PERSPECTIVES: MAGNETISM

Magnets Fast and Small

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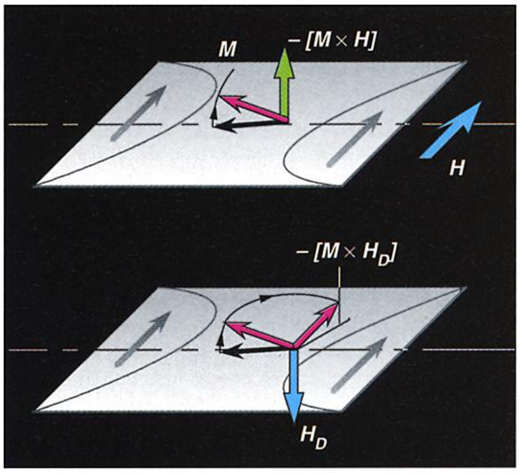
When you place a magnetic dipole, such as an electron or a ferromagnetic domain, in a magnetic field, it will align with the field. It will, however, not be able to do so instantaneously: To reach the new magnetization direction, it will have to spin about the field axis, a process called precessional motion that is gradually opposed by damping. In 1956, Kikuchi (*1*) gave the first theoretical answer to the question of the minimum time needed to reverse a dipole owing to this damped precessional motion. But more than 40 years had to elapse before the minimal field strength required for precessional magnetization reversal could be evaluated experimentally. Last year, Back *et al.* showed (*2*) in a series of spectacular experiments using picosecond field pulses that when an impinging electron beam crosses a cobalt layer with in-plane magnetization, the magnetic field H created by the beam current leads to magnetization reversal of those regions whose magnetization is initially orthogonal to the field direction. This is a rather counterintuitive result, as common sense would suggest that a field applied antiparallel to the magnetization direction would be most effective in achieving reversal. These experiments thus provided a direct proof of precession as the primary source of magnetization rotation.

The experiments performed by Back *et al.* (*2*) were impressive, but even before this work there could be little suspicion, if any, that precession is the fundamental mechanism for magnetization motion: It derives from first principles, provides the basis for understanding ferromagnetic resonance experiments, and underlies the motion of the transition layer between adjacent, differently magnetized ferromagnetic domains (a process called Bloch wall motion). Indeed, Bloch wall motion proceeds by the same process as in Back *et al.*'s experiments: The initial precession about the applied field $\boldsymbol{H}$ gives rise to a sizeable demagnetizing field, H_D, around which the magnetization precesses at longer times (see the first figure).

These experiments show that an intense picosecond field pulse is sufficient to pull the magnetization out of plane, but they cannot unravel the underlying time scale. Nor can they estimate the degree of spatial coherence of precession-induced magnetization motion. The experimental answer can only come from experiments combining state of the art space and time resolution, as reported on page 492 of this issue by Acremann *et al.* (*3*).

Time resolution is dictated by the precession angular frequency ω, which is proportional to the magnetic field H. For example, in a Co film with a 10° out-of-plane magnetization, the demagnetizing field H_D amounts to ≈0.3 T, implying a precession frequency close to 10 gigahertz. In this case, a 10-ps time resolution would allow a precise exploration of one precession cycle.



Trajectory due to precession within a magnetization distribution. The magnetization at the center of the platelet is first pulled out of plane under the action of the torque $\boldsymbol{M} \times \boldsymbol{H}$ **(top)**. The magnetization then rotates under the action of torque $\boldsymbol{M} \times \boldsymbol{H_D}$ **(bottom)**.

Acremann *et al.* (*3*) demonstrate a vectorial magnetooptical microscope with 10-ps temporal resolution. Use of this instrument enabled them to measure for the first time a trajectory in the magnetization space sketched in the first figure. Their results clearly reveal the ≈π/2 phase lag between the out-of-plane and in-plane magnetization component. This experiment combines high spatial and temporal resolution to provide a clear illustration of precession in a Co disk with essentially in-plane magnetization when submitted to an H_z stimulation. A little earlier, Ballentine *et al.* (*4*) also obtained time-resolved component-wise magnetization maps in their study of reversal mechanisms in rectangular permalloy elements. In their experiment, however, the pulsed field was applied along the long axis of the platelets, resulting in complex multidomain states, wall propagation, and annihilation.

What, then, is the relevant length scale? In a ferromagnet, spins are strongly correlated because of exchange interactions. They are, however, also submitted to torques arising from dipolar interactions, anisotropy, and external fields. If the magnetization distribution is inhomogeneous (or if an homogeneous distribution is immersed in an inhomogeneous applied field), magnetization precesses around an effective field whose amplitude and direction soon become functions of position and time. So does the local precession frequency, an argument already put forward by Kittel in his treatment of transverse spin relaxation in nuclear magnetic resonance (NMR) experiments (*5*). This may be understood by applying the construction of the first figure to the side domains of the platelet: The initial torque here is simply nil. Magnetization fluctuations cannot, however, occur over distances below some characteristic length arising from competing interactions, such as exchange and dipolar or exchange and anisotropy (*6*). These lengths may be as small as a few nanometers. They determine the ultimate resolution to be aimed at in magnetic imaging.

Space- and time-resolved magnetization studies raise at least four fundamental issues. First, contrary to the equations widely accepted in NMR, the equation used to describe precessional motion including damping (the Landau-Lifshitz-Gilbert or LLG equation) does not incorporate an explicit characteristic time, although asymptotic expressions can be worked out (*7*). Paraphrasing Kittel when speaking of the equations used in NMR, the LLG equation looks in all ways plausible but does not necessarily describe all spin phenomena in solids accurately. Second, is a single damping parameter sufficient to describe magnetization motion in a wide time span irrespective of the magnetization distribution? High-speed and high-density data recording require this kind of knowledge. Third, the spatial resolution required to image micromagnetic configurations proves extraordinarily demanding, although the battle does not necessarily need to be deemed lost. Synchrotron-based x-ray magnetic linear and/or circular dichroism techniques,

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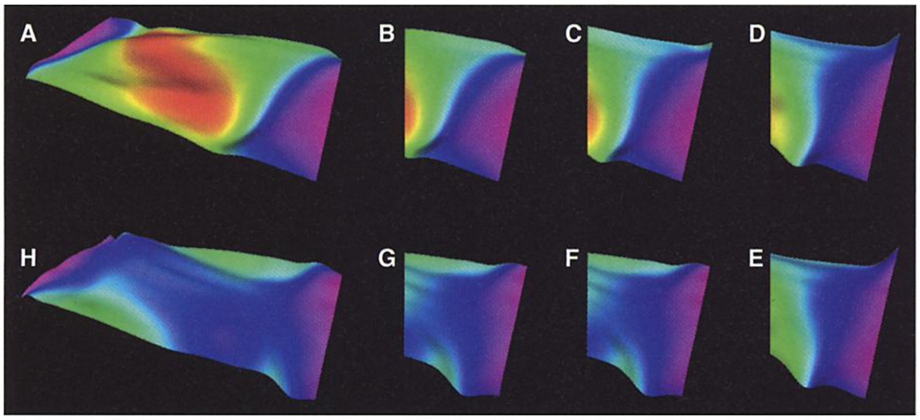

Perspective view of simulated magnetization waves after a transverse field stimulation. The dimensions of the rectangular platelet are: 0.5 μm × 0.25 μm × 5 nm. The right-hand upper corner in each image is seen to beat as a function of time. In this representation, the platelet surface deformation is proportional to the out-of-plane magnetization component, a representation similar to that of fig. 4 in (*3*). Colors monitor the magnitude of the in-plane component along the short side of the platelet. Time between frames: 12.5 ps.

combined with advanced photoemission electron microscopy (*8*), may soon provide images with an estimated spatial resolution of a few nanometers and a time resolution conditioned by the synchrotron source itself. Last, Acremann *et al.* demonstrate dynamical excitations that reverse their amplitude upon reflection along boundaries, contrary to ordinary waves. Such a seemingly non-wave-like behavior has also been observed in time-resolved numerical simulations (*7*) (see the second figure). Clearly, this calls for further understanding.

As now well demonstrated, magnets can respond extremely fast. They can also be made small. But space and time responses are interdependent, potentially giving rise to finite amplitude magnetization waves (nonlinear spin waves). Thus, the use of patterned elements in magnetic memories or the extension of digital recording into the picosecond time domain both lead to the need for focused studies of magnetization dynamics where, both in the space and time domains, neither the magnetization nor the applied field should be viewed as uniform.

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PERSPECTIVES: PLANETARY SCIENCE

The Weather on Titan

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Climate is what you expect, weather is what you get, goes the old definition. We know precious little about either on Saturn's giant moon Titan, the only planetary satellite with a significant atmosphere and the only body in the solar system other than Earth that has a thick atmosphere dominated by molecular nitrogen. Titan's 1.5-bar atmosphere looked bland and nearly featureless to Voyager 1's cameras in 1980. But as Griffith *et al.* (*1*) report on page 509 of this issue, these first impressions were deceiving: Titan's atmosphere seems to have had a turbulent history and may today have a vigorous methane-based meteorology.

For a long time, the big question about Titan's atmosphere was how could it be so thick, given that Titan's same-sized jovian cousins Ganymede and Callisto have none. The conditions for acquiring and retaining a thick nitrogen atmosphere are now readily understood (*2*). The low temperature of the protosaturnian nebula allowed Titan to acquire the moderately volatile compounds methane and ammonia (later converted to nitrogen) in addition to water. The higher temperatures of the jovian moons, which were closer to the sun, prevented them from acquiring such an atmosphere. Recent millimeter-wave measurements of the nitrogen isotopic ratio (*3*, *4*) in Titan's atmosphere suggest that Titan's atmosphere was once some 30 times thicker than it is now. How can Titan's atmosphere be so much thinner now than in the past? One hypothesis is that the sun had an extended phase of high mass loss, with enhanced solar winds (*5*) that eroded the upper atmosphere and thus preferentially the lighter nitrogen isotope. If true, this would have profound implications for solar evolution and the climates of the early solar system.

Strangely, the same isotopic fractionation has not occurred with carbon isotopes in methane, which makes up 2 to 8% of Titan's atmosphere. Like the atmospheres of the terrestrial planets, the methane cannot have been exposed to the same loss process; in other words, it must have appeared later (*4*). This is consistent with the hypothesis that the methane was initially trapped in ice as a clathrate hydrate (*6*) and was only released 500 million years after the end of accretion.

Methane is an ephemeral molecule in Titan's atmosphere: The entire methane content of the atmosphere would be destroyed in only 10^7 years or so by the action of solar ultraviolet light. This process is irreversible, because the hydrogen thus liberated escapes to space and the photolysis products including ethane and a host of other organic compounds, 20 of which have already been detected, drizzle down to the surface. For the methane we see today not to be a bizarre fluke, it must be continuously resupplied from a surface reservoir or by cryovolcanism (that is, volcanism where the molten "rock" is just water ice). Even if the methane is resupplied by continuous or episodic cryovolcanism, rather than a large surface reservoir, it would form at least some lakes and seas because the volcanism rate would be unlikely to exactly match the photolysis rate through time. A surface reservoir—lakes and seas of ethane and methane, both liquids at Titan's surface temperature of 94 K—need not be the single global ocean that post-Voyager models assumed (*7*). Much of the reservoir may exist in the near subsurface, although there is evidence from analysis of recent adaptive-optics images from the Keck Telescope (*8*) that dark regions on the surface are literally pitch black—consistent with pools of hydrocarbons hundreds of kilometers across.

A large surface reservoir of hydrocarbons would also dissolve substantial amounts of nitrogen, and like the martian atmosphere, the Titan atmosphere may be controlled by thermodynamic equilibrium with a surface

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