

tum computing. To that end one would need to maintain coherent superpositions of states from both wells. When an applied external field pulls one well down relative to the other, the spin that tunnels into the lower well quickly cascades to its bottom and does no further tunneling. But if, in the absence of an external field, the two wells are degenerate, a spin could in principle tunnel back and forth in a coherent superposition of states. That is what one wants for quantum computing, and it's what David Awschalom believes he and coworkers at the University of

California, Santa Barbara, have observed in magnetic susceptibility and noise experiments with protein cages full of ferric ions that produce spins exceeding 10^3 . (See the article by Awschalom and David DiVincenzo in *PHYSICS TODAY*, April 1995, page 43.) The spins of these little antiferromagnets vary by a few percent from one cage to the next. What's particularly attractive about Mn_{12} acetate for practical applications is that all those spin 10 molecules in the crystal are identical and rigidly aligned. Unfortunately, at temperatures higher than

a few kelvin, one can no longer count on rigorous spin 10. The search is on for materials that could preserve the virtues of Mn_{12} acetate at liquid-nitrogen temperatures.

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References

1. J. Friedman, M. Sarachik, J. Tejada, R. Ziolo, *Phys. Rev. Lett.* **76**, 3830 (1996).
2. J. Hernandez, X. Zhang, F. Louis, J. Bartolome, J. Tejada, R. Ziolo, *Europhys. Lett.* **35**, 301 (1996).
3. L. Thomas, F. Lioni, R. Ballou, D. Gatteschi, R. Sessoli, B. Barbara, *Nature* **383**, 145 (1996).

Experiment Signals a New Phase of Quantum Dot Measurements

The study of electron transport through minuscule conducting regions known as quantum dots has revealed a variety of fascinating phenomena, in which one can see the effects of individual electrons. The plots of current versus voltage, for example, are no longer the straight lines so characteristic of macroscopic wires, but rather discrete staircases, with each successive plateau representing the presence of one additional electron on the dot.

Just when researchers might have thought they understood much of the electronic behavior of these quantum dots, a group from the Weizmann Institute of Science in Rehovot, Israel, has found a way to measure a different parameter: the phase of the electrons.¹ The phase measurements open a new window on quantum dot transport, and theorists are already puzzled by their first glimpse through it.

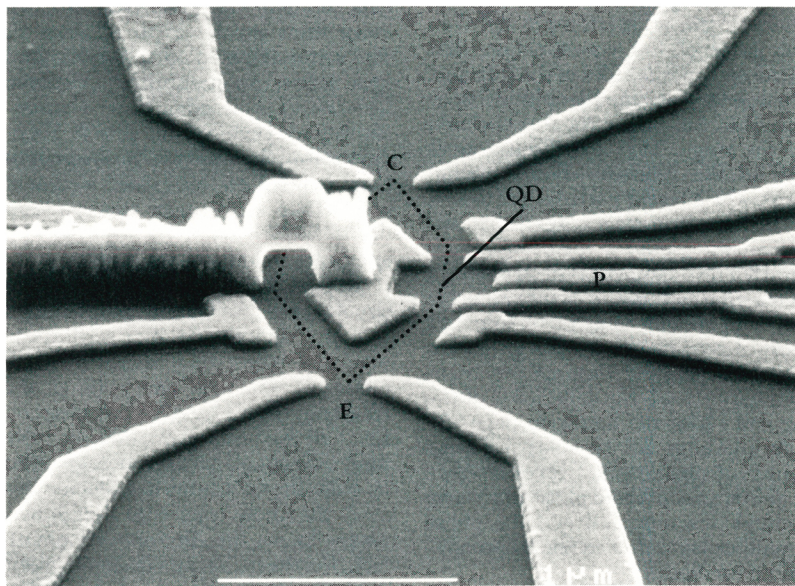
The transmission peak

The quantum dot is a semiconducting (or metallic) region so tiny that it is essentially confined in all three dimensions; like an atom, it contains a finite number of charges and has discrete energy levels. The transmission of electrical current through the dot is measured by attaching leads on each side and applying a voltage across the dot. If one steadily changes the potential on the dot by means of a metallic gate, one can see a succession of resonance peaks in the transmission, with each peak corresponding to the transfer of one additional electron onto the dot. The peak of the resonance occurs when the applied voltage on the dot has lowered the energy levels of the dot so that one level coincides with the Fermi level of the electrons in the leads (which act as charge reservoirs). (See the article by Marc Kastner in *PHYSICS TODAY*, January 1993, page 24.) The

transmission probability has the same resonant shape no matter how many electrons occupy the dot initially. Researchers have measured and understood the shape of the transmission curve, but they do not know how the phase changes at different points on the curve, nor how the phase might differ from one resonance peak to another.

Unfortunately, the phase is lost in measurements of transmission probability, which is the square of the trans-

A sophisticated experiment has measured the phase change in the electronic wavefunction as a charge crosses a quantum dot, a tiny, nearly isolated bit of conducting material. The phase change gives new information about the electronic interactions, previously studied only through measurements of the magnitude of the transmission.



AHARONOV-BOHM RING WITH A QUANTUM DOT, seen in a scanning electron microscope (SEM). The metallic gates (lighter areas) deposited on a semiconductor surface (darker area) define an electronic circuit: Voltages applied to the gates repel electrons, which reside in a two-dimensional layer below the surface, and confine them to regions away from the gates. Electrons entering at emitter (E) can travel around either arm (dotted paths) to the collector (C). Two constrictions in the right-hand arm define the quantum dot (QD). A plunger gate (P) applies a voltage to the dot. An airbridge over the left arm makes electrical contact with the gate in the center. (SEM image courtesy of Vladimir Umansky of the Weizmann Institute of Science.)

mission coefficient. Without direct measurements of the phase, it cannot be known for sure whether the electron transmission is even coherent, that is, whether phase information is retained in the process of resonant tunneling into and out of the dot. Starting with a measurement² in 1992, a number of experiments have produced indirect evidence that the transmission through a quantum dot is coherent, but more direct proof was needed to establish it definitively.

Direct evidence of coherence

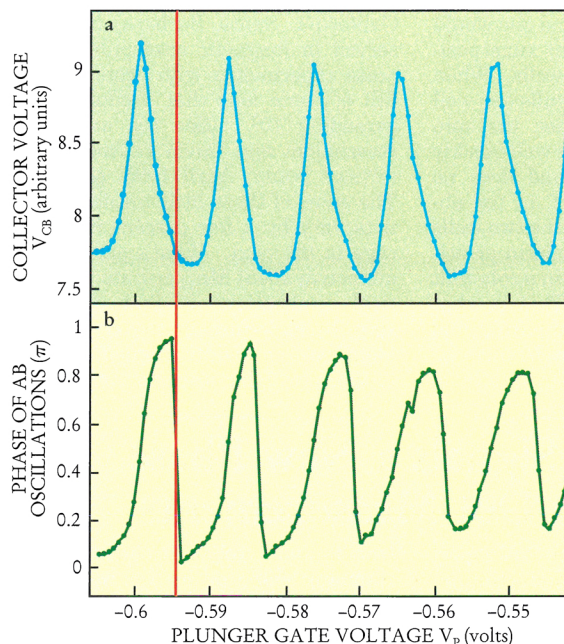
In a recent experiment, a group of Weizmann researchers, led by Moty Heiblum, established directly that resonant tunneling is a coherent process, and in another experiment, they measured the actual phase of the transmission coefficient. In both experiments, the researchers used a similar setup.

To be sensitive to a phase, one needs some kind of interference scheme, and the Weizmann group exploited the interference one gets from the Aharonov–Bohm effect. The researchers built a circuit consisting of a semiconducting path around an insulating region penetrated by magnetic flux lines. According to the principle enunciated by Yakir Aharonov and David Bohm, the electronic wavefunction will acquire a phase as it goes around a flux line. There is phase interference between the parts of the wavefunction that travel on opposite sides of the flux line, causing the combined amplitude to be a periodic function of the flux enclosed by the ring. This interference gives rise to the Aharonov–Bohm oscillations, which have a period equal to h/e .

In the approach taken by the Weizmann group, a quantum dot is inserted into one arm of the Aharonov–Bohm ring so that the charge entering the ring at one end splits into two paths, traveling either through an unobstructed path or through the quantum dot to reach the collector C at the far end. (See the figure on page 19.) The quantum dot becomes a second source of phase shift: If an electron acquires an additional phase in passing through the quantum dot, the phase should cause a shift in the Aharonov–Bohm oscillations.

Patterning such a double-slit interferometer is no easy feat: The conducting region here is not a simple metal but a two-dimensional electron gas formed at the interface of two semiconductors—in this case, gallium arsenide and aluminum gallium arsenide. The electron gas has an elastic mean free path of about 15 μm , longer than the dimensions of the circuit, and the electron phase is retained.

The researchers control the shape



QUANTUM DOT PHASE measurements in an Aharonov–Bohm ring with an embedded quantum dot. **a:** Five successive peaks in the collector voltage, which is proportional to the transmission probability, versus the plunger gate voltage. Each successive resonance peak indicates the transfer of yet another charge onto the dot. **b:** Corresponding phase shifts. Note the similarity of the shape from one resonance to the next, as well as the sharp drop of phase between resonances. (Adapted from ref. 1.)

of the conducting region by placing metallic gates on the surface above the interface and applying a negative voltage to the gates to deplete the electrons from the regions directly below them. In the figure on page 19, one sees the pattern of gates that define two channels through which the electrons can move from emitter E to collector C. The series of gates on the right-hand arm define the quantum dot (labeled QD), which is biased at V_P by a capacitatively coupled metallic gate P. Kastner praised the ability of the Weizmann team to build an “airbridge,” a span of metal that arches over the semiconductor surface to bring a negative voltage to the middle of the ring.

In their first experiments with this circuit,³ the Weizmann group found that the Aharonov–Bohm oscillations persisted when they introduced the quantum dot into one arm of the Aharonov–Bohm ring. That observation told the researchers that the resonant tunneling must be coherent—that is, that the quantum dot did not destroy the phase coherence that is necessary to see the Aharonov–Bohm effect. Furthermore, at a given magnetic field, the phase of the Aharonov–Bohm oscillations was shifted by an amount that depended on how much voltage was applied to the dot. This shift represents the phase that can be attributed to the quantum dot. The researchers were puzzled by the values of the phase shifts they measured in this way because they had expected that the phase of electron transmission would vary continuously as a function of plunger voltage V_P . Instead,

Heiblum and his colleagues found a bimodal behavior: The phase shift was 0 for all values of V_P on one side of the resonance and π for all values on the other side of the resonance. Thus, even though the experiment determined that the resonant tunneling was coherent, it could only measure phase shifts that were multiples of π .

The reason the Weizmann researchers failed to see a continuously varying phase shift was that they were using an Aharonov–Bohm ring with only two terminals to carry current to and from the ring. Such a configuration must obey time reversal symmetry, in which the conductance is the same under reversal of the magnetic field direction. With that restriction, the only allowed values of phase shift are 0 or π . Thus, one cannot use such an arrangement to determine the phase shift of transmission through a quantum dot.

Measuring the phase

In a more recent experiment the Weizmann group modified the system by using four terminals, two for current leads and two for voltage measurements. The two additional terminals relax the symmetry requirements, so that all values of phase shift are allowed. This time, Heiblum and his colleagues found that the phase increased continuously from 0 through π as they varied the gate voltage to go through a resonance. The collector voltage (which is proportional to the transmission probability) for five successive peaks is shown in the top panel of the figure above. One sees there

the resonances induced by the hopping of successively more electrons onto the quantum dot. (Superimposed on that resonance is also the interference of the quantum dot arm with the reference arm, but that interference is minor because the currents are kept small in this experiment.) The corresponding phase shifts are shown in the bottom panel. The phase shift goes almost up to π in passing through a resonance, as expected, but it then drops very precipitously, almost back to zero on the far side of the resonance. Heiblum points out that the phase drops over an energy range smaller than either the thermal energy or the resonance width.

The real surprise for most observers was that the phase was exactly the same at comparable points of succeeding resonance peaks. The phase shift results from the overlapping of wavefunctions as an electron enters a quantum dot, interacts with a quasi-bound state and leaves. But with each successive resonance peak a different number of electrons occupy the quantum dot; the resident electrons fill the available single-particle state and the newcomer must pass into the next available single-particle state. Thus one would not necessarily expect the wavefunction overlaps, and hence the phases, to be the same in successive resonances.

Theorists are now hard at work to explore the implications of these phase measurements. Some feel that the evidence cannot be explained by a simple single-electron picture, but others are not so quick to toss out the model that has worked well in the past.

Buoyed by success, the Weizmann team has gone on to measure the phase and magnitude of the reflection coefficient, as opposed to the transmission coefficient, through a quantum dot.⁴ The measured phases agreed well near resonance with the predictions of a simple model, but deviated from those calculations farther from resonance. As with the transmission phase, the experiment invites further exploration of this newly opened window.

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References

1. R. Schuster, E. Buks, M. Heiblum, D. Mahalu, V. Umansky, H. Shtrikman, to be published in *Nature*.
2. A. T. Johnson, L. P. Kouwenhoven, W. de Jong, N. C. van der Vaart, C. J. P. M. Harmans, C. T. Foxon, *Phys. Rev. Lett.* **69**, 1592 (1992).
3. A. Yacoby, M. Heiblum, D. Mahalu, H. Shtrikman, *Phys. Rev. Lett.* **74**, 4047 (1995).
4. E. Buks, R. Schuster, M. Heiblum, D. Mahalu, V. Umansky, H. Shtrikman, *Phys. Rev. Lett.* **77**, 4664 (1996).

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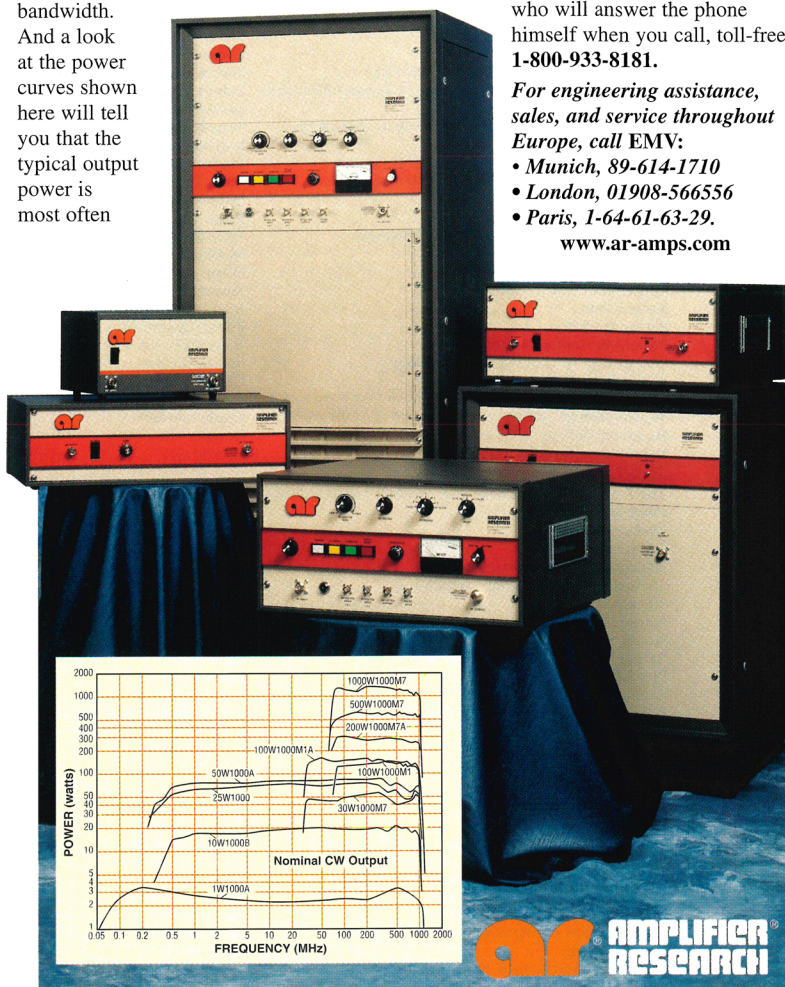
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