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Observation of h/e Aharonov-Bohm Oscillations in Normal-Metal Rings

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Magnetoresistance oscillations periodic with respect to the flux h/e have been observed in submicron-diameter Au rings, along with weaker $h/2e$ oscillations. The h/e oscillations persist to very large magnetic fields. The background structure in the magnetoresistance was *not* symmetric about zero field. The temperature dependence of both the amplitude of the oscillations and the background are consistent with the recent theory by Stone.

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Electron wave packets circling a magnetic flux should exhibit the phase shift introduced by the magnetic vector potential $\mathbf{A}$.[1] In a metallic ring, small enough so that the electron states are not randomized by inelastic (or magnetic) scattering during the traversal of the arm of the ring, an interference pattern should be present in the magnetoresistance of the device.[2] Electrons traveling along one arm will acquire a phase change δ_1, and electrons in the other arm will, in general, suffer a different phase change δ_2. Changing the magnetic flux encircled by the ring will tune the phase change along one arm of the ring by a well-defined amount $\delta_B = (e/\hbar)\int \mathbf{A}\cdot d\mathbf{l}$ and by $-\delta_B$ along the other arm. The phase tuning should appear as cycles of destructive and constructive interference of the wave packets, the period of the cycle being $\Phi_0 = h/e$. This interference should be reflected in the transport properties of the ring as described by Landauer's formula.[2-4] In this Letter, we describe the first experimental observation of the oscillations periodic with respect to Φ_0 in the magnetoresistance of a normal-metal ring.

Interference effects involving the flux h/e have been previously observed in a two-slit interference experiment involving coherent beams of electrons.[5] Magnetoresistance oscillations in single-crystal whiskers of bismuth periodic in h/e have been reported at low fields for the case where the extremum of the Fermi surface is cut off by the sample diameter.[6] Resistance oscillations of period $h/2e$ (flux quantization) have been seen in superconducting cylinders.[7] Four years ago, magnetoresistance oscillations of period $\frac{1}{2}\Phi_0$ were predicted on the basis of weak localization in multiply connected devices.[8] This is the same flux period as observed in superconductors, because of the similarity between the superconductor pairing and the "self-interference" described by the theory of weak localization.[9] Since the first experiment by Sharvin and Sharvin,[10] there have been several observations of the superconducting flux period $\frac{1}{2}\Phi_0$ in normal-metal cylinders and networks of loops.[11] To date, there have been no observations of the one-electron flux period Φ_0, and its existence is controversial. Several recent theoretical papers have argued that the h/e period will be present in strictly one-dimensional rings,[2] and even in rings composed of wires with finite width.[4] Others have claimed that only $h/2e$ oscillations will be observed regardless of device size and topology.[12]

Theoretical work which relies upon ensemble-averaging techniques has uniformly predicted $h/2e$ oscillations[8,12]; calculations of the conductance exclusive of the averaging have predicted h/e oscillations as well.[2,4] The difference between a single ring and a network of rings or a long cylinder is, therefore, crucial. The network of many rings and the long cylinder extend much farther than the distance $[L_\phi = (D\tau_\phi)^{1/2}$, where D is the diffusion constant and τ_ϕ is the time between phase-breaking collisions] that the electron travels before randomly changing its phase. For this reason, it is believed that samples much longer than L_ϕ physically incorporate the ensemble averaging.[4,13] Each section (longer than L_ϕ) of a macroscopic sample is quantum-mechanically independent because the electron states are randomized between the sections. The single mesoscopic ring (diameter $< L_\phi$) does not average in this way because the entire sample is quantum-mechanically coherent.[4,13]

There exists a further complication in normal metals; the magnetic flux penetrates the wires composing the device. Stone[14] has shown that the flux in the wire leads to an *aperiodic* fluctuation in the magnetoresistance. This fluctuation was the main complication in interpreting the earlier experiments[15] where the diameter of the ring was not much larger than the widths of the wires. On the basis of the analysis, a prediction was made that, in a ring having an area much larger than the area covered by the wires, the oscillations would be clearly observed, since the period would then be much smaller than the field scale of the fluctuations.

With this in mind, we constructed several devices each containing a single loop or a lone wire. The samples were drawn with a scanning transmission electron microscope (STEM) on a polycrystalline gold film 38 nm thick having a resistivity $\rho \simeq 5\ \mu\Omega\cdot$cm at $T = 4$ K. The fabrication process has been described previously.[16] A photograph of the larger ring is shown in Fig. 1. Here we will describe the results from two of the

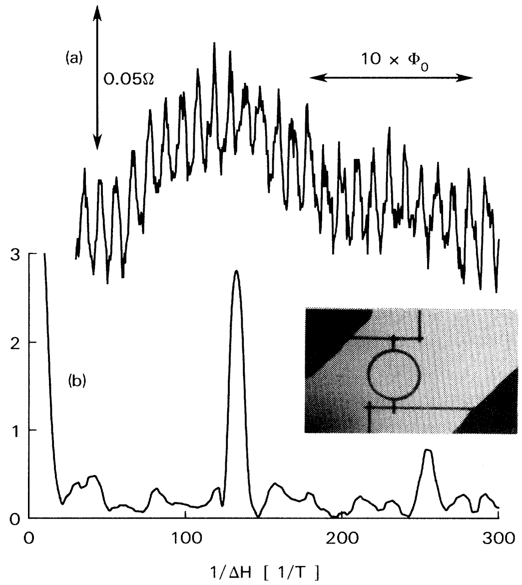

FIG. 1. (a) Magnetoresistance of the ring measured at $T=0.01$ K. (b) Fourier power spectrum in arbitrary units containing peaks at h/e and $h/2e$. The inset is a photograph of the larger ring. The inside diameter of the loop is 784 nm, and the width of the wires is 41 nm.

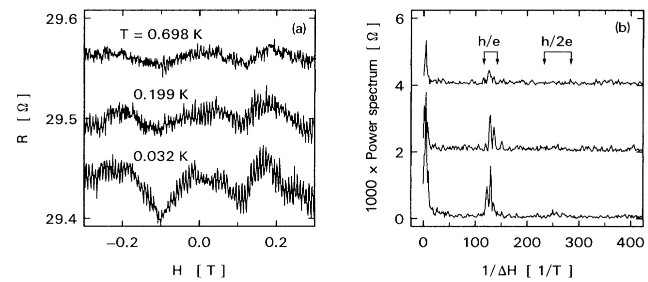

FIG. 2. (a) Magnetoresistance data from the ring in Fig. 1 at several temperatures. (b) The Fourier transform of the data in (a). The data at 0.199 and 0.698 K have been offset for clarity of display. The markers at the top of the figure indicate the bounds for the flux periods h/e and $h/2e$ based on the measured inside and outside diameters of the loop.

rings (average diameters 825 and 245 nm) and a lone wire (length 300 nm). The samples were cooled in the mixing chamber of a dilution refrigerator, and the resistance was measured with a four-probe bridge operated at 205 Hz and 200 nA (rms).

Typical magnetoresistance data from the larger-diameter ring are displayed in Fig. 1(a). Periodic oscillations are clearly visible superimposed on a more slowly varying background. The period of the high-frequency oscillations is $\Delta H=0.007\,59$ T. This period corresponds to the addition of the flux $\Phi_0=h/e$ to the area of the hole. From the average area (one half of the sum of the area from the inside diameter and that from the outside diameter) measured with the STEM, $\Phi_0=0.007\,80$ T. The area measurement is accurate to within $\simeq 10\%$. As a result of the large aspect ratio, we can say unequivocally that the periodic oscillations are *not* consistent with $h/2e$. They are certainly the single-electron process predicted recently.[2,4] In the Fourier power spectrum [Fig. 1(b)] of these data, two peaks are visible at $1/\Delta H=131$ and 260 T^{-1} corresponding respectively to h/e and $h/2e$. (Since the h/e oscillations are not strictly sinusoidal, we cannot be certain whether the $h/2e$ peak is the self-interference process or harmonic content in the Φ_0 oscillations.) That the $h/2e$ period is less significant than the h/e period is consistent with the theory for rings which are moderately resistive.[4] We note that the amplitude of the h/e oscillations at the lowest temperatures is about 0.1% of the resistance at $H=0$, at least a factor of 10 larger than the oscillations observed in normal-metal cylinders and networks of loops.[8,10,11]

Figure 2(a) contains resistance data for three temperatures over a larger range of magnetic field. Surprisingly, the oscillations persist to rather higher magnetic field [$H > 8$ T (our largest available field) or over 1000 periods] than expected from estimates which assumed that the phase difference between the inside edge of the ring and the outside edge should completely destroy the periodic effects. The argument that the flux in the metal should destroy the oscillations relies on the simple assumption that the wire consists of parallel but noninteracting conduction paths. If instead the electron path in the wire is sufficiently erratic to "cover" the whole area of the wire, then no phase difference exists between the inside diameter and the outside diameter.[17]

Figure 2(b) contains the Fourier spectra of the data in Fig. 2(a). Again, the fundamental h/e period appears as the large peak at $1/\Delta H=131$ T^{-1}, and near $1/\Delta H=260$ T^{-1} there is a small feature in the spectrum. There is also a peak near 5 T^{-1} which is the average field scale of the aperiodic fluctuations.[14] The detailed structure of the h/e peak in the power spectrum is probably the results of mixing of the field scales corresponding to the area of the hole in the ring and the area of the arms of the ring.[18] (The simple difference between inside and outside area implies a splitting of more than 20 T^{-1}, whereas the observed splitting in the peak structure has never been more than 7 T^{-1}.) A simple extension of the multichannel Landauer formula for a ring with flux piercing the arms implies that the Arharonov-Bohm oscillations will be modulated by an aperiodic function.[18] Roughly speaking, the field scale in which the aperiodic function fluctuates is that for the addition of another flux quantum to the arms of the ring. The field scale of the modulating function mixes with the Aharonov-Bohm period to give structure to the peak. As seen in Fig.

2(b), the splitting of the h/e peak is about the same as the field scale of the aperiodic fluctuations. The same interference effects within the arms which cause the random background fluctuations result in the amplitude modulation of the h/e oscillations seen in Fig. 2(a).

As previously reported, at the lowest temperatures, the magnetoresistance is *not* symmetric about the point $H=0$. Furthermore, no constant offset in the magnetic field axis can account for the asymmetry. As the temperature increases, the asymmetry becomes less pronounced. In particular, in the range -0.1 T $< H < 0.1$ T, the data are nearly symmetric at $T=0.7$ K. Büttiker and Imry have shown that the asymmetry is consistent with the multichannel Landauer formula.[19]

Measurements on a ring with a smaller aspect ratio (inside diameter of 208 nm and wire width of 37 nm) were also performed, and a typical power spectrum is shown in Fig. 3. The presence of Aharonov-Bohm oscillations was not immediately obvious against the background of aperiodic fluctuations.[15] Comparison of the ring spectrum to that of a lone wire (having approximately the same area as an arm of the ring) makes the presence of the Aharonov-Bohm oscillations clear. The power spectrum of the wire contains no peaks at $1/\Delta H \gtrsim 7$ T^{-1} whereas the ring spectrum contains several peaks between 8 and 30 T^{-1}. The field scale for interference among paths within one of the arms is given by the spectrum of the wire,[14] and the peaks between $8 < 1/\Delta H < 30$ T^{-1} are the signature of the Aharonov-Bohm effect in the ring. The existence of several peaks in this range is consistent with the arguments made earlier about the mixing. The splittings are relatively larger here because the area of the hole and the area of the wires are not very different.

As the temperature increases, all of the magnetoresistance fluctuations shrink. As shown previously,[14,15] the amplitudes P of the aperiodic fluctuations are governed roughly by $P \propto T^{-1/2}$. All of the states within $k_B T$ of the Fermi energy contribute independently to the aperiodic fluctuations, and the amplitude of the fluctuations decreases as $T^{-1/2}$ because of this temperature averaging.[14] We emphasize that this is *not* the usual temperature dependence seen in quasi-one-dimensional, macroscopic samples which results from the temperature dependence of L_ϕ. The h/e peak amplitude also appears to be consistent with the $T^{-1/2}$ temperature dependence. In fact, all of the peaks in the Fourier spectrum (including data reported previously[14]) are consistent with $T^{-1/2}$ for $0.05\text{ K} < T < 0.7$ K.

To summarize, we have made the first observation of the normal-metal flux period h/e in very small, single loops of gold. In contrast to expectations, the oscillations persist to very high magnetic fields apparently without attenuation. Evidence was also found for oscillations of period $h/2e$. The detailed structure of the Fourier spectra indicates the importance of the physics of the wires.

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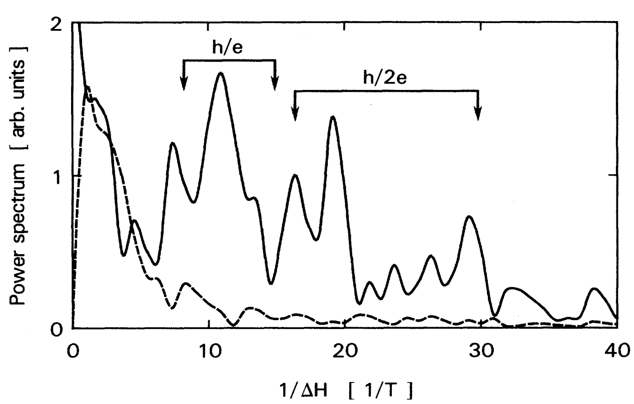

FIG. 3. Fourier transform of data from a smaller-diameter ring (solid line) and from a wire 3000 Å long by 300 Å wide (dashed line) over the range $0 < H < 1.1$ T. The markers at the top indicate the h/e and the $h/2e$ periods for the inside and outside diameters of the ring.

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