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Location of flux-induced vortex

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Abstract

We have obtained experimental evidence for a vortex that mediates between adjacent fluxoid states in a mesoscopic superconducting ring with nonuniform width. We have obtained information about the path of this vortex. For small fluxoid numbers the vortex crosses the sample through the narrowest part and for large fluxoid numbers through the widest part. We review our predictions for critical points. Our results are in agreement with the existent theory.

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1. Introduction

It has been known for a long time that the order parameter can vanish at certain points for static situations in 1D multiply connected superconducting circuits, provided that they enclose a magnetic flux that inhibits superconductivity [1]. An indirect experimental evidence for this scenario is provided by [2]. Particular cases in which a node appears are a loop with an arm [3] and a loop with nonuniform width [4]. It has also been claimed that a node can appear in a uniform loop [5].

In Ref. [4], we studied the phase diagram in the temperature–flux plane for a 1D ring with nonuniform cross-sectional area $w(\theta)$. We defined an eccentricity parameter $\beta = 2\oint w(\theta)\cos(\theta)\,d\theta/\oint w(\theta)\,d\theta$, where the angle origin is chosen such that the integral of $w(\theta)\sin(\theta)$ is zero. As in the usual Little–Parks case, the phase diagram is periodic in the flux Φ with period $\Phi_0 = hc/2e$ and the temperature for the onset of superconductivity is depressed when Φ/Φ_0 is not integer, with the strongest depression being located at $\Phi = \Phi_0/2$ (modulo Φ_0). We denote by P_1 this point of strongest depression in the temperature–flux plane. Assuming $\beta \ll 1$ and using a perturbational approach, we obtained that the temperature of P_1 is determined by $\xi^2(T) = 4r_{1D}^2/(1-|\beta|)$, where $\xi(T)$ is the coherence length at temperature T and r_{1D} the radius of the ring.

The most outstanding feature found in [4] is that for $\Phi = \Phi_0/2$ (modulo Φ_0) the superconducting order parameter has a node, and this node can mediate between states with different fluxoid numbers, enabling a continuous transition between them. However, this node exists only for a limited range of temperature, close to the onset of superconductivity: there is a critical point in the (Φ, T) plane (which we dub P_2), such that below P_2 the node does not appear and the transition becomes discontinuous. P_2 is located along the line $\Phi = \Phi_0/2$ and, using the same perturbational approach mentioned above, its temperature is determined by $\xi^2(T) = 4r_{1D}^2/(1+2\mid\beta\mid)$.

About a decade ago some of us extended these results to multiply connected circuits with finite width. A theoretically interesting situation is that of a sample with a hole, which encloses flux within the hole but does not support magnetic field in the sample itself. If the sample is not "too" symmetric and it encloses an integer plus half

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number of quantum fluxes, then a nodal line (nodal surface in 3D) appears, which destroys the connectivity of the superconducting region [6,7].

We also studied the case of a sample with a hole in a uniform field. We still considered a situation close to cylindric symmetry, close to the onset of superconductivity, and such that the induced magnetic field has negligible influence. In this case, the flux enclosed by the sample is not naturally defined, and some arbitrary convention has to be adopted in its definition. Moreover, the phase diagram is no longer periodic in the flux. Nevertheless, the phase diagram and the transitions between fluxoid states still exhibit similar features to the 1D case. For small fluxoid numbers, the temperature $T(\Phi)$ for the onset of superconductivity has minima between consecutive fluxoid states n and $n+1$, and we now denote by P_1 the positions of these minima (P_1 depends on n). For large fluxoid numbers, $T(\Phi)$ becomes monotonic.

If $\beta \neq 0$, there may be a vortex in the sample, which is a 2D version of the node encountered in the case of the 1D ring. Instead of being present for a sharp flux $\Phi = (n+1/2)\Phi_0$, it is present for a range of fluxes. Since the presence of the vortex is mainly determined by the flux enclosed by the hole, rather than by the field at the sample itself, we dubbed it a "flux-induced vortex" [8]. The position of this vortex is a function of the field and of the geometry of the sample. When the field reaches the lower edge of the appropriate range, the vortex forms at the outer boundary of the sample; as the field increases, the vortex position moves towards the inner boundary, until it finally reaches this boundary and disappears. In this way, the fluxoid number of the sample can change continuously; while the vortex is in the sample, the fluxoid numbers are different at the inner and at the outer boundary.

Flux-induced vortices have several features that are qualitatively different from those of "standard" vortices. Here we will mention two features that seem surprising. The first is that the critical points P_2 still exist (also P_2 depends on n), i.e., the passage between n and $n+1$ is continuous for temperatures above that of P_2 and discontinuous for temperatures below it. We found that [9] if the temperature is fixed at that of P_2, then the magnetic susceptibility as a function of the flux diverges quadratically when P_2 is approached.

The critical character of P_2 looks surprising because, unlike the 1D loops that undergo fluxoid transitions for a sharp enclosed flux, in the present case the transition occurs over a finite range. The only effect produced by a small change in the flux is a change in the position of the vortex and one might therefore expect that the critical point should be smeared. What happens is that in the vicinity of P_2 the ratio between the change in the position of the vortex and the change in flux diverges. Although no experiments have been intentionally designed to test this feature, there is indirect experimental evidence for it [10].

Another surprising feature is the following. For transitions between small fluxoid numbers, the vortex crosses the sample through its narrowest part; however, for large fluxoid numbers, it crosses through the widest part. The distinction between "small" and "large" fluxoid numbers depends on the ratio between the typical linewidth and the typical radius of the sample; for larger ratios, smaller fluxoid numbers are required. In Refs. [8,9], this feature was proven using a perturbative approach; however, numerical studies for boundaries with squared shapes [9] or eccentric cylinders [11] indicate that this trend is a generic feature.

In Ref. [9], we obtained explicit expressions for the positions of P_1 and P_2 (for arbitrary n). P_1 was determined by first evaluating the temperature for the onset of superconductivity and then finding the local minima. P_2 was determined by equations that are equivalent to the requirements that the first and the second derivatives of the flux with respect to the vortex position vanish. The expressions for P_1 and P_2 are somewhat lengthy, and we refer the interested reader to [9] or [12]. Unlike the 1D case, the flux at which P_2 occurs is not the same as that of P_1, but, at least for small values of n, they are quite close.

Here we report on the first experiment that detects the existence and trajectory of a vortex during a fluxoid transition in a mesoscopic asymmetric multiply connected sample. A more detailed report was published elsewhere [12].

2. Experiment and Interpretation

The local density of states (LDOS) at the Fermi surface is a decreasing function of the local strength of superconductivity. The LDOS can be mapped by means of the multiple-small-tunnel-junction method [13], in which several tunnel junctions are attached to a mesoscopic superconductor. The larger the superconducting gap under a given junction, the larger the voltage required at that junction in order to pass a predetermined amount of current (0.3 nA). In particular, the resistance R of a junction is larger when the region under it is superconducting than the resistance R_n of the same junction when this region is normal and, if there is a vortex under the junction, then $R \approx R_n$.

Fig. 1 shows a schematic view of the sample. Two normal-metal leads cover the narrowest and the widest parts of a superconducting Al ring with an eccentric hole (outer

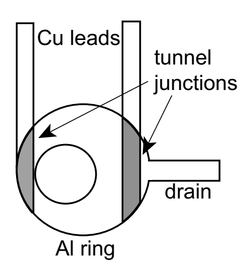

Fig. 1. Schematic view of the sample. Two Cu leads are connected to an Al asymmetric ring through highly resistive small tunnel junctions (shaded areas). An Al drain is directly connected to the ring.