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Propagating vortex beams in Josephson-junction arrays

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Abstract

We have observed ballistic motion of vortices in arrays of superconducting tunnel junctions arranged in a special geometry. Vortices are accelerated in one region, then launched through a channel into a second region where no driving forces are present. At low temperatures, vortices are found to propagate in a beam across the force-free region.

Research on vortex dynamics in two-dimensional superconductors has so far been concentrated on systems where vortices are overdamped. Recently, attention has been drawn to the novel regime of nonviscous vortex motion.[1] The energy stored in the electric field generated by a moving vortex has to be taken into account. This contribution to the energy can be viewed as a kinetic energy term and defines an effective vortex mass which is proportional to the junction capacitance.[1] As a consequence of the massive character of vortices, theoretical predictions have been made for ballistic motion of vortices [2] and quantum behavior of vortices.[1,3] Particularly well suited for studies of dynamics of massive vortices are 2D arrays of *underdamped* Josephson tunnel junctions. In junction arrays parameters can be measured and can be varied over orders of magnitude, allowing one to access the regime of low dissipation. Recent work on vortex motion in underdamped junction arrays clearly demonstrates the existence of a mass term in the equation of motion.[4] Vortices move in the periodic array potential, and there exists a close analogy between the dynamics of vortices in junction arrays and the dynamics of the phase in single junctions.

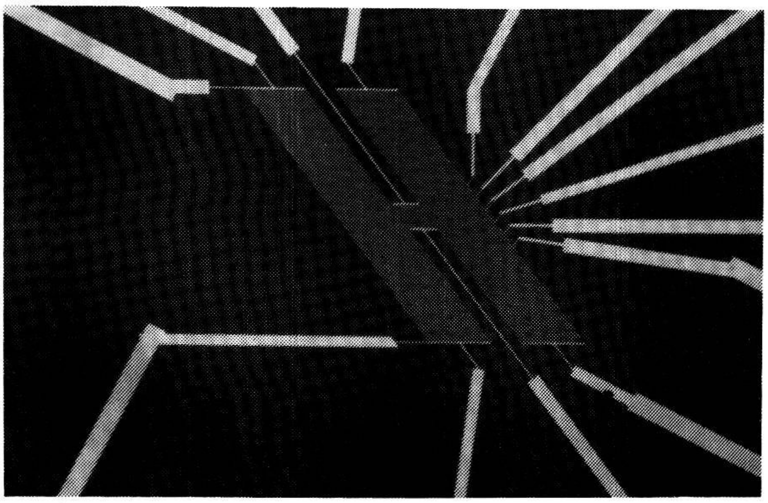

Fig. 1 Special sample geometry to detect ballistic vortices.

In order to detect ballistic vortices, we designed and fabricated triangular arrays of high-quality all-aluminum Josephson tunnel junctions, arranged in a special geometry, illustrated in Fig. 1. It consisted of two arrays (100 cells by 40 cells), coupled by a channel of 7 cells wide and 20 long. Vortices were generated by a small perpendicular magnetic field. A current in the array on the left hand side (array 1) accelerated vortices up to a high velocity. Some of the vortices are launched through the channel into the second array on the right hand side (array 2), where no current was applied. Superconducting banks on both sides of the channel confined vortices in the channel. A set of voltage probes in the array 2 was used to detect the place where vortices left this array.

We have measured the voltage distribution around array 2 as a function of temperature. In case of viscous vortex motion, vortices are expected to pile up near the exit of the channel and then to be driven out of array 2 by the concentration gradient. Voltages are expected between all probes, but the highest along the edges on the left hand side of array 2, because these are closest to the channel exit. At temperatures just below the BCS transition temperature, we indeed found a voltage distribution around array 2 corresponding to this viscous-like behavior of vortices.

At lower temperatures, we clearly observed nondiffusive behavior. The voltage across two probes, separated from each other by 15 cells and situated just opposite to the channel on the right hand side of array 2, closely approached the channel voltage. This observation indicates that almost all vortices passed through array 2 in a narrow beam and that in the low-temperature regime vortices behaved as ballistic particles. When the current direction in array 1 was reversed, accelerating vortices away from the dectector region, no ballistic motion was observed as expected. More details will be published elsewhere.[5]

In array 2 we decelarated vortices by applying a current in the direction opposite to the current in array 1. From this experiment an estimate of the loss of kinetic energy of the vortices could be obtained. The data do not fix the precise value of the vortex velocities, because the exact number of vortices in the channel is unknown. We therefore cannot give an accurate estimate of the vortex mass from this loss of kinetic energy. In future experiments, we will try to generate vortices at a known rate, so that the measured voltage gives the precise value of the velocity. Also, one should think of vortices as quantum mechanical objects. In the present experiment, quantum diffusion may lead to broadening of the beam in array 2. In future, the vortex wavelength can be made larger than the cell size and interference of split coherent beams should in principle be possible.

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