Demonstration of Absolute Magnetic-Flux Quantization in a Superconducting Circuit

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We have demonstrated experimentally that magnetic-flux quantization in a superconducting circuit is obeyed in an absolute sense, and have ruled out the possibility of a fractional quantum of magnetic flux. We use an optically switched superconducting microbridge to destroy and reestablish the phase coherence of the order parameter around a superconducting circuit. Changes in the vector potential while the global phase coherence is destroyed are still observable when the coherence is reestablished, even though the magnetic field is inaccessible to the superconductor.

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Recently, it has been suggested that fractional quanta of magnetic flux through superconducting circuits might exist, questioning the significance of the absolute vector potential in quantum mechanics.[1] The motivation came from recent theoretical work on the statistics of anyons,[2] flux-tube-particle composites which carry fractional angular momentum. In this theory, flux quantization through a superconducting circuit would take on the form

$$\phi=(r+n)\phi_0\,, \tag{1}$$

where n is an integer, $0<r<1$ is a residue, and ϕ_0 is the flux quantum of superconductivity. The superconducting circuit would trap r at the time the global phase coherence was established around the circuit. Subsequent changes in the flux threading the circuit, which arise from vortices passing through a Josephson junction or across a microbridge, would change n but not r, since the local phase coherence is always maintained in such microscopic processes where the dimensions are of order of the coherence length of the superconductor. In addition, it has been argued that r is suppressed in those flux-quantization experiments[3] in which the superconducting circuit is placed in a uniform magnetic field and then cooled through T_c to establish global phase coherence. The charged-particle fluid in the metal senses Coriolis-type force in the presence of the uniform field, and the response to this force results in standard integer flux quantization.[1]

In order to test the theoretical possibility of fractional flux quantization, it is necessary to devise an experimental technique for completely destroying and reestablishing the phase coherence over distances much greater than the coherence length. Repeatedly heating a portion of a macroscopic superconducting circuit does not generate a quantized flux distribution because vortices are trapped in various portions of the superconducting material making up the circuit. Since the location of these vortices changes for each cooling, a continuum of flux values is seen in measurements made with an inductively coupled SQUID magnetometer. Clean flux-quantization data have been obtained in small structures (1 mm across or less), but always using spatially uniform magnetic fields.[3]

We have developed an optically switched superconducting microbridge[4] which circumvents these experimental difficulties and allows for the first time a sensitive test of the fractional-flux-quantization theory. Figure 1 shows a schematic representation of our experiment. The optically switched element is connected directly across the input coil of an rf SQUID sensor (Biomag Technologies, Inc., model 330x). In addition, the circuit threads a toroidal solenoid enclosed in a superconducting shield [Fig. 1(c)] which can couple flux to the circuit while shielding all portions of the superconducting material from the magnetic field. This lead shield has an outside diameter of 4 mm and an inside diameter of 0.5 mm. The shield geometry is not a closed toroid, which would prevent any changes in the magnetic flux coupling to the circuit, but rather there is a long overlap region which is electrically isolated using 25-μm-thick Teflon sheet. We determined the extent of stray flux coupling to the circuit by routing the 250-μm-diam NbTi wire

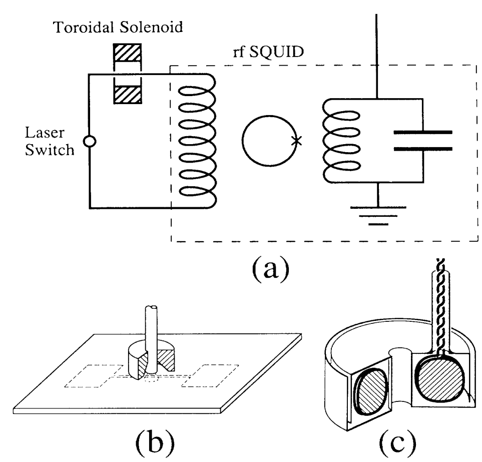

FIG. 1. (a) Schematic representation of superconducting circuit with (b) laser switch and (c) toroidal solenoid which is surrounded by a superconducting shield.

with 25-μm-thick insulation around the toroidal solenoid and past the overlap region and comparing the response to that when the wire is routed through the hole. The ratio of the flux couplings is 1:24000. The optical switch [Fig. 1(b)] consists of a 40-nm-thick niobium film photolithographically narrowed to 2 μm over a 790-μm length. The film has a resistivity ratio of 2.0 (between room temperature and just above $T_c = 8.3 \pm 0.2$ K). A 100-μm core optical fiber is coupled to the back side of the sapphire substrate using a commercially available ruby ferrule. At the chip, about 17 mW of laser power from a neodymium-doped yttrium-aluminum-garnet (YAlG) laser (1.062 μm wavelength) is sufficient to drive a 180-μm length of the line from the superconducting to the normal state (Fig. 2). The critical optical power density is ~ 0.2 $\mu W/\mu m^2$. In the normal state, the resistance of this normal portion of line is 450 Ω, sufficiently high that the Johnson current noise is well below the intrinsic rf SQUID noise. The entire circuit including the SQUID is in an exchange-gas pressure of 0.1 Torr and is inside a niobium superconducting shield surrounded by a Cryoperm Mumetal shield.

In Fig. 3(a) we demonstrate the performance of the switch by repeatedly turning the power on and off using a mechanical shutter between the YAlG laser and the optical fiber. In these data, the current through the toroidal solenoid is held constant. Every cycle, a measurement of the current in the circuit is made both in the superconducting state and in the normal state. Each point in Figs. 3 and 5 is the average over a 16.7-ms window at 1-kHz bandwidth which removes 60-Hz pickup. The SQUID noise with shorted input is $7.8\times10^{-5}\phi_0/(\text{Hz})^{1/2}$ in terms of ϕ_0 at the SQUID, so that each data point has a 1 standard deviation error of $\pm 6.2\times10^{-4}\phi_0$ [Fig. 3(c)]. The greater spread in Fig. 3(b) (by 1.7 when the switch is open) is due to added Johnson noise from a 3-Ω resistor mounted across the input terminals of the SQUID to reduce rf interference. The data in the superconducting state form a discrete Gaussian distribution [Fig. 3(d)] centered on the normal value which corresponds to zero current in the circuit. The quantization is in units of the flux quantum in the SQUID input circuit, where $(\phi_0)_{\text{in}} = 9.5\times10^{-3}(\phi_0)_{\text{SQUID}}$. In terms of $(\phi_0)_{\text{in}}$, the error for each data point is $\pm 6.4\times10^{-2}\phi_0$. Henceforth, ϕ_0 will always refer to the input coil, not the SQUID. The width of the Gaussian is determined by

$$\tfrac{1}{2}kT^* = \phi^2/2L\,, \tag{2}$$

where $L = 2.24$ μH is the inductance of the SQUID input coil, ϕ is the flux coupling to the circuit, and T^* is the

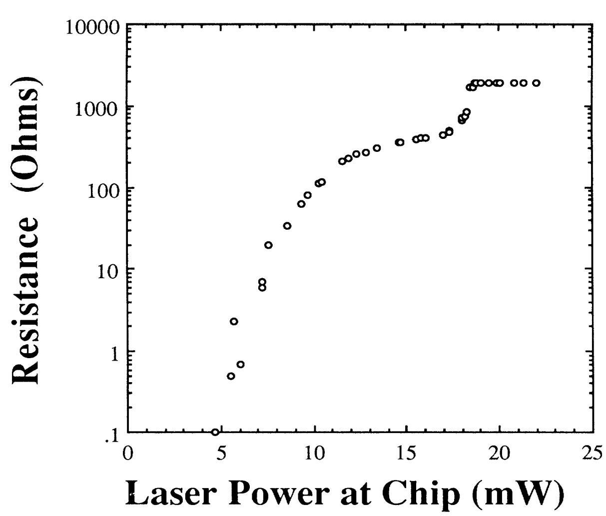

FIG. 2. Resistance vs laser power at the output end of the optical fiber. Measurements made with four-terminal bridge in the limit of zero current.

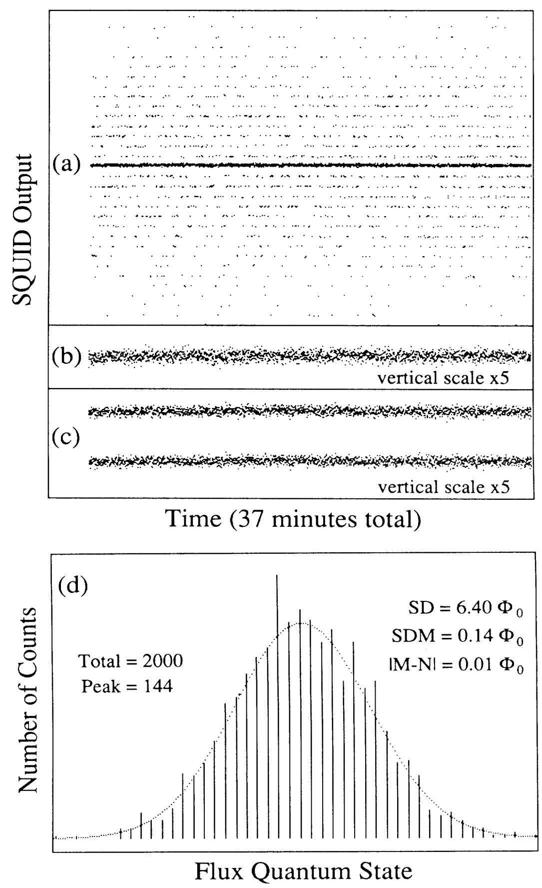

FIG. 3. Data run with no current through solenoid. The flux data in (a) show precise flux quantization levels. The data have been magnified in (b), the normal data, and in (c), where all data have been collapsed to two levels modulo the flux quantum. (d) The distribution of flux levels is centered about the normal level. SD denotes standard deviation; SDM, standard deviation of the mean; M mean value; and N, normal value.

effective freeze-out temperature below which the cooling rate exceeds the rate of thermally excited flux transitions from one quantum state to another. We measure $\phi_{rms} = 6.4\phi_0$ and calculate $T^* = 5.8$ K from the known SQUID input inductance.

In our experiment to test the absolute nature of the Aharonov-Bohm effect, we introduce a slowly changing magnetic flux through the circuit using the toroidal solenoid [Figs. 1(a) and 1(c)]. The local current density $\mathbf{j}$ is

$$\mathbf{j} = (e^*/m^*)\Psi^*\Psi[(h/2\pi)\nabla\phi - (e^*/c)\mathbf{A}], \quad (3)$$

where Ψ is the order parameter with phase ϕ. When the switch is normal, $\mathbf{j}$ is everywhere zero since $(h/2\pi)\nabla\phi$ is free to exactly cancel $(e^*/c)\mathbf{A}$. However, conventional theory predicts that when the switch goes superconducting, the global condition requiring a single-valued phase around the circuit forces a current to flow if $\oint \mathbf{A}\cdot dl \neq n\phi_0$. Figure 4(a) schematically shows the laser-switch duty cycle and Fig. 4(b) the solenoid ramp function. The switch is allowed to go superconducting for 30 ms out of each cycle (1.134 s), just long enough to determine the quantized flux state with good statistics. To change the vector potential, the current through the toroidal solenoid is ramped slowly and continuously. When switched to the normal state, any persistent current dies out in several L/R (~ 5 ns) time constants.

Data are taken before the ramp begins, during the ramping, and after it stops [Fig. 5(a)]. These data look similar to Fig. 3(a); however, now the phase shift of the flux quantization levels is evident during the ramp cycle. The centroid of the distribution remains at the normal position, always the state of lowest free energy. Next, we perform an identical run with the laser intensity turned down so that the switch remains superconducting throughout [see Fig. 5(b)]. We have superimposed these data (with no dc offset) to show that the slopes are the same for the two runs. In Fig. 5(c) we show a magnified view of the difference function $\phi = (\phi_{(a)} - \phi_{(b)})\text{mod}\phi_0$ and $\phi + \phi_0$ to show the quantization scale. The rms noise in Fig. 5(c) is $\sqrt{2}$ greater than for Fig. 3(c) because we have taken the difference of two distributions.

To demonstrate convincingly that the phase coherence of the circuit is destroyed, it is not sufficient to observe a constant dc flux at the normal-state position. Given our distribution width of $\sigma = 6.4\phi_0$ and our SQUID noise level of $6.4\times10^{-2}\phi_0$, any thermally excited vortex transition rate greater than $10^4\phi_0$/s would look the same as the normal state. In such a case, however, the circuit would maintain global phase coherence throughout. To argue that the switch is indeed in the normal state, we have performed a four-terminal resistance measurement with the same range of laser settings used for the data in Figs. 3 and 5. The measurements were made using a Linear Research LR-400 resistance bridge with bias currents well below the critical current of the microbridge. As can be seen from Fig. 2, upon increasing the laser power from zero we see thermally excited phase slips beginning at about 4 mW and continuing at an exponentially increasing rate up to 10 mW. Above about 10 mW, a true normal region begins to grow and reaches a length of 200 μm at about 18 mW, consistent with the optical fiber diameter and beam divergence. Further increases in power heat the entire chip above T_c, producing a broad plateau at the normal resistance of the entire microbridge (1944 Ω for 790 μm length) as measured independently with the laser off just above T_c. The data runs in Figs. 3 and 5 were taken at a laser power of about 17 mW, where a 180-μm length of the microbridge is in the normal state during the laser-on portion of each cycle. Electrons in normal metals maintain quantum phase coherence over distances no greater than several μm,[5] and proximity effects between the supercon-

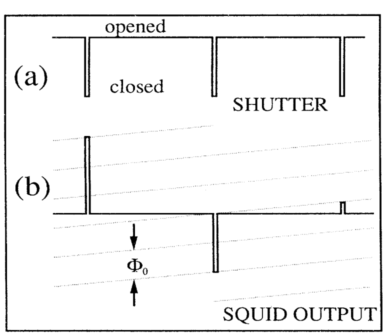

FIG. 4. Schematic representations of (a) the shutter duty cycle and (b) the output of the SQUID in response to a ramping current in the toroidal solenoid.

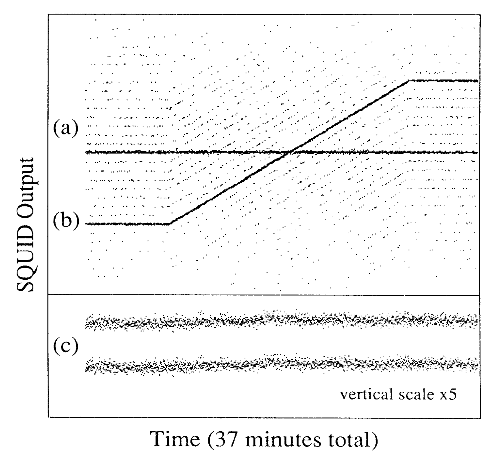

FIG. 5. Data runs with ramped current through toroidal solenoid (a) with laser-switch duty cycle as in Fig. 4, and (b) with the switch superconducting throughout; (c) the difference between (a) and (b) modulo the flux quantum.

ducting phase and the normal phase extend over distances no greater than several μm for a dirty metal like Nb in our quasi-one-dimensional geometry.[6]

To within our experimental uncertainty ($\sim 1\%$ of $16\phi_0$ ramp range), these data show that flux changes made by a toroidal solenoid when the circuit is open and without global phase coherence are always accounted for in full when the circuit is later allowed to return to the phase-coherent quantum state. In our experiment the magnetic flux within the toroidal solenoid is inaccessible to the macroscopic quantum wave function of the Cooper pairs, and the phase coherence is destroyed over a macroscopic distance which is much greater than both the coherence length of the superconductor and the quantum phase coherence length of individual electron wave functions in the normal metal. We find no evidence for fractional flux quantization in superconducting circuits and our data are completely consistent with the absolute significance of the magnetic vector potential in conventional quantum mechanics.

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Note added.-After the submission of our manuscript, Tonomura *et al.*[7] have argued that their beautiful electron diffraction experiment which demonstrates the absolute Aharonov-Bohm effect for electrons also demonstrates the absolute effect for superconductors. However, Liang and Ding[8] replied that in that experiment portions of the superconducting Nb toroid were in direct contact with the Permalloy ferromagnet; thus the condition of an inaccessible field was not achieved. In our geometry, the direct field coupling is more than 1000 times smaller because the circuit wire is physically separated and shielded from the toroidal coil by the lead shield which remains superconducting throughout the experiment.

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[6]See, for example, P. G. de Gennes, *Superconductivity of Metals and Alloys* (Benjamin, New York, 1966), and A. A. Golub and O. V. Grimal'skii, Fiz. Nizk. Temp. **12**, 48 (1986) [Sov. J. Low Temp. Phys. **12**, 264 (1987)].

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