Brief Reports

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Verification of the Aharonov-Bohm effect in superconductors by use of a toroidal flux geometry

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(Received 25 November 1985)

Predictions made by Aharonov and Bohm concerning the effects of electromagnetic potentials on electrons in field-free regions of space have been demonstrated in superconductors with the use of the flux produced by a very fine toroidal solenoid. The use of a toroidal geometry sidesteps the objections raised by Roy concerning the use of sources of flux with linear geometries. The use of superconductors excludes the possibility that stray electrons can pass through the flux-filled region of space to produce the observed phenomena.

The theoretical objections raised by Roy concerning past demonstrations of the Aharonov-Bohm effect[1] using straight solenoids and permanent magnets have been disputed by a number of authors. Roy claimed[2] that effects attributed to inaccessible fields, which had been seen up until that time, could have been caused by the inevitable leakage of flux from the ends of these (necessarily finite) devices, so that the observations did not constitute a valid test of the Aharonov-Bohm effect. Arguments have been put forward[3,4] suggesting that the leakage fields present, while nonzero, are nevertheless small enough that they could not be used to explain the observed phenomena. Regardless of the validity of his claims, Roy admitted that they do not rule out a demonstration of field-free effects using a toroidal flux geometry, which would consistute a valid test of the predictions of Aharonov and Bohm.

Tonomura *et al.*[5] have performed just such an experiment using electron beams and extremely small ($\sim 3\ \mu$m diameter) permalloy toroidal magnets. In this experiment, electron interference micrographs of the magnets are formed, which show a difference between the phases of electrons which travel through the center of the toroids and the phases of those which travel past them. The magnetic field is confined to the insides of the toroids, so that one may conclude that it is the magnetic vector potential, and not the field itself, which is producing the phase shifts. Unfortunately, some of the electrons in the beam actually passed through the magnets (through the region of magnetic field), so that this conclusion is not completely without doubt. The authors offer a good argument as to why the outcome of the experiment should not be affected by this fact, but it would clearly be desirable if an experiment could be performed in which the electrons are completely excluded from the region containing magnetic flux.

The existence of SQUID's (superconducting quantum interference devices) offers the possibility of performing, on a macroscopic scale, an experiment in which electrons are completely excluded from the flux-filled region. Such an experiment was first performed by Jaklevic *et al.*,[6] using a thin film SQUID and a straight solenoid. They were able to demonstrate "field-free" effects on electrons traveling through a region of space in which the magnetic field was less than $\frac{1}{100}$ of its value in the flux-filled region. Since the solenoid producing the flux was straight, the objections of Roy apply in this case.

An experiment has been performed using a newly developed flexible solenoid[7] as a source of magnetic flux and a point contact dc SQUID as a detector. The solenoid had a length of 6.4 cm and a width of 376 μm, giving a length to width ratio of 170 to 1. It could be bent into a loop and joined at the ends to form a torus. The solenoid was backwound with closely spaced turns, so that the amount of leakage flux was very low. The magnetic field outside the solenoid was measured using a S.H.E. model 330X SQUID magnetometer and was found to have a strength approximately 5×10^{-5} times that of the internal field. Current was provided to the solenoid by a S.H.E. CCS current supply. The use of superconducting lead to shield the solenoid lead wires eliminated the effects of stray fields from this source.

The type of SQUID used to make the interference measurements was of the point contact variety first described by Zimmerman and Silver.[8] The reason for using this kind of SQUID (rather than a thin-film device) is that it was relatively easy to fabricate, and because the reliability and sensitivity did not have to be high. Adjustments of the point contacts were made before the apparatus was lowered into the liquid helium. If the SQUID appeared to be inoperative at 4.2 K, it was merely raised out of the helium and readjusted. This turned out to be a satisfactory procedure for the purposes of this experiment.

Measurements were made by observing the I-V characteristic of the SQUID for a given amount of magnetic flux Φ. The maximum lossless current which could be supported by the SQUID was noted, and the current passing through it increased so as to drive its weak links to a normally conducting (resistive) state. The magnetic flux passing through the SQUID was then changed. Since the weak links were in a normally conducting state, the electric field present during the change of the magnetic field (which would generate persistent currents in a fully superconducting SQUID) could only have a transient effect on the state of the SQUID. Following the passage of a time interval sufficient to guarantee the complete elimination of any transients (a few seconds), the SQUID current was decreased to the point where the weak links became superconducting again. It was observed that the variation of the maximum SQUID current is a periodic function of Φ with a period of $(2.1 \pm 0.2)\times 10^{-7}$ G cm^2. This is close to the value of the flux quantum $\Phi_0 = (hc/2e) = 2.07\times 10^{-7}$ G cm^2, which is the theoretically predicted period of the function. The uncertainty in the measured flux resulted partly because of the uncertainty in the solenoid current ($\pm 1\%$), but mostly because of the uncertainty in the area enclosed by the solenoid ($\pm 9\%$).

This result appears to support the ideas of Aharonov and Bohm under conditions which preclude objections arising from the use of linear flux geometries, and the use of experimental arrangements which allow electrons to penetrate the region containing magnetic flux.

The author gratefully acknowledges the support given by J. F. Carolan, including the use of his laboratory, which is supported by the Natural Sciences and Engineering Research Council of Canada. The comments and suggestions made by W. G. Unruh and M. H. L. Pryce are also appreciated.

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