QUANTIZED FLUX PINNING IN SUPERCONDUCTING NIOBIUM

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The purpose of this Letter is to report direct experimental evidence for quantized flux pinning in superconducting niobium in localized units of magnitude $h/2e$. Long-range phase coherence[1] and the consequent quantization of the magnetic fluxoid by a superconducting cylinder has strong experimental support. This support ranges through measurements on the trapped flux,[2] free energy,[3] and phase coherence.[4] This same concept of long-range phase coherence applied to the flux pinned in a type-II superconductor[5] leads to the expectation of flux pinning in localized quantum units, $h/2e$. We believe this to be the first direct experimental confirmation of such quantized flux pinning in a singly connected superconductor.

The experimental concept is based on the utilization of quantum interference effects in superconductors[4,6] as a flux detector. A two-contact superconducting quantum interferometer was used to measure the flux pinned in a 0.05-mm niobium wire passing through the interferometer. The two-contact interferometer is sensitive to the magnetic flux threading through the area ("window") circumscribed by the device. In these experiments the flux is pinned longitudinally in a niobium wire passing through the window. Flux is constant along the length of the wire, changing only when a flux line emerges from the surface. As the wire is drawn through the window, the interferometer responds to such flux leakage, yielding both the sign and magnitude of the flux change. Flux was pinned in a section of the wire by applying a longitudinal magnetic field and at the same time momentarily raising that section of the wire above the transition temperature. The heat-treating oven was made by drilling an axial hole through a $\frac{1}{2}$-watt carbon resistor upon which the field solenoid was directly wound. A momentary heat pulse from a condenser discharge through the resistor was sufficient to expel the liquid helium from the axial hole and raise the temperature of a centimeter or so of the wire above its transition temperature.

Following heat treatment, the wire was scanned by passing it at a rate of 2 mm/min through the window of a two-contact quantum interferometer operating on principles outlined in previous publications.[4,6] The essential property of this interferometer is that the critical current is a periodic function of the flux through the window with a measured periodicity $h/2e$. Thus by observing the shift of the critical-current pattern, one obtains a measure of the change of flux through the window. The experimental arrangement is shown schematically in Fig. 1.

The results of many observations were always of the same nature, namely, that as the wire was scanned, the critical-current pattern, as observed on an oscilloscope, either remained nearly constant, or else shifted quickly by one complete cycle, indicating an increase or decrease of flux

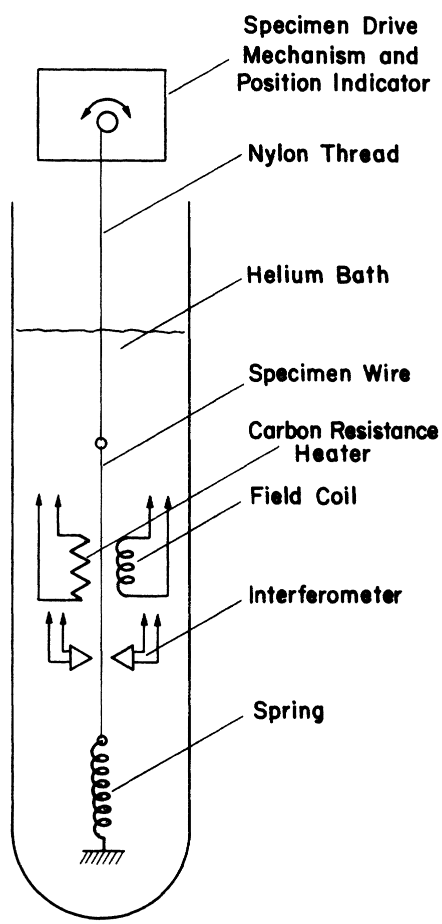

FIG. 1. Schematic representation of the experimental apparatus. This apparatus is shielded by a combination of Mumetal and superconducting shields. The specimen wire is slowly drawn vertically through the interferometer causing discrete phase shifts due to flux leakage.

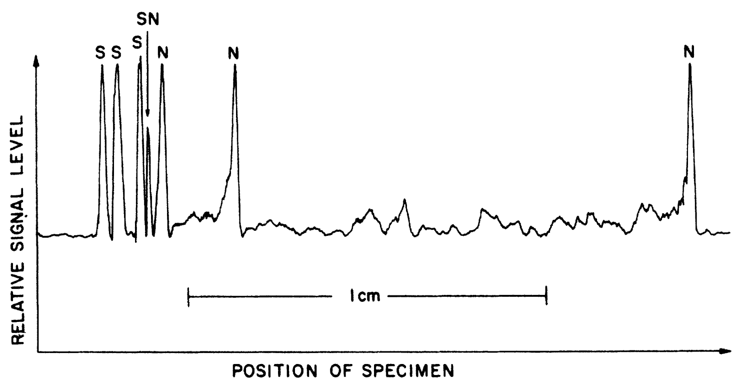

FIG. 2. Interferometer signal level as a function of wire position. Signal level is periodic in the enclosed flux with a period $h/2e$. Constant null position and the observed 2π phase shift associated with the signal peaks can only be explained by flux pinning in quantum units $h/2e$. S and N indicate the direction of the emerging field.

in the wire of $h/2e$. By "heat treating" the wire at low applied fields, we were able to eliminate the flux completely, while at higher fields we could observe the successive inclusion of a single flux quantum (fluxoid), two quanta, three quanta, and so on, up to a hundred or more. The axial resolution of the interferometer was about 0.2 mm, so that in scanning one cm of wire not more than about twenty fluxoids could be resolved even if uniformly distributed. In addition to visual observation of the shift of the oscilloscope pattern, we also utilized a phase-locked detector working into an XY recorder to plot the critical current vs position along the wire. A typical recorder plot is shown in Fig. 2, which shows the pinning of four fluxoids (four N poles and four S poles). The polarity of the poles is not shown by the recorder trace but was determined by visual observation of the direction of shift of the critical current pattern on the oscilloscope. This and other fluxoid configurations could be erased and reproduced at will by appropriate heat treatment, both with regard to number of quanta and actual position of the poles, which were presumably pinned in certain positions by local inhomogeneities in the wire. The small-amplitude background fluctuations on the recorder trace were reproducible and unaffected by heat treatment or even by warming the whole apparatus to room temperature and back to 4.2°. Apparently these were the result of variations in cross-sectional area of the wire acting on an ambient magnetic field through the interferometer window. An ambient field of 50 milligauss in the window and area variations of ~1% would produce the observed effects.

Preliminary data on field thresholds for the appearance of successive fluxoids indicated that the thresholds occur at constant field increments of about 14×10^{-3} gauss corresponding to applied flux increments of about 2.6×10^{-7} gauss cm^2. More data are needed to confirm this and also to show whether the field at which the first fluxoid appears is one-half the field increment for succeeding fluxoids.

Although it has been widely assumed for some time that flux pinned in type-II superconductors exists in the form of individual quantized bundles associated with current vortices, we believe this is the first direct confirmation of the assumption. This confirmation consists of a direct measurement of the pinned flux units as $h/2e$ and supporting evidence from field thresholds for the appearance of successive fluxoids. These experiments are being repeated for a high-purity, annealed, type-II superconductor and the feasibility of observing flux penetration at the critical field is being considered.

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