# Observation of the Aharonov-Casher Effect for Vortices in Josephson-Junction Arrays

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We have observed quantum interference of vortices in a Josephson-junction array. When vortices cross the array along a doubly connected path, the resultant resistance oscillates periodically with an induced charge enclosed by the path. This phenomenon is a manifestation of the Aharonov-Casher effect. The period of oscillation corresponds to the single electron charge due to tunneling of quasiparticles.

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Vortices in superconducting networks with low-capacitance Josephson junctions can behave as macroscopic quantum particles. This idea has been put forward from theory [1–4] and recently experimental studies of vortex dynamics and phase transitions in large junction arrays have provided evidence to support it [5–7]. In this Letter we report on an experiment that directly demonstrates the quantum nature of vortices, through the interference of vortices moving in a ring that surrounds a charge. The sample geometry used is shown in Fig. 1. When the charge on the center island in the array is varied by means of a capacitive gate, the flux-flow resistance shows a strong periodic modulation (Fig. 2). This result is a manifestation of the generalized Aharonov-Casher effect [8]. The full effect should have a periodicity of $2e$ in the induced charge. In our experiment, resetting of the charge occurs by quasiparticle tunneling and the period corresponds to $e$. Notwithstanding this limitation the interference itself is remarkable. A vortex is a point object when addressed in its essential nature of a topological excitation. In all other aspects, however, it is a truly macroscopic object that extends over many Josephson junctions.

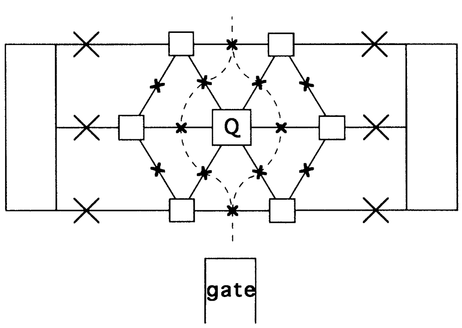


FIG. 1. Schematic layout of the sample. Rectangles are superconducting aluminum islands and crosses denote Josephson junctions. The junctions in the hexagon have a 3 times smaller junction area than the junctions that couple the array to superconducting current and voltage contacts. The dashed lines picture the possible vortex paths.

The Aharonov-Casher (AC) effect is the dual of the more familiar Aharonov-Bohm effect [9]. Instead of the quantum interference of charged particles moving around a magnetic flux, the interference is studied of particles with a magnetic moment moving around a line charge. The AC effect has been observed for neutron beams [10]. Reznik and Aharonov [11] conceptually discussed the possibility of an AC effect for magnetic vortices in a superconductor. van Wees [12] extended this idea to vortices in a ring-shaped two-dimensional array of superconducting islands, connected by Josephson junctions. The vortices here carry no local magnetic flux, because of the long screening length. In the array that van Wees considers, vortices are restricted to a circular path by superconducting bulk contacts around and inside the loop. When a current $I$ is passed from the outer to the inner contact through $L$ junctions along the length of the loop, a vortex experiences a tangential force $F = \Phi_0 I/L$, where $\Phi_0$ is the flux quantum $h/2e$. Because after a vortex has

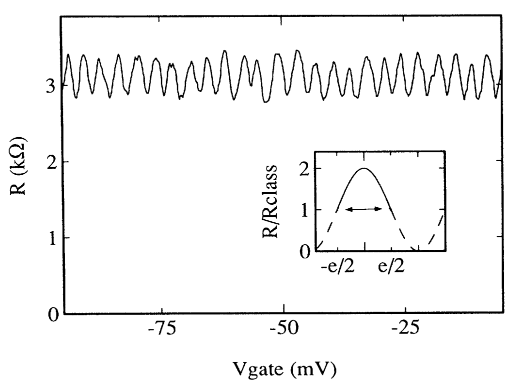


FIG. 2. Differential resistance as a function of gate voltage in a field of 120 $\mu$T. Bias current is 5 nA with 0.25 nA modulation amplitude. Inset: Expected resistance as a function of charge on the center island, normalized to the classical resistance. At $Q = \pm e/2$ quasiparticle tunneling occurs to minimize the charging energy. On sweeping the gate voltage, the charge remains in the range $[-e/2, e/2]$.

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traveled around the loop the vortex position is the same as at the start, the force cannot be expressed as the gradient of a scalar potential. A charge vector potential $A_Q$ is therefore introduced in analogy to the magnetic vector potential and the generalized momentum of the vortex is $p + \Phi_0 A_Q$. Consequently, the force on the vortex can now also be expressed as $F = \Phi_0\, dA_Q/dt$. The quantum phase difference for a vortex moving around the loop once is $\frac{2\pi}{2e} \oint dl\, A_Q$ which equals $2\pi Q/2e$, where $Q$ is the charge on the center electrode.

Recently, several other authors [4,13] have addressed the dynamics of quantum vortices in a charged junction array and have arrived at similar conclusions as van Wees. To obtain an observable effect, fluctuations of the quasiparticle charge must be suppressed. This is possible by using small capacitance junctions. On the other hand, the ratio of the Josephson coupling energy $E_J$ to the charging energy $E_C$ must not be so small that the system is driven into the insulating regime, where Cooper pairs are localized and the phase of the superconducting order parameter is not defined.

When the loop is open, so that vortices can enter at one point and exit at another, the same relative phase difference is imposed on the two vortex paths between the points. Our quantum interference experiment refers to this situation. In our sample (Fig. 1) vortex motion is limited to two possible paths in a hexagon-shaped array consisting of six triangular cells. The hexagon is coupled to superconducting banks with junctions that have a 3 times larger critical current. These side junctions are large enough to confine the vortex to the hexagon but not so large that the freedom of the phases on the outer islands is restrained. With a gate, charge can be capacitively induced on the superconducting island in the middle of the hexagon.

Our array consists of underdamped Al-$Al_2O_3$-Al junctions that are fabricated with a standard shadow evaporation technique [14]. The small junctions have dimensions of $100 \times 100$ nm$^2$. The experiments are performed in a dilution refrigerator at temperatures down to 10 mK inside Mumetal and lead shields. A small magnetic field can be applied by means of a Helmholtz coil. Electrical leads are filtered at the entrance of the cryostat with rfi feedthrough filters and at sample temperature with $RC$ and microwave filters.

We have performed measurements on several samples. In this Letter we limit ourselves to one of them. The junctions in the hexagon have a normal state resistance $r_n$ of 5.5 k$\Omega$ and a capacitance $C$ of about 1 fF. The ratio of $E_J$ to $E_C$ is 1.5. As a function of the applied perpendicular magnetic field, the critical current exhibits sharply pronounced minima for specific values of the field, such as 80, 120, and 200 $\mu$T. In Fig. 3 the current-voltage characteristic is shown in one of these minima. Figure 3(a) shows three distinct voltage steps that correspond to the switching of separate rows to the BCS gap. In Fig. 3(b), on an expanded scale, a resistive regime is visible below the gap. This branch only appears in the minima where the critical current is depressed by a factor of 4 or more. It is connected with the passage of vortices. We refer to this region as the flux-flow regime.

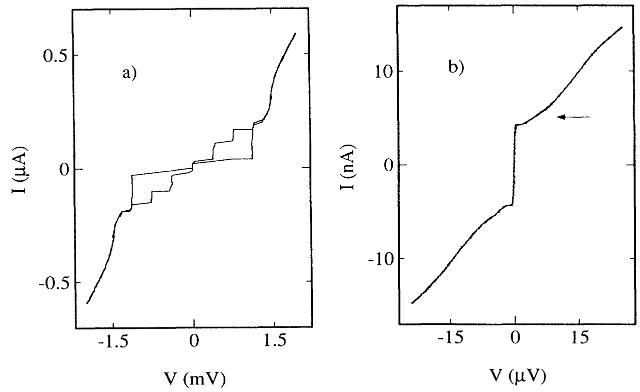


FIG. 3. Current-voltage characteristic in a field of 120 $\mu$T on large scale (a) and on expanded scale (b). The BCS gap $2\Delta/e = 0.4$ mV. The arrow in (b) corresponds to the bias current at which the differential resistance shown in Fig. 2 is measured.

With a standard lock-in technique, we current biased our system in the flux-flow regime, and measured the resistance as a function of gate voltage. Figure 2 shows the result, corresponding to the $I$-$V$ characteristic of Fig. 3, at a bias current of 5 nA. With increasing gate voltage the resistance changes periodically from 2.8 to 3.3 k$\Omega$. The period, as determined by Fourier analysis, is 3.7 mV. With increasing temperature the amplitude of the oscillation decreases and vanishes between 400 and 500 mK. For higher bias currents we generally find a smaller oscillation amplitude. A small periodic modulation of the critical current by the gate voltage is seen in the regimes where the critical current is strongly depressed by the field.

Detailed analysis of the behavior near zero voltage provides evidence for quantum behavior of the vortices, most clearly for a field value of 80 $\mu$T where the apparent critical current is depressed the strongest. Even for zero current, the differential resistance is finite (about 150 $\Omega$) because vortices can quantum tunnel through the system. The apparent critical current, where the differential resistance increases strongly, is smaller than the calculated critical current of the sample by about a factor of 3. We assume this is the point where the pinning potential for the induced vortex in the system has become small enough for the zero point oscillations of the vortex to lead to depinning. A similar zero-bias resistance and suppressed critical current have been observed in larger arrays [7].

In the normal state, induced by a 2 T magnetic field, the zero-bias resistance at 10 mK is only a factor of 1.2 larger than at high temperatures. No clear charging gap is seen. This absence of Coulomb blockade for normal electrons in the sample relates to the absence of localization for Cooper pairs in the superconducting state. With respect to gate voltage, no changes in the $I$-$V$ characteristic could be observed.

We measured the capacitance of the gate to the center island in a specially fabricated sample. Using the same geometry we connected the center island through two high resistance junctions. The period of the oscillations of the normal state Coulomb gap of this double junction is found to be 3.8 mV, which is nearly equal to the period of the flux-flow resistance of the quantum-interference sample in the superconducting state. In the normal state, the period times the capacitance has to be equal to the single-electron charge and the period of the oscillations in the quantum-interference sample therefore also corresponds to the single-electron charge $e$.

The Aharonov-Casher effect has a fundamental period $2e$. The $e$ periodicity of our sample can be understood if we assume the presence of a very small number of quasiparticles. Tunneling of a Cooper pair to or from the island changes the vortex phase difference by $2\pi$. Consequently, a Josephson supercurrent, which passes through the center island of the array, has no influence on the interference. Tunneling of a quasiparticle changes the vortex phase difference by $\pi$. For the center island the charging energy is about $e^2/12C$, which corresponds to 150 mK. At 10 mK the system must remain in the state of lowest energy. When the gate voltage reaches the value where the induced charge exceeds $e/2$, tunneling of a quasiparticle reduces the Coulomb energy. This resetting of the charge by quasiparticles is commonly observed in superconducting double junction systems, in other groups as well as in ours [15]. For our quantum-interference sample the result is that the vortex phase difference is effectively limited to the range between $-\pi/2$ and $+\pi/2$. As illustrated in the inset of Fig. 2, only constructive interference is possible. If no quasiparticles were present, or if the measurement could be performed in a time shorter than the typical quasiparticle tunneling time, one should also be able to access the range of destructive interference. Without quasiparticles the flux-flow resistance should vary between 0 and 2 times the classical value for the same number of vortices passing. With quasiparticles the variation is limited to the range from 1 to 2 times the classical value. In our experiments, the ratio between the maximum and the minimum values of the oscillating resistance shows values up to 1.4. This is remarkably high for a quantum interference experiment, in particular compared with the observed oscillations for electrons or neutrons in a ring as in the other Aharonov-Bohm or Aharonov-Casher experiments. That the theoretical limit is not reached can be due to scattering of part of the crossing vortices by oscillatory modes of the array (spin waves) or quasiparticles. Because in the flux-flow regime energy is dissipated in the system, this seems not unreasonable.

The fact that oscillations can still be observed at 400 mK is remarkable considering the charging energy and the expected level separation of the zero-dimensional vortex quantum states. For free vortices with mass $\Phi_0^2/C$ in a closed one-dimensional loop of six junctions one expects a typical distance between levels of about 100 mK [12]. The predicted quantized voltages, induced by persistant vortex currents in such closed loops, would be washed out by higher temperatures. A similar argument applies to the washing out of Aharonov-Bohm oscillations of electrons in small metal rings [16]. However, in our interference experiment, the sample has very high symmetry between the two paths and the wave vector of the participating vortices is irrelevant. Vortices all have the same phase difference induced by the charge. The interference will only be destroyed when the quasiparticles are no longer localized by the Coulomb energy, because tunneling of a quasiparticle changes the phase difference by $\pi$. In fact, in the range between 300 mK and 400 mK, we expect that during the measuring time many tunneling effects take place. Still, the average time spent at the state of lower Coulomb energy will be longer than the time spent at the higher level. As long as the charge is fixed during the vortex passing time of order $10^{-10}$ s, a small amplitude will survive. We find the observed temperature dependence consistent with this reasoning. In addition the increased presence of quasiparticles at higher temperatures will eventually lead to inelastic scattering processes which destroy the quantum effects.

Essential to our interpretation is that the flux-flow branch, which exhibits the observed oscillations, really corresponds to the crossing of vortices through the array. In former experiments on circuits of these small underdamped junctions a resistive branch between zero voltage and the gap could always be attributed to vortex crossing. In addition, we have performed computer simulations on our experimental circuit solving the full set of RCSJ (resistively and capacitively shunted junction) equations for each junction and including a subgap resistance. The variation of the critical current as a function of magnetic field in the simulation is very similar to that of our experiment. In the minima, the $I$-$V$ characteristic shows the flux-flow branch. By studying the superconducting phase distribution over the islands at each time step, vortices can be seen to move one by one along one of the expected two paths. From the above arguments we conclude that oscillations in our quantum-interference sample indeed arise from the influence of the gate on the dynamical states of the vortex. In a simple series array of junctions, which cannot contain a vortex, the critical current is predicted to oscillate with gate voltage [17]. However, for such samples in the normal state one expects a very strong modulation of the Coulomb gap with gate voltage. This is not found in our quantum-interference sample.

The flux-flow branch is associated with dissipation. In the quantum regime no theoretical description is available for the size of our sample. The vortex energy will certainly be partly transferred to oscillatory modes. In particular, when the vortex leaves the last cell, a rather high amount of configurational energy is released. A reasonable estimate of the relaxation time of spin waves is $r_n C$. In our sample $r_n C$ is about 5 ps. For typical voltages of 10 $\mu$V, the average time between vortex crossing events is 200 ps. We expect that spin waves that are excited by one vortex will die out before the next vortex comes by.

To conclude: we have observed quantum-mechanical interference of vortices around an induced charge. The quantitative results are in excellent agreement with expectations for the Aharonov-Casher effect. Quasiparticles reduce the oscillation period to the single-electron charge $e$. The results clearly demonstrate that a vortex is a macroscopic quantum particle.

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