Lewis-like structural concepts in inorganic chemistry. Future synthetic and computational explorations should be guided by closer attention to the maximally matched donor-acceptor interactions that lead to favorable Lewis-like bonding patterns.

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PHYSICS

So Small Yet Still Giant

An analysis of currents confined to layers in a semiconductor structure reveals information about electron-electron interactions.

Igor V. Lerner

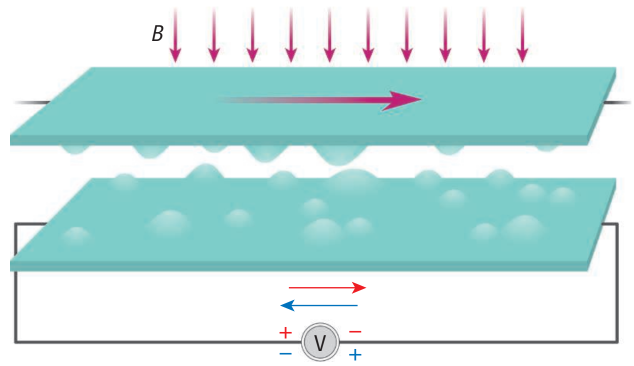
Although electronic devices keep shrinking toward the nanometer scale of atoms, physicists still deal with many-particle systems in which tracing the paths of individual particles is beyond the reach of theory and experiment. Because of this, we have to rely on a statistical approach. Conventional wisdom, inherited from 19th-century statistical physics, says that physical measurements on a given sample are well described by averaging over an ensemble of identical samples.

This notion became obsolete more than two decades ago, however, with the prediction of reproducible conductance fluctuations (i.e., variations from sample to sample) in "mesoscopic" structures with dimensions intermediate between atoms and bulk matter (*1*, *2*). These fluctuations do not decrease with sample size (as they should in classical physics) but still remain much smaller than the average conductance. On page 99 of this issue, Price *et al*. (*3*) report the observation of the Coulomb drag (*4*) in a bilayer system at very low temperatures where the reproducible fluctuations of the drag turn out to be much larger than its average value. Thus, the authors have discovered mesoscopic fluctuations that, in contrast to the conductance fluctuations, fully govern the effect rather than give corrections to it—a very unusual situation in statistical physics. In carrying out this work, they have developed a new tool for studying the wave-like behavior of electrons in solids.

Mesoscopic fluctuations exist because quantum mechanics reigns not only at microscopic scales, as had always been expected, but at the much larger mesoscopic scale, defined as the scale over which the phase coherence of electron quantum waves is maintained. This scale increases as the temperature T decreases, reaching hundreds of nanometers at $T \sim 1$ K. For these temperatures, the wave nature of electrons reveals itself in the interference between waves going along different paths as a result of scattering from impurities. This leads to an irregularly oscillating but reproducible dependence of the sample conductance on magnetic field or electron concentration.

In metallic materials, these conductance fluctuations are always very small. Price *et al.* have made an experimental breakthrough by measuring the Coulomb drag at a temperature so low that this effect is suppressed on average and is governed by the fluctuations. The dominant role of the fluctuations in the Coulomb drag at very low temperatures was recently predicted theoretically (*5*); however, the observed effect turns out to be four orders of magnitude higher than the prediction. Thus, these fluctuations can truly be called giant, although they are still an order of magnitude smaller than the intralayer conductance fluctuations.

The Coulomb drag effect studied by Price *et al.* occurs between two close but spatially separated layers of electrons, when an electrical current flowing through the "active" layer induces a voltage in the second "passive" layer. It works via Coulomb friction: Electrons in the active layer scatter from electrons in the passive layer, transferring momentum to them and thus dragging them in the same direction until the resulting intralayer electrostatic force equals the dragging force. Much experimental effort has been spent to study it under different conditions, although up to now these studies were largely limited to the drag effect at relatively high T where its fluctuations were unobservable.



Coulomb drag and its fluctuations. An electric current in the upper layer drags electrons and holes in the bottom layer, resulting in the electron and hole currents in opposite directions. The net flow, which is due to the electron-hole asymmetry, is detected by a voltmeter V. At low temperatures, the main reason for the asymmetry is the wave nature of electrons revealed in random interference patterns in the local densities of states due to scattering in both layers. This makes the direction of the drag force unpredictable, leading to its random but reproducible fluctuations in an external magnetic field *B* that changes the electron interference pattern in both layers.

The first experimental observations of Coulomb drag (*6*–*8*) took place more than 10 years after it had been theoretically predicted three decades ago (*9*). One of the reasons for such a long delay is that the drag effect is very small. Partly, this is due to a very weak Coulomb coupling between the layers: Momentum transfer between the layers is very inefficient. But quantum mechanics is the

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main culprit and takes the blame for the suppression of the effect.

The reason is that electrons are fermions, and the Pauli exclusion principle at the heart of quantum mechanics tells us that two identical fermions cannot coexist. At zero temperature, therefore, each state can either hold one electron or remain empty; because lower-energy states are filled up first, all the states are occupied up to a certain level, the Fermi energy ε_F, while the states above this level remain empty. Thus, the drag effect is possible only at a finite temperature T, when in both layers the states around ε_F become only partially occupied (that is, electrons are kicked out by thermal energy and can be scattered among the states). Furthermore, charge carriers in the active layer from both positively charged holes below ε_F and negatively charged electrons above ε_F in the passive layer, dragging both in the same direction. Had the electron and hole states been totally symmetric, positive and negative flows would exactly cancel each other, resulting in no drag effect whatsoever.

Thus, the drag effect exists only as a result of the electron-hole asymmetry. On average, the asymmetry is due to a slightly different energy distance of the electron and hole states from the bottom of the Fermi sea. Thus, the asymmetry is small and so is the Coulomb drag. The sign of the effect is positive with the net flow of charge carriers in the passive layer being in the same direction as the current in the active layer.

However, the density of states (the number of energy levels per unit of energy) also fluctuates in the mesoscopic regime (*10*). This led to the suggestion (*5*) that at low enough temperatures the Coulomb drag force could become random, governed by the electron-hole asymmetry due to the fluctuations. The net sign of the effect then becomes random (see the figure). This was expected to be observable only for quite small samples with considerable disorder, where the magnitude of the fluctuations in conductance and density of states within one layer approaches the average.

Price *et al.* courageously ventured to measure the effect in a relatively large and relatively clean sample where the intralayer fluctuations are tiny. The random drag resistance measured by Price *et al.* is small, but it is still four orders of magnitude higher than predicted. The authors have proposed a plausible qualitative explanation for such a dramatic enhancement. In their samples, the electron mean free path for impurity scattering in each layer is much larger than the separation between the layers, so that only large momentum transfer from the active to the passive layer is effective for the drag. As a result, the electron-hole asymmetry is contributed only by fluctuations in the local density of states known to be much bigger (*11*) than those in the density of states of averaged over the entire sample. The drag temperature dependence is very specific for such a mechanism, and the authors show that it is in a good agreement with the measurements.

The fluctuational Coulomb drag effect results from the interplay of the interlayer electron-electron interactions and the interlayer quantum coherence effects. This phenomenon is a sensitive tool to help us learn more about the electron-electron interactions in different materials and structures. Without doubt, the first observation of this effect by Price *et al.* opens a new direction in studying the fundamental properties of electrons in solids at very low temperatures.

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APPLIED PHYSICS

Searching for a Solid-State Terahertz Technology

Advances in device fabrication are facilitating production and detection of electromagnetic radiation at terahertz frequencies.

Mark Lee and Michael C. Wanke

The range of frequencies around 1 terahertz (THz = 10^{12} cycles per second) is like the neglected middle child in the electromagnetic spectrum. Both microwaves (<0.1 THz) and infrared radiation (>20 THz) are used widely, thanks to the combination of high technical performance and mass-produced solid-state microelectronics. Caught in between, the THz spectrum has yet to be used in a mature solid-state device. The pace of recent advances gives hope, however, for a viable THz technology that would permit such applications as sensors for fast, high-specificity chemical detection and new modes of biological and medical imaging.

Microwave electronics ultimately fail at higher frequencies because of fundamental electron velocity limits, causing transistor performance to degrade rapidly above ~0.1 THz. At the other end of the spectrum, infrared photonics cannot be extended down to frequencies less than about 20 THz. Perversely, atmospheric attenuation of THz radiation is also much stronger than for microwave or infrared, leading to far more stringent requirements on signal-to-noise performance in this THz technology gap.

Nevertheless, the impetus to develop a technically practical and economically feasible THz technology infrastructure has arguably never been stronger than it is now. As reviewed by Borak (*1*), the characteristic interactions of THz radiation with various forms of matter can lead to new applications. Laboratories worldwide have carried out proof-of-principle demonstrations to show how THz can be used in rapid-but-precise hazardous chemical sensing, concealed weapon detection, noninvasive medical and biological diagnostics, and high-speed telecommunications. To get such THz applications out of the laboratory and into common use will require elevating the THz microelectronic technology base to be on a par with microwave electronics and infrared photonics.

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