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Condensed-matter physics: Real metals, 2D or not 2D?

[News And Views]

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Outline

The distinction between metals and insulators appears simple - metals conduct electricity whereas insulators do not. Yet, for the past 25 years, arguments have raged over whether a two-dimensional (2D) system can be regarded as a real metal or not. In a 2D system - such as a very thin metal film, or the active region of many semi-conductor transistors - the electrons are constrained to move in a plane of negligible thickness. Although these structures may conduct at room temperature, it was generally accepted that as the temperature (T) is reduced to absolute zero they would become insulating. The cerebrated discovery of the quantum Hall effect in 1980 demonstrated that it is possible to have metallic states in a 2D system that persist to T = 0 by applying a strong magnetic field [1]. But it has never been clear what happens to these states when the magnetic field is turned off, and the existence of a 2D metal without a magnetic field (that is, B = 0) is still strongly debated. Recently, new evidence emerged indicating a transition from insulating to metallic behaviour at B = 0 in extremely pure 2D semiconductors. On page 735 of this issue [2], Hanein et al. report an experiment that suggests a link between this new metallic behaviour at B = 0 and the quantum Hall metal, and raises the possibility that both share a common physical origin.

The notion that 2D metals cannot exist in the absence of a magnetic field dates back 20 years, when powerful 'scaling' theories indicated that any amount of disorder would trap electrons, so preventing conduction and the existence of a metallic state [3]. These arguments are based on the quantum-wave nature of the electrons, whereby a travelling electron wave can be scattered from impurities back to its starting point. If these returning waves interfere constructively, the electrons become localized in one place and are less able to diffuse through the solid. At high temperatures this effect is weak and the sample appears metallic. As the temperature is reduced quantum interference becomes more important, so that at absolute zero all the electrons are localized and completely unable to move. Low-temperature experiments with both thin-metal films [4] and 2D sheets of electrons in field-effect transistors [5,6] confirmed these theoretical predictions, and for nearly two decades it was generally accepted that there can be no 2D metal at B = 0.

It is a historical coincidence that at about the same time as a consensus was being reached that no metallic states could exist in 2D systems, the quantum Hall effect was discovered. The classical Hall effect occurs when a current-carrying conductor is placed in a perpendicular magnetic field. This produces a Hall voltage across the conductor, which rises linearly as the magnetic field is increased. In contrast, the Hall voltage measured in 2D semiconductors at extremely low temperatures rises in steps with a series of abrupt transitions between well-defined plateaux at which the Hall voltage is precisely quantized. It is only possible to explain this quantization of the Hall voltage by the existence of both localized (insulating) and extended (metallic) electron states that persist to T = 0. So, increasing the magnetic field reveals a series of insulator-metal transitions as the current-carrying electrons alternately find themselves in localized and extended states. Despite many years of intense study, it is still not clear what happens to these extended states as the magnetic field goes to zero. Some argue that, below some non-universal magnetic field, the extended states simply disappear; others suggest that, at low magnetic fields, they 'float' up to higher energies, becoming inaccessible to electrons at low temperatures [7].

In 1994, strong evidence for a B = 0 phase transition from an insulator to a metal was found in extremely low-disorder silicon field-effect transistors [8], in apparent contradiction with the prevailing scaling theory. Similar behaviour was subsequently observed in other material systems, independent of the sign of the charge carriers, indicating that the metallic state is a universal property of all low-disorder 2D systems. At present there is no theoretical consensus as to the nature of this unusual metallic phase, but experiments suggest that strong interactions between the charge carriers (not considered in the original scaling theory) and the spin of the electron (or positively charged hole) both play a role [9].

Hanein and co-workers [2] have now carried out an experiment that relates the B = 0 and quantum Hall metal-insulator transitions. By tuning the carrier density in a high-quality 2D GaAs hole system, they are able to alter the magnetic field at which the quantum Hall metal-insulator transitions occur. Their results are unique because they followed these transitions to much lower magnetic fields than in previous studies [10]. They find that the transition associated with the quantum Hall effect at high magnetic fields evolves continuously into the B=0 metal-insulator transition. This implies that the extended states in the quantum Hall regime do not simply disappear as the magnetic field is reduced, nor float up indefinitely in energy, but continue to B = 0 with some finite energy.

These results are intriguing because they link the quantum Hall effect, which can be understood without considering electron-electron interactions, with B = 0 metallic behaviour that is only found in strongly interacting systems. A number of questions remain. If the two metals share a common physical origin, it is difficult to reconcile the fact that the B = 0 metal is destroyed by applying a magnetic field parallel to the 2D plane [11,12], whereas the extended states in the quantum Hall regime are not. Furthermore, although some theories attribute the B = 0 metal to a new, many-body ground state, certain experiments suggest that it may simply be a finite-temperature spin-related scattering effect [13]. If this is the case, then other effects, such as phase-coherent localization, may reappear at even lower temperatures. A great deal of work remains to be done before we can finally answer the simple question: is it possible for a 2D system to be a real metal at B = 0?

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