Comment on "Experimental Determination of the Superconducting Pairing State in YBCO from the Phase Coherence of YBCO-Pb dc SQUIDs"

Recently, Wollman *et al.* [1] performed beautiful SQUID measurements using Josephson junction pairs attached to the *ac* and *bc* surfaces of $YBa_2Cu_3O_{7-\delta}$ (YBCO). The rectangular prismatic samples had sharp corners, dimensions $L_c \ll \min(L_a, L_b)$, and the applied magnetic field $\mathbf{H} \parallel \hat{\mathbf{c}}$ was less than the entry field $H_{\mathrm{en},\perp} \ll H_{c1,\perp}$ for this direction. They [1] stated that the phases ϕ_a and ϕ_b for a SQUID with junctions at points a and b would satisfy $\phi_a - \phi_b + 2\pi\Phi/\Phi_0 + \delta_{ab} = 0$, where Φ is the magnetic flux in the SQUID, $\Phi_0 = hc/2e$ is the flux quantum, and δ_{ab} is the phase difference appropriate for the junction configuration and the orbital symmetry of the superconducting order parameter (OP). For an edge SQUID, they argued $\delta_{ab} = 0$ for both s-wave and d-wave superconductors with order parameters Δ_0 and $\Delta_0[\cos(k_x a) - \cos(k_y a)]$, respectively. For a corner SQUID, however, they claimed $\delta_{ab} = 0$ or π for an s- or the above d-wave superconductor, respectively. This claim was based upon the assumptions of a single d-wave superconducting domain locked onto the YBCO crystal lattice and strong s-d Pb-YBCO Josephson tunneling.

However, Wollman *et al.* [1] ignored the *singular* demagnetization effects associated with the corners of very thin samples. For $H > H_{\mathrm{en},\perp}$, magneto-optical recordings of flux entry into thin rectangular samples of both Sn [2] and YBCO [3] (as in [1]) showed the flux penetration is greatly reduced, or even *vanishes* along the lines bisecting the sample corners, creating a "roof" of four domains separated by a double-Y-shaped phase-shift boundary. This phase-shift geometry is simply obtained from Maxwell's equations under the assumption of screening currents flowing parallel to the sample surfaces [3]. Also, a Ginzburg-Landau theory (valid for either orbital OP symmetry) of flux entry parallel to an infinite curved surface [4] showed that the magnitude of the surface flux penetration barrier increases with the sample surface convex curvature $1/R$, *diverging* as $R \to 0$, appropriate for a sharp corner. Hence, no flux may enter the sample corners for $H > H_{\mathrm{en},\perp}$.

If we index these four flux penetration domains by $i = 1, \ldots, 4$, there will *necessarily* be a phase shift $\delta\phi_{i,i+1}$ between regions i and $i+1$, where $\delta\phi_{4,5} \equiv \delta\phi_{4,1}$. For a single-valued order parameter, $\sum_{i=1}^{4} \delta\phi_{i,i+1} = 2n\pi$. Since the screening current flows in a closed path and from the phase shift observed across the width of rectangular samples [2,3], these phase shifts most likely all have the same sign and $n \neq 0$. For a square sample, symmetry requires $\delta\phi_{i,i+1} = n\pi/2$. Since the phase shift for a path halfway around a vortex is π, these domain boundaries effectively contain antivortices, relative to the domain interiors.

For $H < H_{\mathrm{en},\perp}$, the local magnetic induction $\mathbf{b}$ exists only on or near the sample surface, and is strongly influenced by demagnetization effects. Except for the (irrelevant) limit $L_c/\max(L_a, L_b) \to \infty$, where $\mathbf{b} = \mathbf{H}$ everywhere on the surface, there will *always* be a corner demagnetization effect. For $L_c/\max(L_a, L_b) \ll 1$ as in [1], the demagnetization effects force $\mathbf{b}$ at the sample surface to be *strongly inhomogeneous,* in both magnitude and direction [5], with a *minimum* $b_c = \hat{\mathbf{c}} \cdot \mathbf{b}$ at the corners [2,3]. These $\mathbf{b}$ inhomogeneities are also present just outside the sample, as required by Maxwell's equations [3,6]. These inhomogeneities should also behave as antivortices at the corners, and this *corner effect* could account for the imperfect Frauhofer patterns and phase shifts observed in the corner SQUID and junction experiments with $H < H_{\mathrm{en},\perp}$ in YBCO [1].

Recently, a Nb-YBCO-Nb corner SQUID was compared with a Nb-Nb *cornerless* junction [7], giving a relative phase shift on the order of π. Due to the corner effect, both the results of [1] and [7] could be consistent with s-wave superconductivity. To confirm the corner effect below $H_{\mathrm{en},\perp}$, the corner SQUID and/or junction experiments [1] should be repeated in conventional type-II materials (e.g., Nb) with identical, thin rectangular prismatic geometry. It should also be repeated in YBCO samples with cylindrical geometry or highly rounded corners, where the corner effect would be absent [2].

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