Detection of the Phase Shift from a Single Abrikosov Vortex

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We probe a quantum mechanical phase rotation induced by a single Abrikosov vortex in a superconducting lead, using a Josephson junction, made at the edge of the lead, as a phase-sensitive detector. We observe that the vortex induces a Josephson phase shift equal to the polar angle of the vortex within the junction length. When the vortex is close to the junction it induces a π step in the Josephson phase difference, leading to a controllable and reversible switching of the junction into the 0-π state. This in turn results in an unusual $\Phi_0/2$ quantization of the flux in the junction. The vortex may hence act as a tunable "phase battery" for quantum electronics.

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An Abrikosov vortex carries a flux quantum, $\Phi_0 = hc/2e$, localized at its center, but induces a global 2π phase rotation in the superconducting condensate. This long-range gauge field [1] outside the area pierced by a magnetic field is due to the Aharonov-Bohm effect [2]—a nonclassical phenomenon that illustrates the significance of potentials rather than forces in quantum mechanics [3]. Here we raise the question of whether this phase rotation could be detected by means of Cooper-pair interferometry using Josephson junctions as phase-sensitive detectors. A sketch of the proposed experiment is shown in Fig. 1(a). The supercurrent I_c through the junction is a result of interference of Cooper-pair wave functions, which leads to a Fraunhofer modulation of I_c as a function of magnetic flux Φ. The Josephson phase shift, induced by the vortex, can be determined from a comparison of $I_c(\Phi)$ patterns with and without the vortex [4].

In the London gauge, the phase of the superconducting condensate around the vortex is given by the polar angle Θ_v, which, at the junction interface is equal to

$$\Theta_v(x) = \arctan\left(\frac{x - x_v}{z_v}\right) + \text{const}, \qquad (1)$$

where x_v and z_v are the vortex coordinates and x is the position along the junction length. Profiles of $\Theta_v(x)$ for different distances from the vortex to the junction are shown in Fig. 1(b). Even in quantum mechanics gauge fields have limited physical significance. Only closed path integrals of gauge fields are measurable [1]. For Cooper pairs such integrals around the vortex are equal to 2π, which is indistinguishable from 0 in the absence of the vortex. Open path integrals are not gauge invariant and should not be measurable. Therefore, the question of whether a distant Abrikosov vortex gives rise to a Josephson junction phase shift is nontrivial.

In this Letter we experimentally detect a phase shift induced by a single Abrikosov vortex in a Josephson junction. We observe that the phase shift is equal to the polar angle of the vortex within the junction length. When the vortex is close to the junction it induces a π step in the Josephson phase difference, leading to a controllable and reversible switching of the junction into the 0-π state.

The main challenge for the present experiment is to avoid vortex intrusion into the junction area, which might induce a parasitic phase shift. Conventional Josephson junctions are formed by a barrier sandwiched between thin superconducting films. Abrikosov vortices in such "overlap" junctions tend to minimize their energy by orienting themselves perpendicular to the electrodes, thus introducing a segment of a Josephson vortex (fluxon) in the junction. This is a well-known reason for distortion of $I_c(H)$ patterns in overlap junctions subjected to out-of-

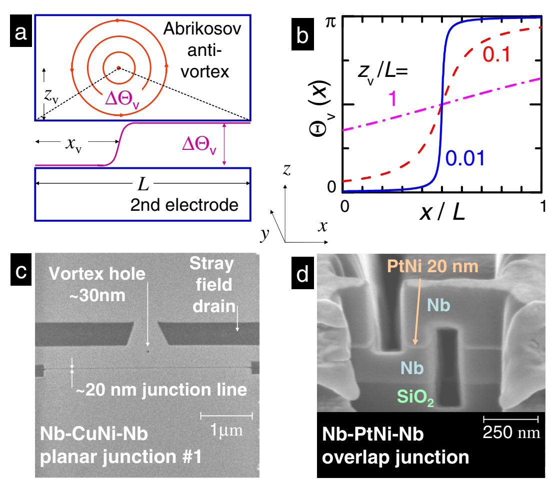

FIG. 1 (color online). (a) Geometry of the experiment: the phase shift from the single Abrikosov vortex is detected by the junction at the edge of the lead. The polar angle of the vortex within the junction length $\Delta\Theta_v$ is marked by the dashed lines. (b) The polar angle of the vortex $\Theta_v(x)$ along the junction length for different distances z_v from the vortex to the junction and $x_v = L/2$. (c) Top view of a planar Nb-CuNi-Nb junction 1, with a vortex hole and a stray-field drain. (d) SEM image of a nanosculptured Nb-PtNi-Nb junction. SEM images in (c) and (d) are shown in the same perspective as the sketch in (a). The magnetic field in our experiment is applied along the y axis (into the paper).

plane fields [5,6]. To avoid fluxon formation we employ two types of specially designed detector junctions (see Refs. [7–9] for details of sample fabrication):

(i) *Planar Nb-CuNi-Nb junctions*, see Fig. 1(c). Such junctions are ideal for the planned experiment: due to their two-dimensional geometry, the Abrikosov vortex, which is oriented perpendicular to the Nb film, cannot cross the junction *line*.

(ii) *Mesoscopic Nb-PtNi-Nb junctions*, see Fig. 1(d). Mesoscopic sizes help to confine the vortex in the middle of the electrode, parallel to the junction plane [10], and allow detection of I_c in very strong magnetic fields (up to 20 kOe), which further helps to align the vortex.

Figure 2(a) shows $I_c(\Phi)$ for a planar Nb-CuNi-Nb junction. Measurements were done by first sweeping the field from 0 to 40 Oe, then to -40 Oe and finally back to 0. The $I_c(\Phi)$ patterns are almost identical for all three sweeps, except for an offset $\Delta\Phi$, which changes stepwise with the field, as shown in Fig. 2(b). The apparent quantization of

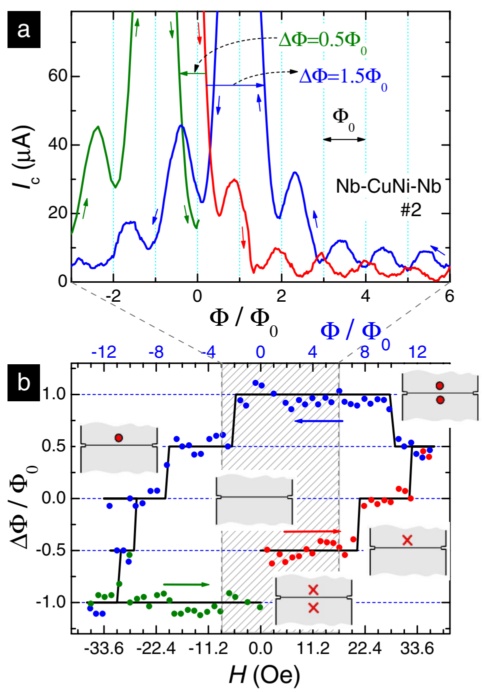

FIG. 2 (color online). (a) Measured $I_c(\Phi)$ patterns for consecutive field sweeps from 0 to 40 Oe, 40 to -40 Oe, and -40 to 0 Oe. The appearance of hysteresis (flux offset) upon sweeping the field is clearly seen. Note that the $I_c(\Phi)$ modulation for the first sweep is out of phase with that on the way back, which indicates that the offset is half-integer of Φ_0. (b) Measured flux offset vs $H(\Phi)$ for the same field loop [hatched area corresponds to the range shown in panel (a)]. Symbols represent minima or maxima in $I_c(\Phi)$. The unusual $\Phi_0/2$ quantization of $\Delta\Phi$ is clearly seen. Each step corresponds to a sequential entrance or exit of one Abrikosov vortex. The expected vortex configurations are indicated by adjacent sketches. Note that the offset of $I_c(\Phi)$ occurs in the direction of the applied field, which implies that the effective trapped flux in the junction is opposite to the applied field.

$\Delta\Phi$ implies that each step is caused by the entrance or removal of an Abrikosov vortex in the electrodes. Remarkably, the offset $\Delta\Phi$ is quantized in *half* flux quanta. As a result, the $I_c(\Phi)$ modulation gets out of phase, i.e., positions of minima and maxima are interchanged, with each step in $\Delta\Phi$. Furthermore, the offset occurs in the direction of applied field, which means that the trapped field in the junction is *opposite* to the applied field.

To clarify the origin of the unusual $\Phi_0/2$ quantization, the junctions were modified by a focused ion beam (FIB) in two steps, as shown in Fig. 1(c). First, a vortex trap was made in order to control the position of the vortex. The trap is a small hole ~30 nm in the center of one of the electrodes near the junction. Second, a stray-field drain was added by removing a substantial part of the electrode in the vicinity of the vortex hole. The drain should substantially decrease the magnetostatic stray fields from the vortex at the junction. The shape of vortex-free $I_c(H)$ patterns remained intact after both modifications, as shown in Fig. 3(a) (the pattern before drilling the vortex hole was exactly the same, not shown). This implies that the junction uniformity was not affected by those modifications.

A vortex in the hole can be controllably introduced or removed by applying an appropriate field and by using Lorentz force from the transport current [9]. Figure 3(b)

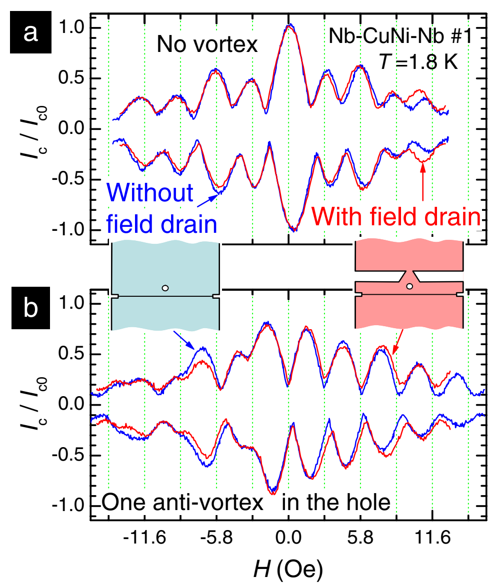

FIG. 3 (color online). $I_c(H)$ modulation for a planar junction with the vortex hole and the stray field drain. Sketches demonstrate junction sample geometries: with the vortex hole only and with the hole and the stray-field drain. The current is normalized on the maximum critical current in the absence of vortices, I_{c0}. (a) Without vortices. (b) With an antivortex in the hole. Clear signatures of the 0-π state are seen: (i) the central maximum is replaced by a minimum, (ii) modulation of $I_c(H)$ gets out of phase with that without the vortex, and (iii) doubling of the periodicity occurs at one side of the pattern. Note that introduction of the stray-field drain affects neither the $I_c(H)$ pattern nor $\Delta\Phi$.

shows a new type of $I_c(H)$, which appears after trapping an antivortex. It has three new characteristic features:

(i) The central maximum is replaced by a minimum.

(ii) The $I_c(H)$ modulation is out of phase with that for the vortex-free pattern, i.e., $\Delta\Phi \simeq \Phi_0/2$.

(iii) The periodicity of $I_c(H)$ modulation doubles at the left side of the pattern, leading to a clear left-right asymmetry [11]. When a vortex is trapped in the hole, instead of an antivortex, the $I_c(H)$ pattern becomes mirror reflected with respect to the $H = 0$ axis (not shown).

These are the well-known fingerprints of 0-π junctions, with a steplike π shift in the Josephson phase difference within the junction [12–15]. Properties of π junctions with negative Josephson coupling and 0-π junctions have attracted significant attention in recent years, both due to the interesting physics involved, and the potential for new applications. So far, three types of 0-π junctions were realized based on (i) the d-wave symmetry of the order parameter in high-T_c superconductors [16–18], (ii) the oscillatory nature of the order parameter in hybrid superconductor-ferromagnet junctions [14,15,19,20], and (iii) the phase shift by current injection into the junction [13,21]. Here we demonstrate that a conventional 0 junction can be switched into the 0-π state by a single Abrikosov vortex.

Importantly, introduction of the stray-field drain does not reduce the offset $\Delta\Phi$, see Fig. 3(b). This clearly shows that the effective trapped flux in the junction is not driven by the simple magnetostatic spreading of the vortex stray-field. To get more insight into the influence of junction geometry on $\Delta\Phi$, mesoscopic Nb-PtNi-Nb junctions were used, where the vortex is geometrically confined in the middle of the electrodes [10], $z_v \simeq d/2$, $x_v \simeq L/2$. All junctions had the same electrode thicknesses d, but different junction lengths L, thus allowing variation of the ratio $z_v/L \simeq d/2L$.

In Figs. 4(a) and 4(b) we show $I_c(H)$ for the same Nb-PtNi-Nb junction with an in-plane field parallel to different facets of the junction. The $\Delta\Phi$ induced by the vortex is clearly seen in both cases. For the long junction case, $L = 1140$ nm, $\Delta\Phi \simeq \Phi_0/2$, which results in out-of-phase modulation of the patterns. However, for the short junction case, $L = 230$ nm, $\Delta\Phi \simeq 0.16\Phi_0$ is considerably smaller.

Figure 4(c) summarizes the measured $\Delta\Phi$ for all studied Nb-PtNi-Nb junctions. Obviously, $\Delta\Phi$, introduced by the vortex increases considerably with the junction length L. The observed offset $\Delta\Phi$ in $I_c(H)$ corresponds to the net variation of the Josephson phase difference along the junction length

$$\Delta\varphi_v(L-0) = 2\pi\Delta\Phi/\Phi_0. \quad (2)$$

Thus the Abrikosov vortex does induce a measurable Josephson phase difference in the junction. The dashed line in Fig. 4(c) indicates that the latter is agreeing well with the polar angle of the vortex within the junction: $\Delta\varphi_v(L-0) \simeq \Delta\Theta_v$ [see Fig. 1(a) and Eq. (1)]. The $\Delta\Theta_v$ was calculated by assuming that the vortex is placed

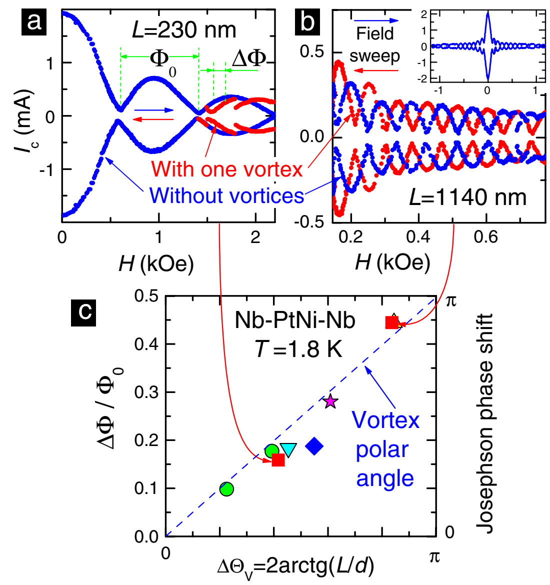

FIG. 4 (color online). Influence of the junction geometry on the flux offset in mesoscopic Nb-PtNi-Nb junctions. (a),(b) $I_c(H)$ for the same Nb-PtNi-Nb junction 1140×230 nm^2 for two in-plane field orientations. First the field is swept up starting from the vortex-free state until Abrikosov vortices enter the electrodes and then back to zero. Entrance of the Abrikosov vortex leads to a sudden appearance of the offset $\Delta\Phi$ in the Fraunhofer pattern. The inset in panel (b) shows the $I_c(H)$ pattern in a wider field range. (c) Flux offset $\Delta\Phi/\Phi_0$ induced by the vortex as a function of the polar angle $\Delta\Theta_v$ of the vortex within the junction. Similar symbols correspond to the same junction with different in-plane field orientations. Red squares correspond to the junction shown in panels (a) and (b). The dashed line indicates that the Josephson phase shift induced by the vortex (right axis) is simply equal to the polar angle of the vortex.

in the middle of an electrode $z_v \simeq d/2$, where $d \simeq 300$ nm is the average thickness of Nb electrodes.

To understand the origin of the observed phenomenon we first exclude several unsustainable scenarios (more discussion can be found in the supplementary [9]).

(i) The vortex does not introduce a segment of a Josephson fluxon in the junction, which might distort $I_c(H)$ [5,6]. In our structures, the Abrikosov vortices were oriented strictly parallel to the junction interface and never cross the junction area. In particular, such crossing is impossible for the planar junctions, because of the two-dimensional junction geometry.

(ii) A direct field of the vortex stretching into the junction cannot explain our data, because the induced field in the junction is opposite to the applied field. Indeed, from Fig. 2(a) it is seen that the central maximum in $I_c(\Phi)$ is shifted to a positive field after applying +40 Oe and to a negative field after applying −40 Oe. Since the central maximum corresponds to $\Phi = 0$ in the junction, the additional field within the junction is always *opposite* to the applied field.

(iii) For the same reason it cannot be related to magnetism in the barrier. Ni in the barrier was used solely to reduce I_c to a comfortable range <1 mA. We have also studied junctions with nonmagnetic barriers, which exhibited similar behavior. Data for two nonmagnetic Nb-Pt-Nb junctions are explicitly shown in Fig. 4(c) (circles and a down triangle) and clearly follow the same trend. The possibility to manipulate $\Delta\Phi$ by transport current [9] indicates that it is caused by vortices.

(iv) The magnitude of the signal can hardly be explained by a finite vortex current at the junction interface. Although it produces a phase shift of the proper sign, its magnitude should decay strongly with the distance from the vortex to the junction [22] and should for no reason produce a quantized $\Phi_0/2$ flux offset in the junction. Similarly, it is not possible to explain the characteristic equality between the Josephson phase shift and the polar angle of the vortex, shown in Fig. 4(c).

(v) Magnetostatic stray field from the vortex would also give a phase shift with the correct sign. The experiment with the stray-field drain, however, demonstrates that the Josephson phase shift is unaffected by variation of magnetostatic conditions. Furthermore, there is no reason for the stray field to be quantized as $\Phi_0/2$. When the vortex is placed very close to the junction, clear signatures of the 0-π junction are seen, see Fig. 3(b). This implies that the induced Josephson phase shift has a form of a sharp π step, which is again difficult to explain in terms of simple magnetostatics because it would require field focusing in one point.

Our data show an unambiguous correspondence between the Josephson phase shift and the polar angle Θ_v, which represents the variation of the phase of the superconducting condensate around the vortex within the London gauge, Eq. (1), as if the phase of the condensate is rigidly coupled to rotation of the current in the vortex. The simulation presented in the supplementary material [9] demonstrates that Eq. (1) provides a good overall agreement with all of our observations. It naturally explains the unusual $\Phi_0/2$ flux quantization in the junction. The associated π-Josephson phase shift in this case is simply equal to the change in Θ_v upon going from the left to the right side of the vortex. When the vortex is close to the junction, $\Theta_v(x)$ changes stepwise, as shown in Fig. 1(b), and the junction switches into the 0-π state. Yet, note that the remarkable success of the London gauge description of the phase shift around the vortex is surprising because phase shifts between any two points (such as the left and right edges of the junction) are not gauge invariant and, therefore, should not be measurable. We assume that the presence of the junction as such plays a crucial role on the way from the unmeasurable phase shift of the superconducting condensate to the measurable Josephson phase difference. Although the seeming rigidity of the gauge field around the Abrikosov vortex remains to be clarified, we demonstrate that it can be employed as a tunable and reversible phase battery for Josephson electronics. Depending on the geometrical factor z_v/L, such a battery can provide either a quantized steplike π shift, or an arbitrary phase shift in the range $0 < \Delta\varphi < \pi$.

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