source of nitrogen, a critical nutrient, in hydrothermal communities. Substantial nitrogen fixation would further increase the nutritional independence of these exotic ecosystems from from the surfaceof the ocean,where light drives the photosynthesis-based primary production-that feeds the major marine food webs. The biogeochemical importance of nitrogen fixation in hot-vent communities must therefore be evaluated directly. The identification of novel sites of marine nitrogen fixation (such as hot vents, which are broadly distributed throughout the deep sea) may also help to determine the magnitude of oceanic nitrogen fixation, which is currently poorly constrained (*4*, *5*).

A large proportion of the microbial populations of the sea are archaea (largely of the Crenarchaeota lineage) (*6*, *7*). However, the physiological and ecological role of these organisms has remained elusive. Recent findings have shown that many marine Crenarchaeota have the ammonium monooxygenase gene and may in fact dominate marine nitrification, the biological oxidation of ammonium using oxygen as the electron acceptor (*8*). Nitrogen fixation in archaea was first reported in 1984 (*9*), and in 2003, Mehta *et al*. (*10*) retrieved the first marine archaeal *nifH* sequences from deep-sea environments, including a hot-vent system (*nifH* is a gene from the nitrogenase operon that codes for one of the enzymes of the nitrogenase complex, dinitrogenase reductase). The current report thus confirms a second role for archaea in the nitrogen cycle of the sea.

FS406-22 has an optimal growth temperature of 90°C and fixes dinitrogen at temperatures of up to 92°C, smashing the previous record of 64°C held by *Methanothermococcus thermolithotrophicus* (*11*) by a comfortable 28°C margin. Enzymes with high thermal stabilities have found broad use in molecular biology and biotechnology. Given the importance of nitrogen fixation in global agriculture and the creative exploitation of novel organisms by the biotechnology industry, a heat-stable nitrogenase system is likely to find a useful industrial application.

Recent analyses have suggested that nitrogenase may have first arisen either before the divergence of the three main branches of life (*12*) or, alternatively, more recently in a thermophilic archaeon (*13*). On the basis of genetic analysis of several of the structural and regulatory genes of the *nif* operon, as well as several related genes, Mehta and Baross argue that their archaeal nitrogen-fixing isolate may be representative of some of the earliest lineages of nitrogen fixation, thus lending support to the second scenario.

For a number of well-characterized enzyme systems of Archaea and Bacteria living at mesophilic temperatures (10° to 30°C), which use molybdenum at the active site, the analog enzyme in hyperthermophiles has replaced molybdenum with tungsten (*14*). Will FS406-22 reveal the first tungsten-based nitrogenase? And, for that matter, if the earliest precursors of life were hyperthermophiles, did tungsten enzyme catalysis predate catalysis based on molybdenum? A few more questions to ponder.

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PHYSICS

# A New Spin on the Insulating State

**Charles L. Kane and Eugene J. Mele**

Theory suggests a practical method for producing a novel insulating state of matter.

Electrical insulators are usually appreciated for their ability to do nothing. Such materials either trap or restrict the motion of free charges in matter. This is useful in all kinds of applications, ranging from the wiring in your home to directing the flow of electrons in the tiny circuits of your iPod. Now, on page 1757 of this issue, Bernevig *et al*. have proposed a new kind of two-dimensional insulator, which permits the flow of charge only at its edges (*1*). This may lead to the development of a new kind of solid-state electronic device.

An insulator has an energy gap separating filled and empty bands of electronic states, and thus is electrically inert because a finite energy is required to dislodge an electron. In the 1960s, Kohn characterized the insulating state in terms of the sensitivity of electrons inside the material to effects on the sample boundary (*2*). His insight was that the electrons of an insulator can be regarded as occupying localized orbitals (see the figure), so that they are insensitive to perturbations on the boundary.

The presence of a bulk energy gap does not guarantee that electrons have this "nearsighted" property. A counter example is provided by the quantum Hall state of a two-dimensional electron gas in a perpendicular magnetic field. In the quantum Hall effect, an energy gap results from the quantization of the closed circular orbits that electrons follow in a magnetic field. The inside of a quantum Hall system is thus inert like an insulator. However, at the boundary of the material a different type of motion occurs, which allows charge to flow in one-dimensional edge states. These edge states are unique in that they allow for charge to flow in one direction only. This makes them insensitive to scattering from impurities and explains the observed precise quantization of the Hall resistance.

Because both have a bulk energy gap, the insulating state and the quantum Hall state appear similar. The difference was explained by Thouless *et al*. (*3*), who generalized Kohn's notion of boundary sensitivity to show that an occupied band is characterized by an integer topological index. This index, $n$, distinguishes the insulating state ($n = 0$) from the quantum Hall state ($n \neq 0$) in a manner similar to the way that the mathematical "genus" of a solid body—which counts the number of holes—distinguishes a marble from a donut or a coffee cup. For quantum Hall states, the conducting edge states are a consequence of this topological structure.

Recently a new class of topological insulators has been predicted to be possible at zero magnetic field. This occurs because electrons have a quantum property called spin, which can have two possible polarizations, "up" and "down." In 2005, we showed theoretically that a single two-dimensional sheet of graphite, called graphene, has a small energy gap that

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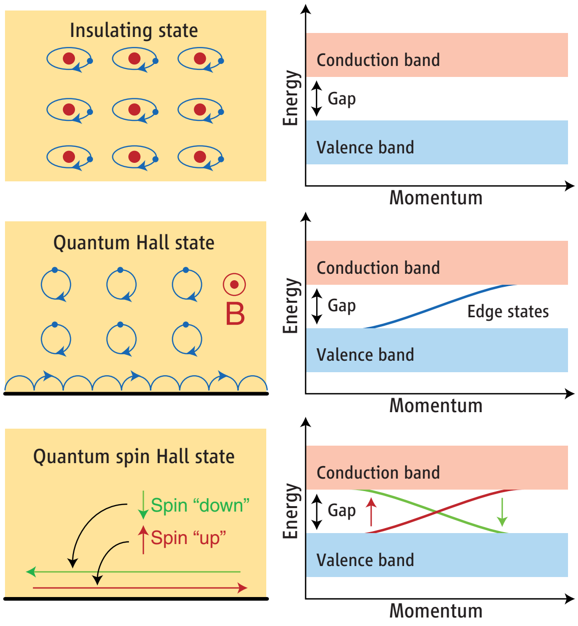

**States of matter. (Top)** Electrons in an insulator are bound in localized orbitals (left) and have an energy gap (right) separating the occupied valence band from the empty conduction band. **(Middle)** A two-dimensional quantum Hall state in a strong magnetic field has a bulk energy gap like an insulator but permits electrical conduction in one-dimensional "one way" edge states along the sample boundary. **(Bottom)** The quantum spin Hall state at zero magnetic field also has a bulk energy gap but allows conduction in spin-filtered edge states.

arises from the interaction between the electrons' spin and orbital degrees of freedom (*4*). The resulting electronic state is inert in the bulk like an insulator, but has conducting edge states. We found that a new topological invariant distinguishes this state from a conventional insulator and guarantees the presence of those edge states (*5*). In the simplest picture, the edge states are spin-filtered in that electrons with spin-up propagate in one direction, whereas electrons with spin-down propagate in the opposite direction. In this sense, this state exhibits a quantum spin Hall effect.

The quantum spin Hall effect will be hard to observe in graphene because carbon's weak spin-orbit interaction makes the energy gap quite small and susceptible to thermal fluctuations. The new proposal by Bernevig *et al.* is exciting because it solves this problem and provides a feasible method for observing the quantum spin Hall effect. They considered a semiconductor heterostructure consisting of a thin layer of HgTe sandwiched between crystals of CdTe. Their convincing theoretical analysis shows that in an appropriate range of layer thickness this two-dimensional structure should exhibit a robust quantum spin Hall effect. HgTe, CdTe, and their alloys are a well-studied family of semiconductor materials with strong spin-orbit interactions. The proposed device can be made with current technology, thanks to decades of experience in the growth of high-quality semiconductor structures.

In addition to providing a venue for a new fundamental state of matter, the structure proposed by Bernevig *et al.* may be of practical interest because it provides a method for the electrical manipulation of spins and spin currents with little or no dissipation. The experimental demonstration of the quantum spin Hall effect would be an important step in this direction.

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CHEMISTRY

# Generating a Photocurrent on the Nanometer Scale

Scientists have devised a nanometer-scale analog of the bulk photoconductors used in copiers and laser printers.

**Frank Würthner**

Photocopiers and laser printers play an important role in our day-to-day life, but we rarely pay attention to how these devices work. They rely on photoconductors, which are insulators in the dark but become conductive under light illumination. About three decades ago, environmentally more benign organic photoconductors replaced the toxic inorganic selenium alloy (*1*). The photoconductors in use today are bilayer systems consisting of a charge-generating layer and a charge-transporting layer (*1*).

On page 1761 of this issue, Yamamoto *et al.* describe a nanometer-scale analog of such bulk photoconductors. They report well-defined self-assembled coaxial nanowires, in which hexabenzocoronene (HBC) layers are laminated by trinitrofluorenones (TNF) (see the figure) (*2*). Like their macroscopic counterparts, these nanowires are insulators in the dark but generate a photocurrent upon irradiation with ultraviolet or visible light.

Earlier attempts to create supramolecular organic photoconductors have mainly focused on columnar liquid-crystalline materials (*3*–*5*). Müllen and colleagues have shown that HBC-based columnar liquid crystals can achieve charge carrier mobilities three orders of magnitude higher than those of commercially available amorphous organic materials (*4*). Recently, Percec *et al.* have reported more complex photoconducting columnar liquid crystals, in which the active units (carbazoles and TNFs) are confined in the center of the columns (*5*).

These studies aim to create a highly organized, higher-mobility bulk material that can replace existing low-molecular-weight organic photoconductors or can be used in other applications, such as field-effect transistors. In contrast, the coaxial nanowires described by Yamamoto *et al.* are not primarily targeted for implementation in existing technologies. Rather, the incentive for this work comes from the desire to create nanometer-scale functional supramolecular entities. Such entities are ubiquitous in nature, for example in photosynthesis, where different self-assembled units interact to accomplish light harvesting, charge separation, and water oxidation in the confined space of a membrane (*6*). The tubular organization of the HBC molecules in the system of Yamamoto *et al.* (see the figure) has a striking similarity to

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