Sensing a Small but Persistent Current

Norman O. Birge

Michigan State University, East Lansing, MI 48824

The idea that a normal, non-superconducting metal ring can sustain a persistent current – one that flows forever without dissipating energy – sounds preposterous. We all know that metal wires have an electrical resistance, and currents passing through resistors dissipate energy. Besides, how would such a persistent current decide which way to go around the ring – clockwise or counterclockwise? Doesn't time-reversal symmetry forbid a current choosing one direction over the other?

The latter argument is indeed correct. The persistent current can exist only in the presence of a magnetic field piercing the ring, which breaks time-reversal symmetry. It is easy to show that all physical properties of a metal ring vary periodically with the magnetic flux through the ring (1), with period equal to the magnetic flux quantum, $\Phi_0 = h/e$. It was shown 25 years ago that among those periodically-varying physical properties is the ring's persistent current (2), and that this current exists even in realistic metal rings containing atomic defects, grain boundaries, and other kinds of static disorder (3). The current is extremely small, however, and experimental attempts to measure it are notoriously difficult. Recently, Jack Harris and his colleagues at Yale have developed a new way to measure persistent currents with sensitivity much higher than their predecessors'. Their results, reported in this issue of Science (4), help resolve some of the discrepancies that have plagued the field for nearly 20 years.

Several factors conspire to render detection of the persistent currents extremely difficult. To start with, the current flows only around a closed ring, so one cannot insert an Ammeter into the circuit to measure it directly; instead, one must measure the very small magnetic moment produced by the current. Theory predicts that the magnitude of the persistent current is roughly equal to the charge of a single electron divided by the time it takes an electron to diffuse around the ring; to keep this time small, experimenters have dealt with rings with diameters ranging from half a micrometer to a few micrometers. The persistent current diminishes rapidly as the temperature is raised; hence the experiments are performed at temperatures near or below one Kelvin. The sign of the persistent current in a real sample depends on the details of the disorder, and varies randomly from ring to ring, so one must measure many rings to get a good estimate of the typical current. Finally, spurious magnetic moments due to contamination on the surface of the sample can easily swamp the magnetic moment due to the persistent current.

The first two persistent current experiments employed very different strategies. In 1990, Laurent Lévy and his collaborators at AT&T Bell Laboratories measured an array of ten million copper rings, with the idea that their small signals would add together to make a much larger signal (5). Because the persistent current in each ring has a random sign, however, the total signal is proportional only to the square root of the number of rings (6). It turns out that there is a second kind of persistent current, whose period is half of the magnetic flux quantum, i.e. $\Phi_0/2 = h/2e$. The "h/2e" persistent currents are normally much smaller than the "h/e" persistent currents, but they have the same sign in every ring, so the total signal is proportional to the number of rings. Lévy and his collaborators did indeed observe the h/2e persistent current, but both the magnitude and the sign of their results disagreed with the theoretical predictions of that time (7). A possible resolution of that discrepancy has been proposed recently (8). In 1991, Richard Webb and his collaborators at IBM measured the persistent current in three individual gold rings (9). They observed a persistent current with flux periodicity of h/e, but with a magnitude at least 30 times larger than predicted by theory. Later experiments by Webb on an array of 30 rings gave results closer to the theoretical prediction (10), but still left several questions unanswered. Experiments on semiconducting rings (11), meanwhile, have given results in closer agreement with theory.

The field received a huge boost in the past year from two experiments. In addition to the experiment by Harris' group at Yale, Kathryn Moler and her collaborators at Stanford and Colorado used a scanning SQUID microscope to measure the persistent currents in 33 Au rings, one ring at a time (12). The ability of the microscope to spatially scan over the sample led to several improvements over previous measurements, including a better understanding of the background signals and better statistics due to the measurement of many rings. Nevertheless, each data point required 12 hours of signal averaging, due to the very small size of the signals. The observed h/e-periodic persistent currents varied randomly in sign from ring to ring, as expected, and had an overall magnitude in good agreement with theory. The Yale experiment used a radical new technology to improve the measurement sensitivity and enable measurements in high magnetic fields. Rather than use the traditional SQUID detection system, the Harris group adapted methods from nanoelectromechanical systems (NEMS). Specifically, they fabricated the rings on the ends of ultra-small mechanical cantilevers, as shown schematically in the figure. The cantilevers oscillate at a frequency determined by their stiffness and mass. The key point is that the oscillation frequency can be measured with extremely high precision. When the cantilevers are placed in a large magnetic field, the interaction of the persistent current with the field leads to a very small torque on the cantilever, which in turn changes its oscillation frequency ever so slightly. Using this technique, the Yale group was able to achieve a sensitivity about 100 times higher than the SQUID-based measurements. The large magnetic field suppressed any background signal due to contamination from impurity spins, and the large range of field enabled the experimentalists to obtain a statistical sampling of the persistent current in a *single* ring. They measured the h/e persistent currents in a single ring and in arrays containing 242, 990, and 1680 rings. The total signal is proportional to the square root of the number of rings, confirming the randomness of the sign discussed above. Both the overall magnitude of the persistent current and its temperature dependence agree extremely well with theory (13). The h/2e persistent currents, however, are not visible in this experiment due to the presence of the large magnetic field.

It is safe to say that the h/e persistent currents in isolated metal rings are now well understood. So where do we go from here? The Yale group proposes coupling small rings to more complicated circuits, to see how the latter influence the former. And the h/2e puzzle remains, at least until the recent hypothesis (8) can be checked experimentally. The one thing we can probably count on is that some clever experimentalists will think of new ways to push the limits of our understanding.

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Figure Caption

A single ring or array of rings is fabricated near the tip of a nanomechanical cantilever that servers as an oscillator. The magnetic field perpendicular to the plane of the rings, $B_\perp$, produces flux through the rings, which causes the persistent currents to appear. The interaction of the persistent current with the magnetic field parallel to the plane, $B_{||}$, causes a torque on the cantilever, which changes its oscillation frequency slightly. The vibration amplitude is highly exaggerated in the figure.

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