as much terrestrial carbon is received by inland waters as reaches the world's oceans (*11*). Calcareous catchments also release considerable carbon to lakes as bicarbonate and carbonate. In total, inland waters may bury about four times as much carbon as do the oceans (*10*).

Much of the organic carbon received by lakes is mineralized and emitted to the atmosphere as carbon dioxide or methane. According to recent studies, inland waters—including eutrophic reservoirs and saline lakes as well as running waters—emit roughly as much carbon as is absorbed by the world's oceans (*10*, *12*). These contributions are given little consideration in global climate models. Including lakes and reservoirs in models may shift estimates for many landscapes to greater sources of carbon dioxide.

The dissolved organic carbon originating from terrestrial systems is usually colored and serves important functions in lakes. For example, it attenuates both damaging ultraviolet radiation and the longer wavelength solar radiation that regulates the thermal structure and physical habitat of the lake, thus changing nutrient and contaminant cycling. Dissolved organic carbon can be flocculated, contributing to carbon sedimentation, or mineralized through photolytic and biological processes (*13*). Widespread regional changes in dissolved organic carbon concentrations in inland waters remain poorly understood (*14*).

The biodiversity of many freshwater habitats is gravely threatened. During the 20th century in North America alone, 123 species of freshwater animals were recorded as extinct, with 49% of mussels, 23% of gastropods, 33% of crayfishes, 26% of amphibians, and 21% of freshwater fishes imperiled by the end of the century (*15*). The Laurentian Great Lakes are in the process of an "invasional meltdown" (*16*), due largely to species imported in the ballast water of Eurasian ships. Reservoirs and other human-made impoundments, including constructed ponds and wetlands, are 2.4 to 300 times as likely to harbor invasive species as natural lakes (*17*). They accelerate the spread of invasive species by decreasing the distance to the nearest "stepping stone" of water (*17*). The Three Gorges Dam has allowed the spread of 55 invasive species throughout its 58,000 km^2 catchment, including the water hyacinth, regarded by many as the world's worst invasive species (*18*).

Lakes also serve a sentinel function for many of the changes to forests and wetlands caused by a warming climate. For example, a 74 to 118% increase in the area burned by forest fires in Canada is predicted to result from increasingly severe dry weather by the end of the century (*19*). After a fire in the catchment of Moab Lake, Jasper National Park, Canada, increased nutrients and mercury caused changes in food web structure that resulted in greatly increased mercury concentrations in fish (*20*).

The outlook for lakes and reservoirs and the ecosystem services that they provide is bleak. Yet records from these inland waters may provide the insights necessary to address the dual challenges of climate change and increased human domination and their effects on lakes and the larger landscape. Global lake observatory networks that monitor and integrate these signals are needed in combination with experimental studies if we are to decipher all the information contained in the waters and sediments of lakes.

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PHYSICS

Fast Electrons Tie Quantum Knots

Special relativity and quantum physics combine to generate unusual arrangements of electron spins in two different solids.

Jan Zaanen

Objects traveling near the speed of light bring space travel to mind, but in familiar solids containing heavy elements (such as in a gold ring), the velocities of electrons are high enough that effects arising through special relativity come into play. The main effect for electrons is that the orientation of their spins depends on their trajectories. This effect, called spin-orbit coupling, seemed to be understood thoroughly by the 1960s, but new theoretical and experimental studies are driving its revival. Two reports in this issue discuss how spin-orbit coupling causes novel forms of electronic organization that can be captured by topology, the branch of mathematics that classes objects on the basis of properties that do not change upon deformation (and so lumps coffee cup handles together with doughnuts).

On page 915, Mühlbauer *et al.* (*1*) report the most complex form of magnetic order yet observed: In the presence of a magnetic field, the electron spins in manganese silicide (MnSi) form a lattice of topological "particles" called skyrmions (see the figure, panels A and B). On page 919, Hsieh *et al.* (*2*), using spin-resolved photoemission, find a superficially similar picture in the orientations of the electron spins in the metallic surface of bismuth antimonide ($Bi_{1-x}Sb_x$) (see the figure, panel C). However, these patterns now occur in the space of wave vectors of the electron wave functions associated with this metallic surface. Their shapes and topology are dictated by a bulk insulating state. Unlike ordinary insulators, this bulk is a macroscopic object that carries a net quantum entanglement, referring to the eerie property

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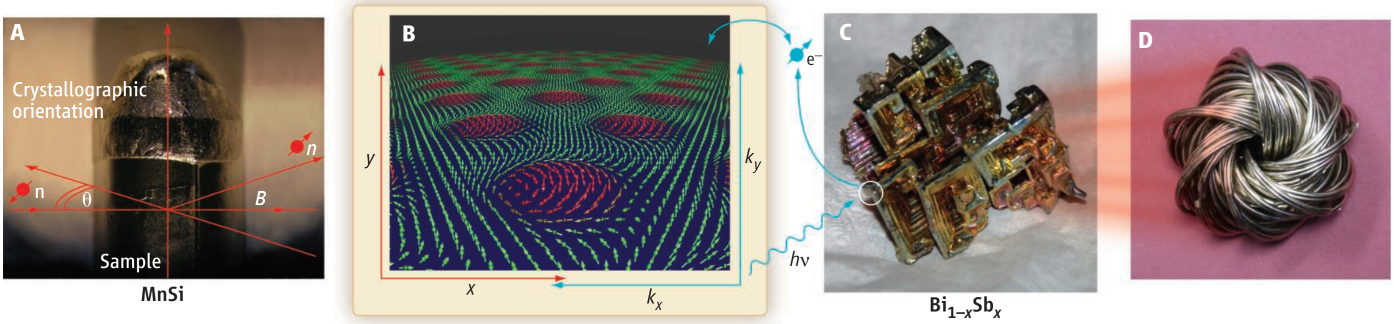
of the quantum world where every state is influenced by every other state in a way that has no counterpart in the realm of everyday experience. This bulk entanglement in turn dictates how the surface quantum states are linked together.

Relativistic effects in quantum mechanics were first treated with the Dirac equation, and electron spin was discovered through its solution. The aspect of relativity that matters for spin-orbit coupling is the unification of electricity and magnetism by the principle of relative motion. When a magnetic dipole, such as the electron spin, moves relative to an electrical field at rest, it experiences the latter as a magnetic field. As a result the spins will precess, and this eventually causes the phenomena reported by Mühlbauer *et al.* and Hsieh *et al.*



Topological knots. In the metal MnSi (**A**), a form of magnetic order, probed by neutron scattering (neutrons *n* scattering by angle θ in a magnetic field *B*), occurs in real space (*x* and *y*)that can be viewed as a lattice of topological particles called skyrmions, which are the red lumps in (**B**). In the "topological" insulator $Bi_{1-x}Sb_x$ (**C**), the entanglement of the individual electrons, probed by photoemission, adds up to an overall macroscopic quantum state whose topology is like that of metal rings (**D**) (*7*), having the effect that the spins order in a pattern similar to the skyrmions (see text) with wave vectors k_x and k_y describing the surface electron waves (*2*).

The magnetism exhibited by MnSi is unusual but can be described in a physically intuitive way. Magnetism in metals, such as iron, can occur spontaneously through the ordering of its unpaired electron spins. Electrons try to move as freely as possible, but they also repel each other and hinder each other's motions. Also, the Pauli exclusion principle forbids two electrons to occupy the same quantum state, so electrons automatically avoid each other when their spins point in the same direction, thereby forming a ferromagnet. However, unlike a metal such as iron, the crystal structure of MnSi lacks inversion symmetry. This symmetry breaking adds the effect of spin-orbit coupling, and the spins of the electrons now precess. However, this motion can be organized in such a way that a frozen-out magnetic structure forms.

The simplest structure of this kind is the helical magnet, in which the spins precess around a preferred axis. For particular values of the pitch of this spin helix, the precessional motions neatly synchronize in a static pattern that also maximizes magnetic ordering. Such helical magnetism forms spontaneously from a paramagnetic phase in MnSi at temperatures just below 30 K. However, when a magnetic field is applied (between 0.1 and 0.2 T), a mysterious "A phase" is found (*3*). Using neutron scattering, Mühlbauer *et al.* have now resolved the spin structure of this phase: It is the "skyrmion lattice" (see the figure, panel B). The reasons for its stability are complicated and include help from thermal fluctuations, but the key feature is that the red regions in panel B of the figure (the skyrmions) crystallize as if they were atoms.

Skyrmions were introduced in 1962 by the high-energy physicist Skyrme (*4*). Topology classes objects together if they can be smoothly morphed into the same shape, so the hole in a doughnut is the "same" as the handle on a coffee cup. The skyrmion is such a "handle," but rather than forming in a ceramic, it forms in vectors that can point in arbitrary directions in space, such as the magnetization of MnSi. The red regions can be removed only by coordinating the rotations of a huge number of spins, which is highly improbable. Because of this integrity, the skyrmions are said to be "topological particles." Like atoms in a crystal, they can be stacked in a lattice, which is how the magnetic order revealed by Mühlbauer *et al.* should be understood.

Physical intuition is harder to come by in understanding the topological band insulator of Hsieh *et al.*, because of the remarkable phenomenon that a macroscopic piece of bismuth antimonide carries a net entanglement. Entanglement refers to the "spooky" quantum phenomenon that correlates the information in quantum states together in ways that make it possible to compute exponentially faster than with classical states; this is the idea behind quantum computing. Typically, only a few microscopic degrees of freedom can be entangled because under normal circumstances, the contact with the classical macroscopic world will destroy the entanglement long before the quantum system itself becomes macroscopically large. However, in $Bi_{1-x}Sb_x$, topological effects help protect its net entanglement against collapse.

To see how strange this state is, we need to compare it with conventional insulators. The electron waves in crystals diffract against the potentials formed by the lattice to create energy bands; in an insulator, there are no electronic states at the Fermi energy because an energy gap separates the valence and conduction bands. These can be viewed as an electronic "nothingness" that is quite akin to the fundamental vacuum of the Dirac theory. Two years ago, however, two groups predicted theoretically (*5*, *6*) that this "insulating nothingness" can have topological structure. Resting on quite fanciful topology (see the figure, panel D) (*7*), the quantum entanglements of all occupied electron states can combine in one overall topological quantity, forming the "topological insulator" that carries a global entanglement (*5*, *6*).

Despite the spooky nature of this entanglement, it can still be probed experimentally. The surface of the crystal corresponds with the interface between the normal fundamental vacuum and the topological insulating bulk of the crystal. The entanglement topology of the bulk now dictates that, at the surface, the band gap of the insulator has to fill up with special states, which causes the surface to become a special "helical metal" (*5*, *6*). In this case, helical refers to the odd number of electron bands crossing the Fermi energy of the metal that forms at the surface; in a normal metal, this number is always even.

The special nature of the single-electron wave functions required for topological insulators arises naturally in insulators that have small band gaps and strong spin-orbit coupling because they contain heavy atoms. Experimental evidence for the strange surface states was found shortly after their prediction (*8*) in transport measurements in a device containing a thin layer of HgTe forming a "quantum spin Hall insulator," the two-dimensional version of the topological insulator (*9*). Shortly thereafter, it was realized that topological insulators could form in three dimensions (*6*), and the heavy semimetal bismuth, alloyed with antimony to turn it into a small-gap insulator, was identified as a candidate (*5*). Transport measurements on the surface of a crystal are very difficult, but angle-resolved photoemission can image the surface electron bands directly. Last year, Hsieh *et al*. (*10*) showed that there are an uneven number of surface bands crossing the Fermi energy.

Spin-orbit coupling lies at the heart of the topological insulator, but how does this relate to the effects of relativity discussed in the context of a MnSi skyrmion lattice? Electrical fields are present at the $Bi_{1-x}Sb_x$ crystal surface, but these will not give rise to magnetism. However, under the influence of the topological bulk, the surface spins do not order in physical position space, but rather in the space formed by the wave vectors of the quantum waves describing the electrons moving on the surface. This two-dimensional wave vector space repeats periodically, and because the surface is metallic, it contains a periodic array of Fermi "surfaces" enclosing the regions with occupied states.

When the bulk is a topological insulator, the remarkable coincidence is that the skyrmion lattice described by Mühlbauer *et al.* forms an acceptable cartoon of what this "magnetism in wave vector space" looks like. The skyrmions are now regions of occupied states, and their rims are the Fermi surfaces. The spins at the Fermi energy are precisely oriented as the whirls formed by the "golden" spins.

However, the cartoon is not a literal description as electron energies move away from the Fermi energy. The whirl-like arrangement of the Fermi surface spins should actually persist both for the occupied and unoccupied states, with the spins slowly vanishing upon moving away from the Fermi surface. Using spin-resolved photoemission, Hsieh *et al.* observe precisely this "wave vector space magnetism," which is direct evidence that $Bi_{1-x}Sb_x$ is a topological insulator.

The discovery by Mühlbauer *et al.* that spins can order in the form of a lattice of topological particles confirms that skyrmions indeed can behave like atoms and opens up new avenues of research related to electrical transport, especially in relation to the very strange metallic states found in MnSi when it is put under pressure. Hsieh *et al*. show that a simple alloy of bismuth and antimony allows us to hold something very nonintuitive—a macroscopic quantum entangled state—in the palms of our hands, and the theorists continue to suggest new ideas for experimental study. The electrodynamics of topological insulators is also quite strange: When an electrical charge is brought to the surface, it will bind automatically to a magnetic monopole formed in the bulk, and this "dyon" should behave like a particle with fractional quantum statistics (*11*). Alternatively, when a superconductor is brought into contact with a topological insulator, its magnetic vortices are predicted to turn into particles that can be used for topological quantum computing (*12*).

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NEUROSCIENCE

Pains and Pleasures of Social Life

Analyses of brain activity reveal a link between social and physical pains and pleasures.

Matthew D. Lieberman and Naomi I. Eisenberger

Life is full of complex social events such as being accepted or rejected, treated fairly or unfairly, and esteemed or devalued by others. Our responses to these events depend primarily on our psychological interpretation of them, in contrast to events like spraining an ankle or eating chocolate, for which our responses seem more dependent on the physical acts themselves. Nevertheless, our emotional responses to these psychological events rely on much of the same neural circuitry that underlies the simplest physical pains and pleasures. On page 937 of this issue, Takahasi *et al*. (*1*) show that experiencing envy at another person's success activates pain-related neural circuitry, whereas experiencing schadenfreude—delight at someone else's misfortune—activates reward-related neural circuitry.

Neuroscientists have identified neural systems responsible for experiences of pain and pleasure. The cortical pain network consists primarily of the dorsal anterior cingulate cortex (dACC), insula, and somatosensory cortex, with subcortical contributions from the periaqueductal gray and thalamus (*2*) (see the figure). Whereas the somatosensory cortex is associated with sensory aspects of cutaneous physical pain (e.g., its location on the body), the dACC is associated with the distressing aspect of pain.

The brain's reward circuitry (see the figure) consists of neural structures receiving the neurotransmitter dopamine from the ventral tegmental area, and responds to physically rewarding stimuli such as food, drugs, and sexual activity. The nucleus accumbens in ventral striatum plays a critical role in reward learning and pleasurable states, while the ventromedial prefrontal cortex and amygdala are also major dopaminergic targets that have been implicated in reward processes (*3*).

Although it is expected that these networks produce robust responses to physical pains and pleasures, it is surprising that social pains and pleasures activate these same networks. For example, being socially excluded activates the dACC and insula, with the dACC showing greater activity to the extent that an individual feels greater social pain (*4*). Grieving over the death of a loved one and being treated unfairly also activate these regions (*5*, *6*). Alternatively, social rewards

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