wave speed, *PcP* precursors are rarer than *ScS* precursors. Furthermore, variations in compressional-wave speed are not necessarily correlated with variations in shear-wave speed, such that *PcP* precursors may be absent when *ScS* precursors exist, and vice versa, in accordance with the observations. To produce the precursors, Liu *et al.* need to locally enhance the wave-speed gradients, as illustrated in the bottom panel of the lower figure. This is justifiable, because existing tomographic models are the result of a damped least squares inversion that underestimates the amplitudes and gradients of heterogeneity.

Future tomographic inversions could use observations of precursors as additional constraints on lower mantle structure. Of course, the actual picture is more complex. For example, over relatively short epicentral distances, Schimmel and Paulssen (*13*) report precursors to *ScS* that cannot be explained by large-scale heterogeneity. Perhaps these precursors are produced by the same small-scale scatters that are needed to explain *PKP* precursors (*11*). Further complications involve the existence of thin (<50 km), ultra-low-velocity zones (*14*) and anisotropy (*15*) near the core-mantle boundary. These thin, slow regions at the base of the mantle are reminiscent of the heterogeneous crust on top of the mantle. Are they a result of differentiation of the mantle, like the crust, or are they produced by chemical interactions between the mantle and core?

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Buried Spins in Slow Motion

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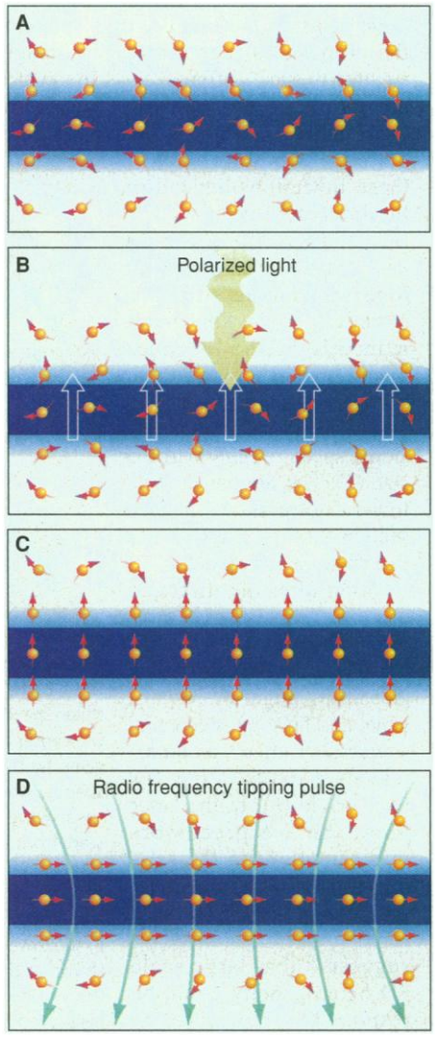
The past decade has seen tremendous refinement in nanofabrication, as semiconducting and metallic systems are now routinely made at the atomic level in ordered layers and clusters. This has fueled the advance of techniques for studying small-scale phenomena, and a vast number of probes have been introduced to examine topography, magnetization, capacitance, and chemistry. Near-contact interactions between sample and probe have enabled scanning surface spectroscopies to explore atomic-scale systems, but often nanostructures lie buried within a particular device, rendering them less accessible.

Recently, interest in electronic spin polarization embedded in solid-state systems has grown with a view toward creating spin transistors and spin memory devices and making use of spin coherence in semiconductors for quantum computation. Ultimately, the most demanding requirements are imposed by quantum computing, in which the interaction between spins must be dynamically controlled by the experimenter and yet, somewhat ironically, the spins must be largely isolated from their environment (*1*). In some cases, however, studying the virtues of a given spin system can be a tricky matter. On page 686 of this issue, Kuzma *et al.* use a clever method to study the spin polarization of a two-dimensional electron gas buried within a semiconductor heterostructure (*2*).

In these systems, a magnetic field applied perpendicular to the electron gas completely changes its spectrum of excitation modes. Electrons fall into quantized energy levels known as Landau levels, and the number of levels occupied by the electron gas as the temperature approaches absolute zero is known as the filling factor ν. Researchers have found that when ν is a fraction such as 1/3, charge carriers in these systems are best described not as simple electrons but rather as many-body excitations that, although constructed from electronic states, lose the electron's fermionic character (*3*). Their spin polarization is an important quantity that sheds light on this many-body system but until recently has been difficult to measure because the system must remain at millikelvin temperatures at which conventional optical probes can heat the electron gas. Using a site-selective nuclear magnetic resonance technique (*2*), Kuzma *et al.* discovered several unexpected properties of this exotic system.

The authors studied an electron gas that accumulates in the GaAs quantum well layers of an AlGaAs/GaAs semiconductor superlattice. Because there is a hyperfine interaction between conduction electron



Spin control. The sample is brought into the ν = 1/3 regime by lowering its temperature to as low as 300 mK and applying a perpendicular magnetic field. (**A**) A radio frequency pulse randomizes the nuclear spins, after which (**B**) the electronic polarization is optically pumped by circularly polarized light. The circular polarization of the light is converted into electron spin. (**C**) During this process, the hyperfine interaction polarizes nuclei that are in contact with the electron gas (shaded region), and after optical pumping these remain polarized. (**D**) The gas cools back down to its base temperature and regains its equilibrium properties, at which time a radio frequency tipping pulse is applied to the nuclear spins, initiating their precession.

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spins and ^{71}Ga nuclear spins in these semiconductors, the magnetization of the conduction electrons yields an effective magnetic field H_{eff} acting on the nuclear spins in contact with the electron gas. In particular, if the nuclear spins are polarized by an external field $H_{ext} \| H_{eff}$ and subsequently tipped to lie in a direction perpendicular to H_{ext} and H_{eff}, nuclei in contact with the electron gas will precess at a rate proportional to $H_{ext} + H_{eff}$, emitting radio frequency radiation with a spectral content that can be measured. Because the nuclei in the rest of the sample will only feel the external field, a shift in frequency may be observed between the two groups of nuclear spins. This "Knight shift" is then a measure of the electron gas spin polarization.

If all the ^{71}Ga nuclei in the sample precess, then those contributing to the Knight shift are obscured because their relative abundance is small. However, Kuzma *et al.* used an optical technique to selectively polarize nuclei in the vicinity of the electron gas, thereby minimizing this background, permitting detailed studies of the the electron spin polarization (see figure).

Because the optically induced nuclear spin polarization diffuses away from the region of the electron gas somewhat before the tipping pulse, the spectral content of the spin precession shows a residual contribution from the barrier region of the host semiconductor. This signal's frequency is then used as a reference from which the Knight shift can be accurately measured. The data of Kuzma *et al.* demonstrate that the spin polarization of the electron gas decreases as the system is tuned away from $\nu = 1/3$, revealing the presence of spin-reversal charged excitations. Moreover, rather than observing an individual, shifted frequency, a distribution of Knight shifts is obtained that results from the spatial inhomogeneity of the electron gas magnetization. Although broadening can be expected simply from the variation in the gas density along its confinement axis, the authors observe an additional linewidth accompanying the reduced polarization that suggests the localization of these spin-reversed excitations in the plane of the electron gas layer. Surprisingly, they find that this spatial inhomogeneity of the spin polarization is maintained over a 40-μs time scale, which is extraordinarily long for a 2D electron system.

These findings suggest a remarkable decoupling between the energy of the two-dimensional electron gas spins and their environment. As discussed above, this is an important first ingredient in the fabrication of spin-polarized solid-state devices and is characterized by the longitudinal relaxation time, or $T_1 > 100$ μs, of the electron gas magnetization. A second important quality is the ability to manipulate the spin system, and Kuzma *et al.* have also shown that radio frequency radiation couples to these spin excitations. This suggests the exciting possibility that resonance techniques conventionally targeted at nuclear spins may ultimately prevail in controlling these electronic spins as well.

Because these spin excitations appear thermally insulated, the coherence of the spin system may also be similarly isolated, as the exchange of energy between the spins and a heat bath puts a limit on their coherence time. For noninteracting electron spins, the transverse spin relaxation time T_2 characterizes the intraspin quantum coherence time and may be measured by preparing an ensemble of such spins in a superposition of their energy-split basis states and studying the resulting spin precession. Within a collection of interacting spins, the issue of single-spin coherence is more difficult to resolve by such means; however, recent optical experiments have shown that environmental contributions to electronic spin decoherence in semiconductors can be dramatically reduced by the removal of magnetic impurities and the introduction of electrical dopants. With Kerr and Faraday rotation studies of electron spin precession, T_2 values of greater than 100 ns have been reported in Si-doped bulk GaAs (*4*). These phenomena are so robust that spin precession in electron gases endures for nanoseconds even at room temperature (*5*). An important common feature shared by these experiments and those of Kuzma *et al.* is that a sea of electrons enables long-lived spin phenomena. For collective spin excitations (*2*), the issue of coherence remains an open question. Spin precession measurements are appropriate for simple spin systems represented by a basis of Zeeman split levels because the coherent evolution of such a system results in classical precession. However, for collective modes, more subtle tests of coherence are probably necessary and can only be devised when the spectrum of these modes is better understood.

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MEETING THERAPEUTICS

Genetic Medicine—When Will It Come to the Drugstore?

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The latest discoveries in the field of genetic drugs—molecules that directly target the nucleic acids DNA and RNA—were discussed at the recent Nobel workshop "Gene-Targeted Drugs: Function and Delivery" held in Stockholm, Sweden (*1*).

The appealing feature of the widespread "antisense" approach to genetic drug design, in which a single-stranded oligonucleotide DNA analog binds to and inhibits the RNA copy of a gene, is the apparent chemical simplicity of the molecular recognition: Formation of the antisense DNA–RNA hybrid is based on well-understood Watson-Crick base-pairing. In spite of the apparent transparency of the mechanism, however, oligonucleotides—typically 15 nucleotides long—are large molecules and are difficult to deliver to the insides of cells. Another class of antisense molecules, the phosphorothioates, have a sulfur in the oligonucleotide backbone instead of an oxygen atom and are the most promising DNA analogs so far. Currently six such antisense agents from ISIS Pharmaceuticals are in human clinical trials for use in the treatment of cancer and HIV, and as anti-inflammatory agents. M. Manoharan (ISIS) reported their recent efforts at tuning the pharmacokinetic and pharmacodynamic properties of their potential drugs by combining several modifications of the oligonucleotides. For example, modification at the 2′-position of the sugar by creating methoxyethyl, aminopropyl, and fluorine conjugates has dramatic effects on stability and target-binding efficiency. The complexity of these drug molecules' actual behavior in living systems was discussed by S. Agrawal (Hybridon Inc.). Nonspecific effects due to their association with proteins and to the base sequence of the oligonucleotide can limit or even alter the expected antisense effects. The problem of poor uptake into cells was addressed by C. Stein (Columbia University), who discussed novel delivery vehicles based on

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