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Quantum conductors in a plane

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When electrons are confined to move in a plane, strange things happen. For example, under normal circumstances, they are not expected to conduct electricity at low temperatures. The absence of electrical conduction in two dimensions (2D) at zero temperature has been one of the most cherished paradigms in solid-state physics (1). In fact, the 1977 physics Nobel Prize was awarded, in part, for the formulation of the basic principle on which this result is based. However, recent experiments (2) on a dilute electron gas confined to move at the interface between two semiconductors pose a distinct counterexample to the standard view. Transport measurements reveal (2) that as the temperature is lowered, the resistivity drops without any signature of the anticipated up-turn as required by the standard account. It is the possible existence of a new conducting state and hence a new quantum phase transition in 2D that is the primary focus of this session. In the absence of a magnetic field, the only quantum phase transition known to exist in 2D that involves a conducting phase is the insulator–superconductor transition (for a review, see ref. 3). Consequently, this session focuses on the general properties of quantum phase transitions, the evidence for the new conducting state in a 2D electron gas, and the range of phenomena that can occur in insulator–superconductor transitions.

Unlike classical phase transitions, such as the melting of ice, all quantum phase transitions occur at the absolute zero of temperature. Although initially surprising, this state of affairs is expected, as quantum mechanics is explicitly a zero-temperature theory of matter. As such, quantum phase transitions are not controlled by changing system parameters such as the temperature as in the melting of ice, but rather by changing some external parameter such as the number of defects or the magnitude of an applied magnetic field. In all instances, the underlying quantum mechanical states are transformed between ones that either look different topologically or have distinctly different magnetic properties. Two examples of quantum phase transitions are the disorder-induced metal–insulator transition and the insulator–superconductor transition. In a clean crystal, electrons form perfect Bloch waves or traveling waves and move unimpeded throughout the crystal. When defects (disorder) are present, electrons can become characterized by exponentially decaying states which cannot carry current at zero temperature because of their confined spatial extent. In a plane, the localization principle (1) establishes that as long as electrons act independently, only localized states form whenever disorder is present. However, if electrons are attracted through a third party to one another, they can form pairs. Such pairs constitute the charge carriers in a superconductor and are called Cooper pairs. Superconductors are perfect conductors of electricity and therefore have a vanishing resistance. However, formation of Cooper pairs is

not a sufficient condition for superconductivity. If one envisions dividing a material into partitions, insulating behavior obtains if each partition at each snapshot in time has the same number of Cooper pairs. That is, the state is static. However, if the number of pairs fluctuates between partitions, transport of Cooper pairs is possible and superconductivity obtains.

The fundamental physical principle that drives all quantum phase transitions is quantum uncertainty or quantum entanglement. A superconductor can be viewed as an entangled state containing all possible configurations of the Cooper pairs. Scattering a single Cooper pair would require disrupting each configuration in which that Cooper pair resides. Since each Cooper pair exists in each configuration (of which there are an infinite number), such a scattering event is highly improbable. We refer to a superconducting state then as possessing phase coherence—that is, rigidity to scattering. Insulators lack phase coherence. In the insulating state, the certainty that results in the particle number within each partition is counterbalanced by the complete loss of phase coherence. In contrast, in a superconductor, phase certainty gives rise to infinite uncertainty in the particle number. Consequently, the product of the number uncertainty times the uncertainty in phase is the same on either side of the transition as dictated by the Heisenberg uncertainty principle. In essence, quantum uncertainty is to quantum phase transitions what thermal agitation is to classical phase transitions. Both transform matter from one state to another.

In the experiments revealing the new conducting phase, the tuning parameter is the concentration of charge carriers (2, 4–6). For negatively charged carriers, such as electrons, a positive bias voltage is required to adjust the electron density (2, 4)—the more positive, the higher the electron density. Subsequently, if the electrons are confined to move laterally at the ultrathin (25-Å) interface between two semiconductors, transport will be in 2D, as it is confined to a plane. Devices of this sort constitute a special kind of transistor, not too dissimilar from those used in desktop computers. As illustrated in Fig. 1, when the electron density is slowly increased beyond $\approx 10^{11}$ per cm^2 , the resistivity changes from increasing (insulating behavior) to decreasing as the temperature decreases, the signature of conducting behavior.

At the transition between these two limits, the resistivity is virtually independent of temperature. While it is still unclear ultimately what value the resistivity will acquire at zero temperature, the marked decrease in the resistivity above a certain density is totally unexpected and, more importantly, not predicted by any theory. Whether we can correctly conclude that a zero-temperature transition exists between two distinct phases of matter is still not settled, however. Nonetheless, the data do possess a feature common to quantum phase transitions (7), namely scale invariance. In this context, scale invari-

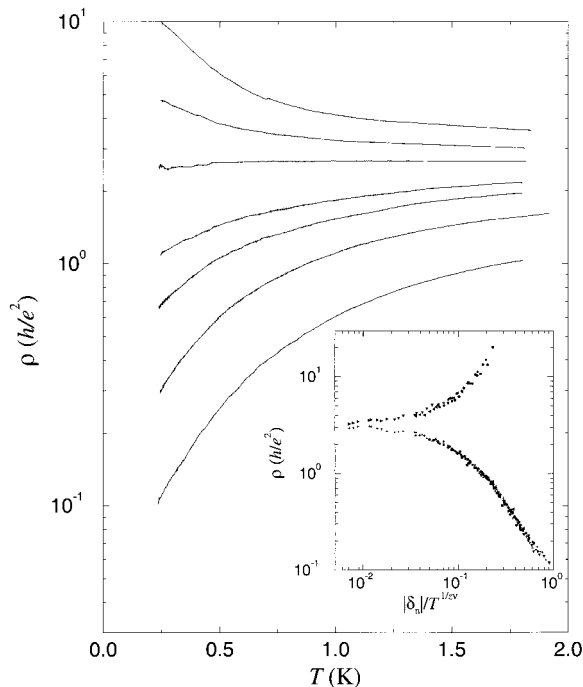


FIG. 1. Resistivity (ρ) vs. temperature for 2D electrons in silicon in zero magnetic field and at different electron densities (n) (from top to bottom: $0.86, 0.88, 0.90, 0.93, 0.95, 0.99,$ and 1.10×10^{11} per cm^2). Collapse of the data onto two distinct scaling curves above and below the critical transition density (n_c) is shown in the *Inset*. Here $\delta = (n - n_c)/n_c$, $z = 0.8$, and $\nu = 1.5$.

ance simply implies that the data above the flat region in Fig. 1 all look alike. This also holds for the data below the flat region in Fig. 1. As a consequence, the upper and lower family of resistivity curves at various densities can all be made to collapse onto just two distinct curves by scaling each curve with the same density-dependent scale factor. The resultant curves have slopes of opposite sign as shown in the *Inset* of Fig. 1. It is difficult to reconcile this bipartite structure unless the two phases are in fact distinct electrically at zero temperature.

These experiments lead naturally to the question, what is so special about the density regime probed? We know definitively that at high and ultra-low densities, a 2D electron gas is localized by disorder. Because the Coulomb interaction decays as $1/r$ (with r the separation between the electrons), whereas the kinetic energy decays as $1/r^2$, Coulomb interactions dominate at low density. At sufficiently low electron densities, the electrons form a crystal. It is precisely between the ultra-low crystalline limit and the noninteracting high-density regime that the possibly new conducting phase resides. This density regime represents one of the yet-unconquered frontiers in solid-state physics. Experimentally, it is clear that whatever happens in this intermediate density regime is far from ordinary as evidenced by the observed destruction (8) of the conducting phase by an applied in-plane magnetic field. As an in-plane magnetic field can only polarize the spins, the conducting phase is highly sensitive to the spin state, a key characteristic of superconductivity.

Experimentally, a direct transition from a superconductor to an insulator in 2D has been observed by two distinct mechanisms. The first is simply by decreasing the thickness of the sample (for a review, see ref. 3). This effectively changes the scattering length and hence is equivalent to changing the amount of disorder. As a result, Cooper pairs remain intact throughout the transition. Whereas single electrons are localized by disorder, Cooper pairs in a superconducting state are not. Under normal circumstances, Cooper pairs give rise to a zero resistance state at $T = 0$. The second means by which a

superconducting state can be transformed to an insulator in 2D is by applying a perpendicular magnetic field (7, 9, 10). A perpendicular magnetic field creates resistive excitations called vortices (the dual of Cooper pairs), which frustrates the onset of global phase coherence. Surprisingly, however, in both the disorder (11) and magnetic field-tuned transitions (9, 10, 12), the resistivity has been observed to flatten on the “superconducting” side. The nonvanishing of the resistivity is indicative of a lack of phase coherence. Phase fluctuations are particularly strong in 2D and are well known to widen the temperature regime over which the resistivity drops to zero. However, the precise origin of the flattening of the resistivity (an indication of a possible metallic state) at low temperatures is not known.

Ultimately, the resolution of the experimental puzzles raised here must be settled by further experiments. But a natural question that arises is, are the two phenomena related? This question is particularly germane (13) because the only excitations proven to survive the localizing effect of disorder in 2D are Cooper pairs. It is partly for this simple reason (13) and other more complex arguments (14, 15) that superconductivity has been proposed to explain the new conducting state in 2D. Because phase fluctuations create a myriad of options (“metal” or superconductor at $T = 0$) for Cooper pairs in a plane, measurements sensitive to pair formation must augment the standard transport measurements to definitively settle whether Cooper pair formation is responsible for the new conducting state in a 2D electron gas. But maybe some yet-undiscovered (16) conducting spin singlet state exists that can survive the localizing effect of disorder. But maybe not, and possibly only “classical” trapping effects (17) are responsible for the decrease of the resistivity on the conducting side. Although the former cannot be ruled out, the latter seems unlikely, as new experiments (18) reveal that the new conducting phase is tied to the formation of a Fermi surface and is related to the plateau transitions (19) in the quantum Hall effect. This implies that indeed a deep quantum mechanical principle is responsible for the new conducting state, perhaps as has been suggested (13) that the proximity of the new conducting phase to a strongly correlated insulator mediates pairing as in copper-oxide superconductors.

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