimental evidence for NLME is shown in Fig. 2 in which the frequency shift is plotted as a function of the in-plane vector field $H_p$ (size and orientation). The quadratic dependence of the resonance shift with magnetic field is in high agreement with the theory. The NLME angular dependence is measured by rotating a constant field $H_p$ within the sample plane, while monitoring continuously the resonance frequency $f(H_p)$. Transmission scans obtained for an 180° rotation of a field $H_p=1$ T are shown as a contour plot in Fig. 2b (the resonance peaks are identified by triangles). The frequency shifts at 1T corresponding to Fig. 2a are shown with their original symbols and indicated by the lateral arrows. The $\cos(2\phi)$ observed dependence is in agreement with the theoretical calculations, and is due to the coupling between the RF mode and the Meissner currents (depicted in red and green in Fig.1b). Our method is robust and readily usable to probe unconventional pairing symmetries in other materials. In such case, field rotation in the plane of a thin film strip results in the orientational dependence of $f(H_p)$ which, in addition to the geometrical factor $\cos(2\phi)$, would contain the intrinsic contribution from the orientational dependence of the order parameter. Separation of the two contributions will reveal the symmetry of the order parameter using the NLME angular spectroscopy proposed in this work.

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References