Persistent Currents in Normal Metal Rings

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Abstract:
Measurements of persistent currents in diffusive metal rings can be used to test the validity of the theory that explains electronic diffusion in metallic systems. The value of these currents is a stochastic function of the disorder profile, and thus different from sample to sample. Our test consists of studying the distribution function of the measured persistent currents. In order to probe the underlying distribution of the stochastic function we need to study the statistics of many independent samples. We do so by measuring eight different samples over a large magnetic field range.

Summary of Research:
A remarkable prediction of mesoscopic physics is that a resistive metal ring can support a dissipationless electrical current [1]. This persistent current (PC) is quantum in nature and is analogous to the net orbital angular momentum of the electrons orbiting some atoms. In order for this persistent current to be appreciable, though, the circumference of the ring must be smaller than both the electron phase coherence length in the metal and the thermal length, both of which are on the micron size scale for millikelvin temperatures. Another crucial point is that in order to observe all this motion happening within the ring, we need to break time-reversal symmetry by applying a magnetic flux through the ring. This results in stationary flux-dependent circulating current with periodicity of flux quantum $\hbar/e$ with $\hbar$ being Planck’s constant and $e$ the electron charge.

The order of magnitude of the PC for our rings is of the order of 1 nA. Although a current of 1 nA is not technically hard to measure, the experimental difficulty arises from the fact that the PC flows only within the ring and so it can only be measured by non-invasive methods. Our group has recently showed that torsional magnetometry can be used to measure PC with an excellent sensitivity [2]. Our approach consists of fabricating ultra-sensitive cantilevers integrated with single metal rings. An SEM picture of a characteristic sample is shown in Figure 1. When a current flows in the ring, its magnetic dipole moment couples to the mechanical motion of the cantilever. This makes the resonance frequency of the cantilever a function of the current in the ring. We monitor the cantilever resonance frequency using laser interferometry as we sweep the magnetic field. The sensitivity compared to previous measurements was increased to 0.2 nA/√Hz for a ring with 2 µm circumference at 9 T.

One important point about the PCs in our rings is that, like many mesoscopic effects in disordered systems, they depend on the particular realization of disorder and thus vary between nominally macroscopically identical systems.
Theory has predicted the persistent current to be a random variable whose ensemble average vanishes and have a particular typical magnitude (or second cumulant) already studied by our group in previous measurements[2]. Theory also predicts that for metallic rings all of the other higher cumulants vanish, and thus we expect the distribution function to be Gaussian [3]. Our new measurements tested this prediction.

The inset of Figure 2 contains a representative plot of measured persistent current versus magnetic field, showing its characteristic periodicity in applied field. As observed in Figure 2, the persistent current oscillation also has a finite correlation (shown as an aperiodic modulation of the amplitude) in applied magnetic field due to the field penetrating the metal [4]. This implies that distant magnetic field points give statistically independent measurements of the current magnitude. Thus, the expected magnetic dependence of the measured PCs is given approximately by the following equation:

$$I(B_m, \phi) = I^+(B_m) \cos\left(2\pi \frac{\phi}{\phi_0}\right) + I^-(B_m) \sin\left(2\pi \frac{\phi}{\phi_0}\right)$$

where the variables $I^+$ and $I^-$ are stochastic variables that vary with the magnetic field $B_m$. These are shown in the main plot of Figure 2. Our goal is determining whether the distribution of $I^+$ and $I^-$ agrees with the predictions done so far that they are Gaussian.

This finite correlation also allows us to effectively take a large number of independent measurements by sweeping the magnetic field over a large range. We performed measurements over seven more samples on top of a single ring measured in previous measurements. The consolidated data of our measurements is shown in Figure 3. The estimates of the measured first six cumulants agree with the expected values within the statistical and experimental error, thus confirming that the measured distribution of the amplitude of the persistent currents is Gaussian.

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