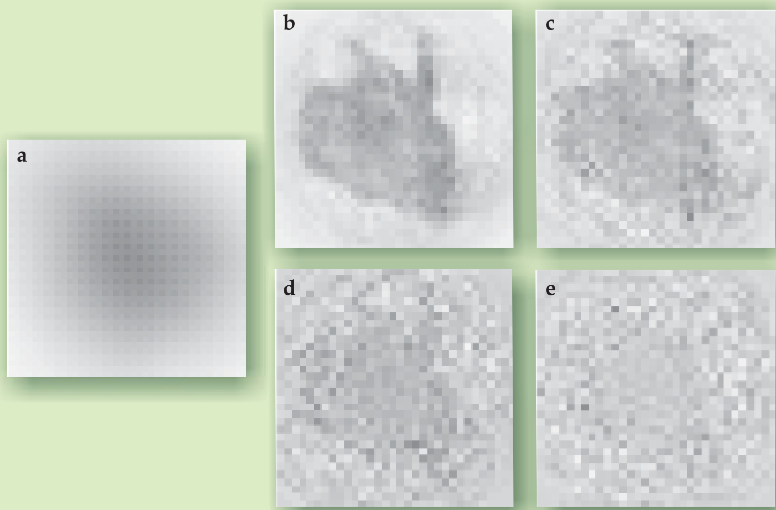

Figure 3. Reconstructing the source image of the hare from the IR image **(a)** on the membrane of the model pit organ. Panels **(b)**–**(e)** show the image sharpened by means of the reconstruction matrix of equation 1, calculated for assumed root-mean-square membrane sensor noise equaling, respectively, 0.25%, 1%, 2%, and 5% of the IR signal on the sensor cells. (Adapted from ref. 1.)

pit-organ paradox when they observed *in vivo* that an external point source of heat produces a big thermal blob on the membrane that, nonetheless, results in a highly localized signal on the optic tectum's IR map.

How does the reconstruction matrix become imprinted on the snake's neural circuitry in the first place? "It can't be genetic coding," says van Hemmen. "The snake would need a suitcase full of genes to encode such detail. Besides we know that snakes and barn owls need a season of actual learning, not just anatomical maturation, to acquire their extraordinary skills."

In an animal's neural network, the triggering of a downstream neuron typically depends on independent inputs from several neurons joined to it by narrow synaptic clefts across which chemical neurotransmitters communicate the incoming electrical excitations (see PHYSICS TODAY, October 2000, page 20). A synapse can be excitatory, inhibitory, or just ineffectual. It's well known that a synapse can be strengthened or weakened by its past history. In one common mode of this sort of "learning," the excitatory synapse from one of several input neurons is strengthened by the frequent experience of being followed promptly by the successful triggering of the postsynaptic neuron—which success depends on the entire ensemble of independent inputs.

The proximity, overlap, and neural connections between the visual and IR neural maps in the tectum suggest that visual images are performing what van Hemmen calls supervised teaching of the young snake's IR circuitry. The synapse strengths, he argues, are gradually optimized to minimize discrepancies between what the snake sees in daylight with its eyes and with its pits.

"The African clawed frog we recently studied makes an even stronger case for this kind of supervised neural-network learning from visual inputs," says van Hemmen.[4] Its eyes seem to have little other purpose. Once enough visual assistance has taught the young frog to "see" insects on the pond's surface through its lateral line of surface-ripple detectors, the night hunter's eyes becomes largely useless.

Bertram Schwarzschild

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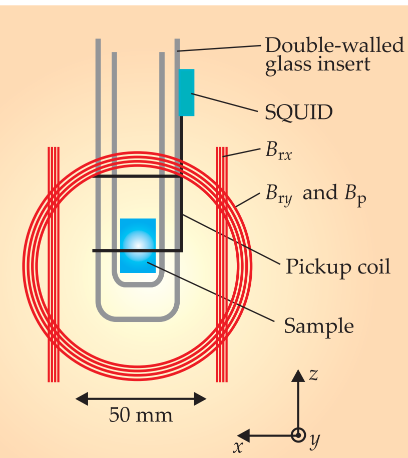
Nuclear spin polarization induced solely by a rotating magnetic field

The effect is so small that its experimental measurement had to await today's sensitive detectors.

To polarize the nuclei in a material, the standard approach is to apply a static magnetic field in the desired direction. A second method, recently demonstrated by experimenters at the University of California, Berkeley, is to apply a rotating field and induce magnetization in the direction of the rotation axis.[1]

Nuclear polarization by a rotating field is a consequence of the phenomenological equations governing nuclear resonance written down by Felix Bloch[2] in the 1940s. The equations were modified some 10 years later[3,4] to describe cases in which a magnetic field rotating in the xy plane is comparable in magni-

Figure 1. Experiment to measure spin polarization induced by a rotating magnetic field. The sample of liquid methanol is surrounded by coils that produce the rotating magnetic field components B_{rx} and B_{ry} as well as a static, y-axis precession field B_p used to measure the spin polarization. The free-induction decay of the protons' spins induces in the pickup coil a current that is detected by the superconducting quantum interference device (SQUID). The sample is kept at room temperature while the SQUID is in a liquid helium bath. (Adapted from ref. 1.)



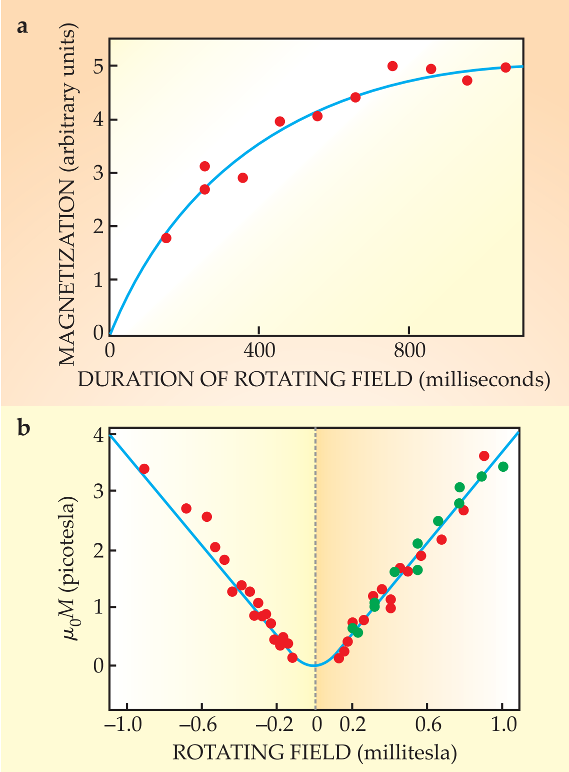


Figure 2. Behavior of magnetization as a function of two variables. (**a**) Magnetization M is larger when the rotating field is left on for longer time intervals. The solid curve is a fit to a single-exponential relaxation with time constant 350 ms. (**b**) The induced field $\mu_0 M$ is shown as a function of the rotating field. The sign of the magnetization M changes when the direction of rotation is reversed. The solid line is calculated from the modified Bloch equations, with no free parameters. Colored dots represent data from two types of methanol samples. (Adapted from ref. 5.)

tude to a fixed field $\mathbf{B}_z$. The modified equations predict—quite surprisingly—that the magnetization induced in such cases has a z-component even when the static field $\mathbf{B}_z$ is absent.

Polarization by a rotating field was not entirely unproven. It was demonstrated for the case of electron spins in 1957 measurements done at Columbia University by the late George Whitfield and Alfred Redfield (now at Brandeis University).[5] The comparable experiment on nuclear spins was out of the question at the time because the magnetic moments of nuclei are three orders of magnitude smaller than those of electrons. In the nuclear case, the magnetic fields resulting from spin polarization are on the order of picotesla.

Serendipitously, one of the people involved in the earliest experiments on electron spins in rotating fields—Erwin Hahn—is at Berkeley, where he sometimes collaborates with researchers who have developed superconducting quantum interference devices capable of detecting picotesla fields. Hahn recently joined with two such SQUID experts, Seung-Kyun Lee and John Clarke, to measure—at long last—the static magnetization induced in nuclear spins by a rotating field.[1]

"The experiment is a tour de force," comments Michael Romalis of Princeton. "It demonstrates a counterintuitive effect that is accurately described by the widely used Bloch equations." Lee notes that the experiment tests the modified Bloch equations in a new region of parameter space, in which the longitudinal relaxation time is much greater than that of electron spins. As a result, the new experiment on nuclear spins is likely to find some practical applications.

Earliest experiments

To understand how a polarization can develop in the absence of a stationary magnetic field, consider a magnetization $\mathbf{M}_0$ subjected to a magnetic field $\mathbf{B}_r$ that rotates with a frequency ω in the xy plane. If the Larmor precession frequency Ω of $\mathbf{M}_0$ about $\mathbf{B}_r$ is much larger than ω, $\mathbf{M}_0$ will tend to precess at a very small angle over many cycles, and will remain virtually parallel to $\mathbf{B}_r$.

If, however, ω is comparable to or larger than Ω, $\mathbf{B}_r$ will "pull away" from $\mathbf{M}_0$. This process increases the angle between $\mathbf{B}_r$ and a lagging $\mathbf{M}_0$ and accounts for an added torque that causes the magnetization to move away from the xy plane. In a frame of reference rotating along with $\mathbf{B}_r$, $\mathbf{M}_0$ will become aligned with an effective field given by the vector sum of $\mathbf{B}_r$ (stationary in the rotating frame) and an apparent field ω/γ oriented along the z-axis and where γ is the spin's gyromagnetic ratio. The net result in the laboratory frame is a static magnetization component M_z along the z-axis.

Hahn was at IBM's Watson Scientific Computing Lab at Columbia University in 1954 when several theorists formulated their modifications to the Bloch equations, containing the prediction of a z-axis polarization. Bloch had expressed to Hahn, his former postdoc, his concern about the validity of the modified equations. Hahn recognized that any polarization signal in low fields would be easier to detect with electron spins than with nuclear spins. (He had discovered spin echoes just a few years earlier.) Hahn devised a method of detecting the polarization by measuring induction signals from fast relaxation recovery following RF pulse saturation. He interested Whitfield, a student of his at the time, in using such methods to explore the modified Bloch equations, but because Hahn soon left Columbia for Berkeley, Whitfield worked on the experiment with Redfield.

Whitfield and Redfield measured the polarization induced by a combination of fixed and rotating fields in a paramagnetic solid. By reducing the fixed field to zero, the two researchers confirmed the prediction that the rotating field alone can induce a stationary component of magnetization in the z direction. Although that phenomenon is implied by the equations, it had not been fully appreciated before the Columbia experiment.

New interest in an old problem

Hahn's interest in testing the modified Bloch equations on nuclei was revived recently by the progress being made on SQUID detectors at Berkeley. The group there has reported high-resolution nuclear magnetic-resonance spectra measured in fields of a few microtesla.[6]

Most NMR measurements are done at high fields, as much as 20 T, using a detector in which the signal is proportional to the rate of change of field induced in a pickup coil, according to Faraday's law. Thus, the signal is proportional to the Larmor precession rate of the nuclear spins, which in turn is proportional to the applied static field. Furthermore, the degree of magnetization scales with the field strength, so that the size of the induction signal goes as the square of the field strength. To get the highest signal, it's advantageous to work at high fields.

By contrast, a DC SQUID detector responds only to the net flux through the coil, not to the flux's rate of change. It can thus be sensitive at low frequency precession rates, such as those produced by nuclear spins in magnetic fields as low as a few microtesla.

A schematic of the apparatus used by Lee, Hahn, and Clarke is shown in figure 1. The liquid sample (methanol) was placed between two sets of Helmholtz coils, which produced a 260-μT field, $\mathbf{B}_r$, rotating at 9.6-kHz in the xy plane (with oscillating components B_{rx} and B_{ry}). A second set of coils on top of the B_{ry} coils produced a 3.3-μT static precession field B_p in the y-direction, which was used to measure the resulting spin polarization. No stationary field was applied in the z-direction. The SQUID was immersed in liquid helium-4 at 4.2 K while the sample, insulated in its double-walled glass insert, was kept at room temperature by heating coils. The entire apparatus was shielded from ambient magnetic fields so that the residual field was 0.24 μT.

Any magnetization induced by $\mathbf{B}_r$ is expected to persist after $\mathbf{B}_r$ is turned off, because the relaxation time of nuclear spins in the liquid is long, on the order of 1 second. The relaxation time was much shorter than 1 second in the 1957 Columbia experiment on electrons.

Once $\mathbf{B}_r$ was turned off, the static precession field B_p was turned on, causing the induced magnetization vector to precess around the y-axis. The SQUID recorded the resulting variations in flux through its pickup coils. With time, the amplitude of those variations decreased due to the decay of the magnetization.

Figure 2a shows the magnetization induced in the protons of the methanol as a function of the time that the rotating field is left on. The magnetization saturates with a time constant (350 ms in this case) that is not very different from the longitudinal relaxation time for the protons in the liquid. Figure 2b shows $\mu_0 M$ as a function of the strength of the rotating field. The solid curve is not a fit to the data but is calculated from the modified Bloch equations with no fitting parameters.

Possible applications

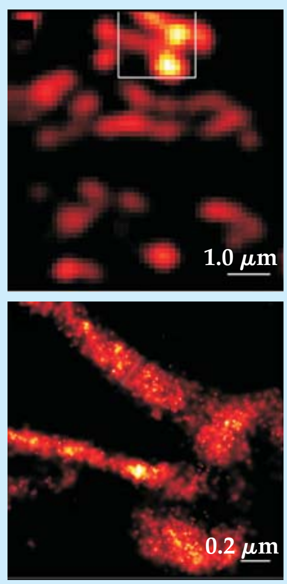
The magnetizations produced are extremely small, and the measurements are quite daunting. Nevertheless, the Berkeley researchers still mention one possible application in their paper, and have tested for it. They point out that polarizing nuclei with a rotating field might be particularly advantageous for NMR measurements on a liquid in the presence of magnetic materials. As an example from the field of geochemistry, one could determine the diffusion rate of water in iron-containing rocks by measuring spin echoes on the induced proton polarization. In turn, the diffusion rate provides information on the porosity of the rock, which is of considerable interest in evaluating potential oil wells. The rotating-field technique helps avoid complications of time-dependent, inhomogeneous fields due to remanent magnetization of the rock.

physics update

Supplementary material related to these items can be found at www.physicstoday.org.

Dune tunes. World travelers, including Marco Polo and Charles Darwin, have occasionally come across sand dunes that issue loud sounds, sometimes of great tonal quality. Now, a team of scientists has proven that the sounds come not from some musical resonance such as vibrations of the dune as a whole, but rather from the relative motions of sand grains in avalanches larger than a critical size. Using field studies and controlled experiments, the scientists—from the University of Paris VII (France), Harvard (US), the CNRS (France), and the University Ibn Zohr (Morocco)—also found that the grains couple into synchronized layers that vibrate like a musical instrument's soundboard, creating a pressure wave. It takes only a few layers to generate the observed acoustic power of about 110 dB. The mechanical coupling depends crucially on the grains' surfaces, which in singing dunes were found to have a silica gel coating known as desert glaze. The online version of this update item has links to sound files. (S. Douady et al., *Phys. Rev. Lett.* **97**, 018002, 2006.) —PFS

Optical molecular microscopy. In recent years, several techniques have been developed to beat the diffraction limit for optical microscopy. Two independent teams of researchers have now developed another diffraction-beating technique, based on a workhorse of modern cell biology—a fluorescing molecule, or fluorophore, that can be made to attach to a variety of targets in a cell. In the new technique, the fluorophores are photo-switchable; when dimly and briefly illuminated at an appropriate wavelength, only a few in the field of view are activated at any one time. The brightest ones can then be localized to within a few nanometers. By repeatedly imaging the same area and adding up many such sparse images, researchers build a composite that displays the entire field of view with near-molecular resolution. A group led by Eric Betzig (Howard Hughes Medical Institute [HHMI], Janelia Farm Research Campus, in Ashburn, Virginia) and Harald Hess (NuQuest Research LLC in La Jolla, California) calls the technique PALM, for photoactivated localization microscopy. A PALM image can be acquired in 2–12 hours. Shown here is a standard fluorescence microscopy image (top) of mitochondria in a frozen thin slice of a cell; the boxed area is enlarged in the PALM image below, in which more than 5500 molecules were localized. Meanwhile, a group led by Xiaowei Zhuang (Harvard and HHMI) calls the technique STORM, for stochastic optical reconstruction microscopy, and acquires complete images in minutes. Zhuang's group uses fewer molecules than the other group but still resolves 10–20 of them within a normally unresolvable area. An additional complication Zhuang's group solved involves using a fluorophore that can be switched on and off hundreds of times. (E. Betzig et al., *Science*, DOI:10.1126/science.1127344, 2006; M. J. Rust et al., *Nature Methods*, DOI:10.1038/nmeth929, 2006.) —SGB



A BEC magnetometer. Physicists at the University of Heidelberg have used a highly elongated Bose–Einstein condensate as a sensitive probe of the magnetic field emanating from a nearby sample. Where the field is weaker, more atoms within the BEC pile up in the trap, which hovers just a few microns from the surface under study. The density of atoms in the BEC can thus be converted into a map of the field at the sample surface. The sensi-

Another possible application is the detection of the state of water in reinforced concrete, where the steel bars could be strongly magnetic.

Lee, Hahn, and Clarke repeated their measurements of spin polarization with their liquid sample mounted on a ferrite ring. The presence of the ferrite prevented detection of proton spins prepolarized by a fixed field but did not impact the measurement of proton spins polarized by a rotating field.

Hahn is interested in further testing the modified Bloch equations. What happens when the transverse and longitudinal relaxation times T_2 and T_1, assumed equal in the recent Berkeley experiment, are not equal and not very large? How does the transient magnetization build up from zero to equilibrium? Additional physics to plumb includes nuclear spin coupling in liquids and solids. The mechanism of the induced static polarization in the liquid case bears a resemblance to the Barnett effect—the spontaneous magnetization of a ferromagnetic or paramagnetic body when spun on its axis.[7]

Barbara Goss Levi

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tivity of this process is given by the energy scale of the BEC's transverse confinement and is limited largely by atomic shot noise, the noise arising from fluctuations in the number of atoms at a specific location in the trap. Thus far, nanotesla field sensitivity and 3-μm spatial resolution have been achieved with the device. Some methods (such as with scanning Hall probe microscopes) can attain finer spatial resolution, and other methods (such as with superconducting quantum interference devices, or SQUIDs) can attain greater magnetic sensitivity, but the Heidelberg device has a region of sensitivity–resolution space all to itself. (S. Wildermuth et al., *Appl. Phys. Lett.* **88**, 264103, 2006.) —PFS

Predicting crystal structures with evolution. Even for simple solids, calculating the arrangement of the constituent atoms from first principles is exceedingly difficult, partly because of the need to sort through an astronomical number of possible ways that atoms can compose a basic repeatable unit cell—roughly 10^{39} different arrangements for 30 identical atoms. Enter Artem Oganov, a materials scientist at ETH Zürich, and Colin Glass, a PhD student, who approached the problem by combining electronic structure calculations and a specifically developed evolutionary algorithm that requires only the chemical composition; no additional input from experiment is needed. In exploring the myriad possibilities, the algorithm proceeds in a step-by-step, continual-optimization fashion that avoids configurations less likely to succeed. The algorithm is efficient and robust: In their first tens of tests, over a range of extreme pressure and temperature conditions and with up to 40 atoms per unit cell, Oganov and Glass have reproduced experimentally known structures with nearly perfect success and predicted several new structures. For example, calcium carbonate ($CaCO_3$) is known to be stable at pressures above 40 GPa and is thought to be a major host of carbon in Earth's lower mantle. But the structure of that high-pressure phase of $CaCO_3$, called postaragonite, was completely unknown until the new algorithm predicted it, along with a higher-pressure form with unusual tetrahedral carbonate ions. Both structures (shown here) have since been experimentally confirmed by Japanese colleagues. The ETH researchers have also found stable and metastable phases of carbon, oxygen, hydrogen, and other elements and compounds. (A. R. Oganov, C. W. Glass, *J. Chem. Phys.* **124**, 244704, 2006.) —PFS