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Fate of the Josephson effect in thin-film superconductors

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Superconductivity seems like a magic example of quantum mechanics on a macroscopic scale. At low temperatures certain materials undergo a thermodynamic phase transition in which they apparently lose all resistance to the flow of electricity and tend to expel any magnetic fields inside them. This vanishing of resistance permits currents in wire loops to persist almost indefinitely and is the basis of important magnet technologies. Hermele et al. discuss a novel 'bowtie' geometry for superconducting thin films in which they predict that the electrical resistance will be almost, but not quite, zero even at very low temperatures.

The question of just how difficult it is for persistent currents to decay is a subtle one. In order for current in a ring to decay, vortices must pass through the ring to undo the phase winding of the order parameter. The vortices face an energy barrier in passing through the superconductor. If the wire is three dimensional, the energy barrier will become arbitrarily large as the diameter of the wire increases, the rate at which thermal fluctuations can overcome this barrier will become arbitrarily slow, and the current will persist essentially forever. If the wire is effectively one-dimensional (very long but of small fixed cross section) quantum tunneling of the vortices makes the energy barrier effectively smaller, leading to a finite resistance which will vanish only slowly (as a power law[1]) as the temperature is lowered to zero. Two-dimensional films are an intermediate case. The film resistance goes to zero below the Kosterlitz-Thouless critical temperature but (because the of the lack of true long-range order in two dimensions), the amount of supercurrent that a film can support is, strictly speaking, infinitesimal.

Hermele et al. consider a novel geometry in which two large superconducting film wedges with opening angle θ joined at the corners. At this thin spot, it would seem to be relatively easy for vortices to pass through the sample causing finite resistance. However detailed calculations show that the physics is in a sense intermediate between that of one- and two-dimensional systems. The resistance is finite at any finite temperature but (because the film width grows with distance from the corner) it vanishes much more rapidly than in the one-dimensional case, namely proportional to an exponential $\exp(-T_0/T)$, where the characteristic temperature scale T_0 is a measure of the energy barrier and is equal to the superlfuid stiffness energy in the film multiplied by a universal factor which depends only on the opening angle θ.

For experimental tests of this prediction, it will be essential to choose the film thickness and the disorder carefully so that the temperature scale T_0 is large enough that it can be conveniently reached with standard cryogenic techniques yet not so large that the resistance is immeasurably small. Also, since the characteristic quantum and thermal fluctuations of the phase arrows will occur in the microwave region of frequency, careful engineering of the high frequency impedance (and thermal noise) presented to the junction by the electromagnetic circuit environment will be essential. Indeed the central theoretical result of the paper can be re-expressed in terms of weak tunneling of vortices through the narrow part of the sample in the presence of a frequency dependent environmental impedance determined by the wedge opening angle θ.

References:

1. The quantum path integral for vortices tunneling across a one-dimensional wire looks something like the classical statistical mechanics of a superfluid in 1+1 dimensions, where the extent of the extra dimension is inversely proportional to temperature. This causes the quantum action for tunneling events to vary logarithmically with temperature and hence the exponential of the action to be a power law in temperature. For an elementary introduction to these ideas see: Sondhi et al., 'Continuous Quantum Phase Transitions,' *Rev. Mod. Phys.* **69**, 315 (1997).