Mesoscopic Physics

Coherent manipulation of Andreev states in superconducting atomic contacts

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Coherent control of quantum states has been demonstrated in a variety of superconducting devices. In all of these devices, the variables that are manipulated are collective electromagnetic degrees of freedom: charge, superconducting phase, or flux. Here we demonstrate the coherent manipulation of a quantum system based on Andreev bound states, which are microscopic quasi-particle states inherent because they have energies in a continuum of states. Localized states arise in situations where the superconducting gap Δ or the superconducting phase undergo strong spatial variations: examples include Shiba states around atoms (1) and Andreev states in vortices (2) or in weak links between two superconductors (3). Because they have discrete energies within the gap, Andreev states are expected to be amenable to coherent manipulation (4–8). In the simplest weak link, a single conduction channel that is shorter than the superconducting coherence length ξ, there are only two Andreev levels ±EΔ(±Δ) = ±Δ/2(1 − sin2(δ/2)), which are governed by the transmission probability of electrons through the channel and the phase difference δ between the two superconducting condensates (3). Despite the absence of actual barriers, quasi-particles (bogoliubons) occupying these Andreev levels are localized over a distance ~ξ around the weak link by the gradient of the superconducting phase, and the system can be considered an atomic-size contact. The Andreev physics because they accommodate a small number of short conduction channels (2). We create them using the microfabricated break-junction technique (3). Figure 2 presents the sample used in the experiment. An aluminum loop with a narrow suspended constriction (Fig. 2C) is fabricated on a polyimide flexible substrate mounted on a bending mechanism cooled down to ~30 mK (7). The substrate is first bent until the bridge breaks. Subsequent fine-tuning of the bending allows creating different atomic contacts and adjusting the transmission probability of their channels. The magnetic flux threading the loop controls the phase drop δ = 2πΦ/Φc (Φ, flux quantum) across the contact and, thus, also controls the Andreev transition frequency ω(δ) = 2EΔ/h (Planck’s constant).

To excite and probe the Andreev dot, the loop is inductively coupled to a niobium quarter-wavelength microwave resonator (17) (Fig. 2B) in a circuit quantum electrodynamics architecture (18, 19). The resonator is probed by reflectometry at a frequency fR close to its bare resonance frequency fR ≈ 10.134 GHz. The actual resonator frequency is different for each one of the three Andreev dot states: In the odd state, the resonance frequency is unaltered, whereas the two even states lead to opposite shifts around fR (20). The Andreev transition |g⟩ → |e⟩ is driven by a second tone of frequency f2. Details of the setup are shown in figs. S1 and S2 (20).

Here we present data obtained on a representative atomic contact containing only one high-transmission channel. Data from other contacts are shown in figs. S6 to S8. First, we performed pulsed two-tone spectroscopy by applying a 13-μs driving pulse of variable frequency, immediately followed by a 1-μs-long measurement pulse (f0 ≈ 10.1337 GHz) probing the resonator with an

Fig. 1. Single-channel Andreev quantum dot. (A) Energy levels: Two discrete Andreev bound levels detune symmetrically from the upper and lower continua of states (light gray regions for |E| > Δ). Photons of energy 2EΔ can induce transitions between the two Andreev levels (magenta arrows). (B) Occupation of Andreev levels in the four possible quantum states of the Andreev dot. Only the lower Andreev level is occupied in the ground state |g⟩ (blue box). In the excited state |e⟩ (red box), only the upper Andreev bound level is occupied. In the doubly degenerate odd state |o⟩, both Andreev levels are either occupied or empty. (C) Energy of the four Andreev dot states for a channel of transmission probability ρ = 0.98, as a function of the phase difference δ across the weak link.

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The spectrum is periodic in flux, with peaks separated by 

\[ f_0 \pm f \]

The coherent manipulation at \( \delta = \pi \) of the two-level system formed by \( \ket{g} \) and \( \ket{e} \) is illustrated in Fig. 4. Figure 4A shows the Rabi oscillations between \( \ket{g} \) and \( \ket{e} \) obtained by varying the duration of a driving pulse at frequency \( f_0 = f_{\pi}(\pi) \) (movie S1). Figure 4B shows how the populations of \( \ket{g} \) and \( \ket{e} \) change when the driving-pulse frequency \( f_0 \) is swept across the Andreev frequency.
After a \( \pi \) pulse, the populations relax exponentially back to equilibrium with a relaxation time \( T_1(\delta = \pi) \approx 4 \mu s \) (Fig. 4D). The Gaussian decay of detuned Ramsey fringes (Fig. 4F) provides a measurement of the coherence time \( T_2^*(\delta = \pi) \approx 38 \) ns. This short coherence time is mainly due to low-frequency (i.e., lower-than-megahertz) fluctuations of the Andreev energy \( E_0(\delta, \delta) \), as shown by the much longer decay time \( T_2(\delta = \pi) = 565 \) ns > \( T_2^* \) of a Hahn echo (Fig. 4C). Measurements at \( \delta = \pi \) on other contacts with the same sample, with transmissions corresponding to a minimal Andreev frequency \( 3 \) GHz < \( f_A(\tau, \pi) < 8 \) GHz, give \( T_1 \) mostly around 4 \( \mu s \) (up to 8.5 \( \mu s \)), \( T_2^* \) around 40 ns (up to 180 ns), and \( T_2 \) around 1 \( \mu s \) (up to 1.8 \( \mu s \)), but no clear dependence of the characteristic times on \( \tau \) is observed (figs. S7 and S8).

Figure 4E shows the measured relaxation rate \( \Gamma_1 = 1/T_1 \) as a function of the phase \( \delta \). The expected Purcell relaxation rate arising from the dissipative impedance seen by the atomic contact (light blue line in Fig. 4E) matches the experimental results only close to the degeneracy points where \( f_A = f_E \) (vertical dotted lines) but is about five times smaller at \( \delta = \pi \). On the basis of existing models, we estimate that relaxation rates due to quasi-particles (24–28) and phonons (7, 8, 21) are negligible. Empirically, we fit the data at \( \delta = \pi \) by considering an additional phase-independent rate (180 kHz). In (C) and (E), vertical dotted lines indicate degeneracy points.

The linewidth of the spectroscopy line, which is a measure of the decoherence rate, shows a minimum at \( \delta = \pi \) (Fig. 4C). The Gaussian decay of the Ramsey oscillations points to \( 1/f \) transmission fluctuations as the main source of decoherence at \( \delta = \pi \), where the system is insensitive to flux noise to first order (28). Fluctuations of \( \tau \) can arise from vibrations in the mechanical setup and from motion of atoms close to the contact. Figure 4C also shows the linewidths calculated, assuming \( 1/f \) transmission noise and both white and \( 1/f \) flux noise (20). The amplitude of the \( 1/f \) transmission noise, \( 2.5 \times 10^{-8} \) Hz\(^{-1/2} \) at 1 Hz, was adjusted to fit the measurement at \( \delta = \pi \). The amplitudes of the white and \( 1/f \) flux noise were then obtained from a best fit of the linewidth phase dependence. The extracted \( 1/f \) noise amplitude (5 \( \mu \)V\(^2\) Hz\(^{-1/2} \) at 1 Hz) is a typical value for superconducting devices and has a negligible effect to second order (29). The source of the apparent white flux noise (48 \( nV/\sqrt{Hz} \)) has not yet been identified.

Andreev quantum dot has been proposed as a new kind of superconducting qubit (5, 6), which differs markedly from existing ones (30). In qubits based on charge, flux, or phase (30), the states encoding quantum information correspond to collective electromagnetic modes, whereas in Andreev qubits they correspond to microscopic degrees of freedom of the superconducting condensate. Our results are a proof of concept of this new type of qubit. Further work is needed to fully understand the sources of decoherence and to couple several qubits in multichannel contacts (5, 8). With its parity sensitivity, the Andreev
quantum dot is also a powerful tool to investigate quasi-particle–related limitations on the performance of superconducting qubits (28, 31, 32) and detectors (33). Furthermore, our experimental strategy could be used to explore hybrid superconducting devices in the regime where Andreev states evolve into Majorana states (34–36).

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SUPPLEMENTARY MATERIALS
www.sciencemag.org/content/349/6253/1102/suppl/DC1
Materials and Methods
Figs. S1 to S9
Movie S1
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CRITICAL PHENOMENA

Critical behavior at a dynamic vortex insulator-metal transition

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An array of superconducting islands placed on a normal metal film offers a tunable realization of nanopatterned superconductivity. This system enables investigation of the nature of competing vortex states and phase transitions between them. A square array creates the electrostatic potential in which magnetic-field–induced vortices are frozen into a vortex insulator. We observed a vortex insulator–vortex metal transition driven by the applied electric current and determined critical exponents that coincide with those for thermodynamic liquid-gas transition. Our findings offer a comprehensive description of dynamic critical behavior and establish a deep connection between equilibrium and nonequilibrium phase transitions.

Critical behaviors near phase transitions can be classified into universality classes determined only by a few properties characterizing the system, such as space dimensionality, range of interaction, and symmetry (1, 2). A paradigmatic concept of universality brought deep understanding of equilibrium critical phenomena [see, e.g., (3) and references therein]. Phase transitions and criticality far from equilibrium are less well understood. The experimental evidence for universality of nonequilibrium phase transitions is still scarce, calling for intensified experimental efforts.

Superconducting vortices offer a unique tunable laboratory for studying classical critical dynamics. To that end, we prepared an array of superconducting islands where vortices are pinned between the islands in the areas of weaker proximity-induced superconductivity—that is, at the energy dips of an eggrate potential (4). If thermal fluctuations are not strong enough to overcome the combined localizing action of mutual repulsion and pinning, vortices form the so-called vortex Mott insulating state at commensurate fields corresponding to an integer number of vortices per pinning site (5). The predicted vortex Mott state seen in experiments on antidot arrays in superconducting films (6, 7) was conclusively confirmed in (8). In our experiment, performed in a classical regime, varying the magnetic field provides precise control over the vortex density and tunes the ratio of the vortex repulsion to the mobility, enabling the observation of a vortex insulator–metal transition.

Each of our samples consists of a 40-nm Au layer, patterned as a four-point setup in a van der Pauw configuration for transport measurements, on a Si/SiO2 substrate (9). The Au pattern is overlaid with a square array of superconducting niobium (Nb) islands 45 nm thick. An array contains 90,000 Nb islands placed with a period of a = 267 nm. The diameter of an island is 220 ± 3 nm and the island separation is 47 ± 3 nm. Shown in Fig. 1A, a to D, are scanning electron microscopy (SEM), atomic force microscopy (AFM), and optical images of a sample and the height profile along one of the principal axes of the array. The superconducting transition temperature of the array, determined as the midpoint of the temperature resistance curve in the upper inset in Fig. 1A, is 7.3 K, which is 2 K lower than that of bulk Nb (Tc = 9.3 K). This implies that the array is a strongly coupled network of superconducting islands (10–12). The parameters of our array ensure that the inter-site barriers are high enough to provide pinning sufficient for formation of the vortex Mott insulator state and that vortex motion is thermally activated.

The measurements are carried out in a shielded cryostat at temperature 7 = 1.4 K. Figure 2A shows