ences) (*9*)] can provide discipline-specific metadata and effective quality control with secure badging for journal verification. The Research Data Alliance (RDA) is developing approaches and infrastructure for the publishing community.

Finally, not every sample can be saved. Museums and other special-purpose repositories (e.g., ice-core labs) face resource and space limitations. Curators must decide what to keep. Samples supporting peer-reviewed publications should have priority. Digitized samples and collection information or other metadata will facilitate remote examination. Digital catalogs can provide persistent access to metadata on samples used in publications. These should include information on access linked to publications via resolvable unique identifiers such as the IGSN. The System for Earth Sample Registration (SESAR), iDigBio, and Cyverse provide examples of metadata profiles.

By working together, stakeholders can create a virtuous cycle of increasing data and sample accessibility. The days when scientists held on to samples and data hoping to squeeze out one more publication are ending. Sharing can be more productive than hoarding when researchers get credit for use of their data or samples. The citation advantage for papers with open data (*10*) suggests that stakeholders help themselves by promoting transparency and reproducibility. ■

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PHYSICS

Electrons go with the flow in exotic material systems

Electronic hydrodynamic flow—making electrons flow like a fluid—has been observed

By **Jan Zaanen**

Turn a switch and the light goes on. The layman's perception is that this is like opening a tap so that the water starts running. But this analogy is misleading. The flow of water is governed by the theory of hydrodynamics, whereby the behavior of the fluid does not require knowledge of the motions of individual molecules. Electrical currents in solids, however, are formed from electrons. In metals, these do not collide with each other, but they do scatter from lattice imperfections. The resulting "Knudsen flow" of electrons is reminiscent of the avalanche of balls cascading through a dense forest of pins, as in a Pachinko machine. On pages 1058, 1055, and 1061 of this issue, evidence is presented that electrons can actually yield to the laws of hydrodynamics (*1*–*3*). What is additionally surprising is that these observations are in agreement with mathematical techniques borrowed from string theory (*4*). These techniques have been applied to describe strongly interacting forms of quantum matter, predicting that they should exhibit hydrodynamic flows (*5*).

The experiments have been made possible by progress in new materials and nanofabrication techniques. Two of the papers report on complementary aspects of the electron hydrodynamics in graphene (*1*, *2*). The third paper deals with an oxide material that exhibits highly surprising transport properties. By confining the electrical currents to nanoscale pipes, hydrodynamic flow is demonstrated (*3*).

The flow of substances is governed by simple conservation laws: Matter, energy, and electrical charge are naturally conserved, while in a perfectly homogeneous space the velocity of an aggregate of matter is not changing either; that is, momentum is also conserved. A classical fluid, such as water, looks like a dense traffic of colliding water molecules exchanging momentum at a very high rate. However, their combined momentum does not change unless the space they are moving in is made inhomogeneous by, for example, putting the water in a pipe such that the overall momentum relaxes and the kinetic energy turns into heat. Electrons in solids, however, move in a background of static ions, breaking this translational invariance, and imperfections occur even in the most perfect periodic crystals. It is now a matter of numbers. Could it be the case that an individual electron can lose its momentum because of scattering from the ionic disorder before it meets another electron (Knudsen flow) (see the figure, left panel), or will the electron fluid equilibrate first through many electron-electron collisions without noticing the imperfections (hydrodynamic regime) (right panel)?

To better understand the situation, we must invoke quantum physics. On the microscopic scale, electrons in solids are strongly interacting, but quantum many-body systems submit to the principle of renormalization, in which the electrons' behavior is dependent on the scale at which the system is observed. In conventional metals, the renormalized electrons increasingly ignore each other as the energy decreases. On the macroscopic scale, the electrons behave like the individual balls of the Pachinko machine. However, it might well happen that the effects of the interactions increase as the energy decreases (giving rise to a complex quantum soup), and until now we did not have the mathematical tools to describe transport in the resulting highly collective quantum state. Recently, it has been shown that the mathematical machinery developed by string theorists can

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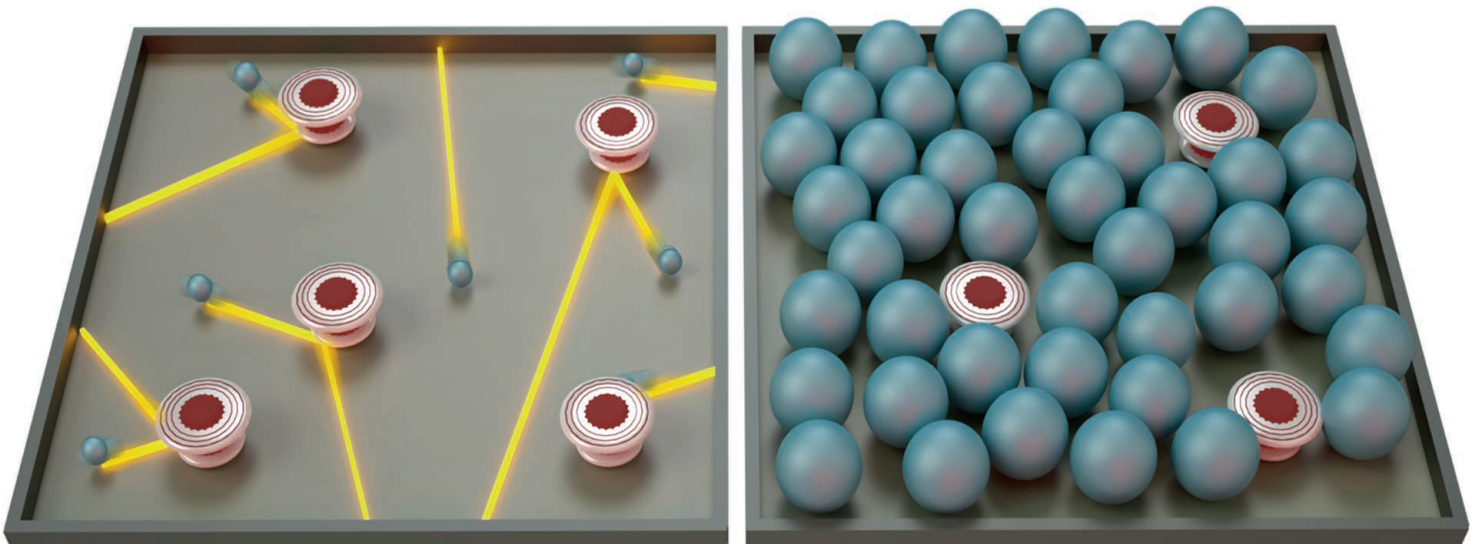

Distinguishing different flow regimes. (**Left**) In conventional metals, the flow of electrical current is due to electrons (balls) moving independently as a consequence of quantum physics while scattering against crystal imperfections (bumpers). (**Right**) In normal fluids such as water, the molecules collide with each other, equilibrating in a macroscopic fluid that is described by the theory of hydrodynamics. Electrons in particular solids that form strongly interacting quantum systems are also found to exhibit hydrodynamic transport properties (*1*–*3*).

be used to describe general features of such quantum soups (*4*), predicting that at finite temperature they have a strong tendency to form hydrodynamic fluids. Evidence for such behavior has surfaced in seemingly unrelated areas of physics (*4*): the quark-gluon plasma created in high-energy colliders, and the unitary fermion gas of cold-atom physics. These findings raised the question of whether such behavior could also occur for electrons in metals (*5*).

Graphene is a strong candidate to meet the required conditions. An advantage of this material is the remarkable perfection of its crystal structure. Its electrons are also known to mimic the behavior of the relativistic fermions of high-energy physics (*6*). Considering their many-body physics, the electrons in graphene exhibit the special renormalization property that the interactions are marginally irrelevant, meaning that at zero temperature the electrons behave as independent particles, but upon raising energy or temperature the interactions grow rapidly, tending toward the quantum soup of string theory (*7*).

To observe the predicted hydrodynamic behavior, Crossno *et al*. (*1*) exploited the property of the graphene electron system that it is like a "Dirac vacuum" with no net density of particles. Upon raising temperature, negatively and positively charged "particles" and "antiparticles" are thermally excited, but they occur in precisely the same amount. In an electrical field, the particles and antiparticles move in opposite directions, with the effect that the whole system does not move. However, by applying a temperature difference, a heat current is induced with the particles and antiparticles moving in the same direction; this current is sensitive to momentum conservation (*8*). The data signatures of hydrodynamical behavior can then be discerned, which on closer inspection appear to be consistent with the notion that these are rooted in the strongly interacting quantum nature of this electron system (*9*).

Bandurin *et al*. (*2*) present complementary evidence. They exploited qualitative differences in the flow patterns associated with hydrodynamic versus Knudsen flows. They manufactured a device to probe the current patterns that are formed upon injecting a current through a narrow nozzle in a graphene sheet. These turn out to be impossible to explain on the basis of Knudsen flow, but are in accord with the whirling patterns formed by a hydrodynamic description (*10*).

Moll *et al*. (*3*) studied $PdCoO_2$, a material as disorder-free as graphene but entirely different in other respects. Although oxide metals are strongly interacting electron systems, this one is known to be a weakly interacting metal. But its transport properties are anomalous—it is exceptionally conductive. Moll *et al*. flowed electrons in long conduction channels, or pipes, with variable widths. In hydrodynamic flow, the resistance is determined by the channel width in such a way that it can be sharply distinguished from the Knudsen flow (*11*).

It is a remarkable coincidence that three groups have presented independent evidence for electron hydrodynamics. Such hydrodynamic flows are much richer than the diffusive currents that have been the traditional mainstay of solid-state electronics. It will therefore be interesting to see whether behavior associated with hydrodynamics (shocks, turbulence, etc.) can be incorporated into electronic device technology. There is also the possibility of using hydrodynamic flow as a diagnostic to detect whether the states of strongly interacting quantum matter predicted by theory are actually realized in nature. Although these applications represent tantalizing possibilities, it will be a grand challenge for experimentalists to tame these usually difficult materials to a degree that they can be subjected to the controlled nanofabrication required to detect the hydrodynamic flow. ■

ILLUSTRATION: PETER AND RYAN ALLEN/SECOND BAY STUDIOS

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