

threshold, the K_2Rb and KRb_2 disappeared and were replaced by a peak at the mass of $K_2Rb_2^+$.

More to come

"We were really just hoping to see products," says Ni, "and were not even considering the intermediates at first. But now that we've seen them, there's a lot more to explore." Although she naturally wonders what products VMI might detect emerging from a gas of NaK, RbCs, or any of the other bialkali molecules whose direct reaction is energetically forbidden, Ni notes that those experiments aren't on the agenda—at least not for her group. "All our lasers are specifically optimized to work with rubidium and potassium," she says. "We'd need a whole new set of lasers to study sodium or cesium." But, she notes, further experiments on KRb could provide insight into the reaction mechanisms of other molecules.

The feasibility of Bohn's proposed sticky-complex mechanism, after all, depends critically on how long-lived the $Na_2K_2^+$ and $Rb_2Cs_2^+$ complexes really are. Theory offers a way to predict the lifetime of a molecular complex as a function of the density of states of its available decay channels, but the method remains to be tested in the quantum regime. A direct experimental measurement of the $K_2Rb_2^+$ complex lifetime would be a valuable benchmark for understanding the decays of other similar complexes.

So far, Ni and colleagues have just an order-of-magnitude estimate of the $K_2Rb_2^+$ lifetime—between 350 ns and 3.5 μ s—based on the strength of their measured $K_2Rb_2^+$ signal and their best guess of the complex's photoionization cross section. With technical improvements to their experiment, they hope to be able to measure the lifetime directly based on the elapsed time between when the complexes escape the trap and when they're ionized.

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Spin waves control the magnetization around them

The quasiparticles essential for proposed magnonic devices exert a spin-transfer torque of the same magnitude as that of electrons.

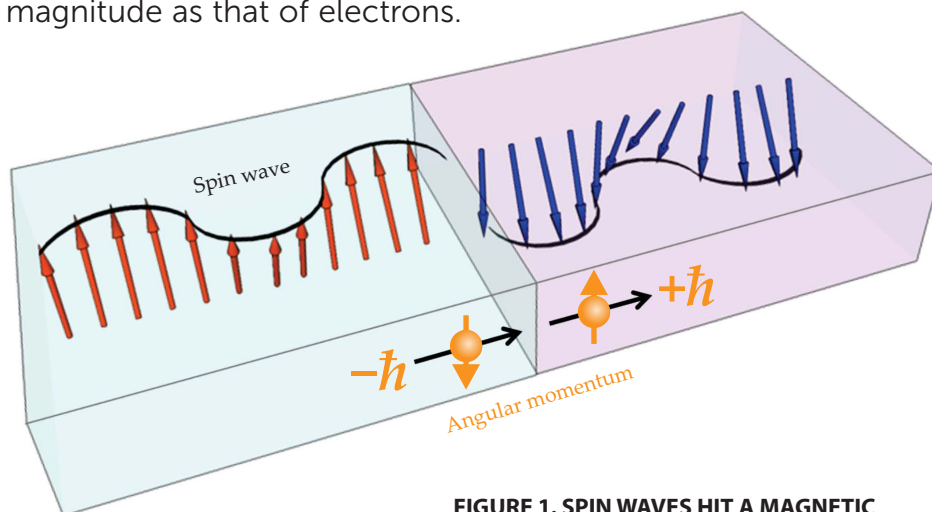


FIGURE 1. SPIN WAVES HIT A MAGNETIC DOMAIN WALL (the boundary between the blue and pink boxes) in a magnetic film. As it moves from left to right, the spin wave carries spin and angular momentum (orange) and comprises the collective precession of electron spins (red and blue arrows). At the domain wall the phase and angular momentum of the spin wave flip. (Adapted from ref. 2.)

As electronics get faster and smaller with more densely packed elements, Joule heating from electron motion and the resulting collisions becomes more prominent. Heat limits the performance of electrical devices and requires built-in cooling methods—from fans to heat sinks. A device that transports information without moving electrons would avoid such power dissipation, and so-called magnonic devices would do just that.

In magnonics, spin waves embody and transfer information through the collective precessions of electron spins that transport angular momentum while the electrons stay put. Although related, magnonics is distinct from spintronics, which uses the electron spin as an additional degree of freedom but still relies on electron motion in the form of electrical spin currents.

The spin-wave quasiparticle, known as a magnon, flows and carries spin angular momentum in much the same way that electrons do. In a well-prepared sample, it can propagate as far as centimeters—three orders of magnitude farther than electrical spin currents—and spin waves have already performed as logic gates.¹

Despite their advantages, magnons are trickier to direct and measure than elec-

trons are. A step toward making magnons more manageable has now been taken by two groups—one led by Luqiao Liu of MIT and the other by Hyunsoo Yang of the National University of Singapore. Their experiments have revealed how magnons both control and are controlled by their magnetic environment. The results suggest a design for all-magnon devices that are free from Joule heating and prove that magnons are capable of applications like manipulating magnetic memory.

Generating spin waves

The key for both studies was producing strong spin currents. A few techniques can generate spin waves, but they share a basic scheme: Take a material with the electron spins aligned in one direction and flip or disturb one spin state. The interaction between the flipped electron and its neighbors starts the electron spin pre-

cession and sends spin waves through the material. Techniques use different methods for disturbing the electron spins and different materials for magnon propagation.

Each group chose a different magnon-generation strategy and material system. Liu and his colleagues were interested in how spin waves respond to the interface between two magnetic domains, or a domain wall, as a possible method to manipulate the waves.² Because an external magnetic field could destroy the domain wall, the researchers required an alternative method to nudge the electron spins into a spin wave. They also needed a material that isn't too magnetically damping—otherwise it will extinguish spin waves—and that is thick enough to host a strong spin-wave signal. It's also easier to introduce spin waves in a material with strong magnetic anisotropy.

Liu and his colleagues settled on a cobalt–nickel multilayer film. In their device, the spin wave is set in motion by an embedded microwave antenna, which provides an alternating local magnetic field that induces spin precession. Microwave antennas are the classic technique for creating and detecting spin waves, and their dimensions set the resulting spin wave's wavelength.

In the second study, Yang and his colleagues opted for a newer strategy that requires two specialized material layers: One turns an electrical signal into a strong electrical spin current, and the other efficiently transports spin waves.³ The electrical spin current in the first layer induces spin waves in the second layer through the spin Hall effect. (See PHYSICS TODAY, May 2010, page 13.)

For the electrical spin-current layer, a topological insulator—such as Yang's selection, bismuth selenide—is a natural choice. Although insulating in its bulk, it has surface states that are metallic and have distinct channels based on the spin. (For more on topological insulators, see PHYSICS TODAY, April 2009, page 12.) For the spin wave layer, the group selected nickel oxide, an antiferromagnetic insulator with a few crucial advantages. Insulators in general are more efficient than conductors at carrying spin waves because insulators don't have conduction electrons bumping around and disrupting the waves. Antiferromagnets have the added benefit of hosting spin

waves that are in the terahertz range, which allows data to be transmitted at high speeds.

Changing the domain wall

With their spin-wave sources selected, the groups were ready to explore how spin waves interact with magnetization. Two of Liu's graduate students, Jiahao Han and Justin Hou, built a setup capable of simultaneous imaging in two modalities. Microwave transmission imaging tracks the amplitude and phase of the spin wave; magneto-optical Kerr effect (MOKE) imaging maps the magnetization through changes in the phase and intensity of light reflected off the sample.

Liu set up the Co–Ni films with an up magnetic region (blue box in figure 1) and a down magnetic region (pink box). As the spin wave moved from the up to the down domain, or vice versa, its amplitude shrank, and its phase shifted by 175° consistently across different devices. Their observed phase shift is close to the 180° phase shift predicted back in 2004 by Jürgen Kirschner of the Max Planck Institute of Microstructure Physics in Halle, Germany.⁴ A 180° phase shift is particularly well suited for logic gates in potential wave-based computing.

Kirschner also predicted that the domain wall would move because of conservation of angular momentum. At the wall, the magnon's angular momentum changes by $2\hbar$ from spin down to spin up, and there's no reflection. The momentum is thus transferred to the domain wall, and the torque from that spin transfer drives the wall in the opposite direction of the spin wave.

When Liu and his group mapped the magnetization, they saw the domain wall shift a few micrometers after the spin wave passed through. Other groups have observed a magnetic domain wall shift from the electron spin-transfer torque,⁵ but Liu and his group are the first to see the behavior from magnon torque.

Spin waves flip the switch

Yang and his postdoc Yi Wang were initially interested in electron spin-transfer torque in Bi_2Se_3 and ferromagnet heterostructures as a method to switch magnetization. They investigated how the torque exerted by electrons as they flow into a magnet changes with the thickness of a NiO layer inserted below

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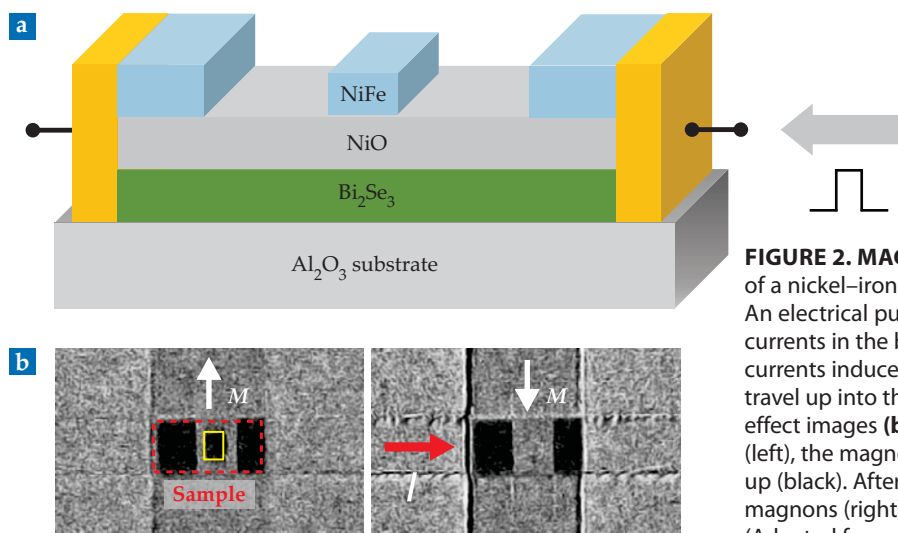


FIGURE 2. MAGNONS FLIP THE MAGNETIZATION of a nickel–iron alloy magnet in the device shown in (a). An electrical pulse (gray arrow) creates electrical spin currents in the bottom bismuth selenide layer, and those currents induce magnons in the nickel oxide layer that travel up into the NiFe magnet. In magneto-optical Kerr effect images (b), before the magnons are introduced (left), the magnet’s magnetization M (yellow rectangle) is up (black). After the electrical pulse I (red arrow) induces magnons (right), its magnetization is down (gray). (Adapted from ref. 3.)

the magnet (see figure 2a). The additional layer should diminish the electron torque simply because a current can’t pass through an insulator. Other researchers had found, however, that the electron torque was enhanced⁶ with the addition of a 1- to 2-nm-thick layer of NiO, and Yang and Wang planned to replicate those results.

Yang and his group didn’t see the enhancement for reasons not yet clear. For thicknesses up to 10 nm, the electron torque did decrease for thicker NiO layers, as expected. They were surprised to find that spin torque experienced by the magnet increased monotonically as the thickness increased from 10 nm to 25 nm, peaking at about half the maxi-

mum value. That was their first indication that magnon spin torque was present and nearly as strong as the electron torque.

The group’s MOKE maps revealed that magnon spin-transfer torque is strong enough to flip the magnetization of an entire magnet (yellow rectangle in figure 2b). When the spin wave flowed into a



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nickel-iron alloy magnet, it flipped the 6-nm-thick layer's magnetization from up (black) to down (gray) and then from down back to up. In a future all-magnon device, spin waves may be a way to program magnetic bits without Joule heating—in fact, Yang's next step is to design a device without any electrical components.

Up next for magnons

Spin-wave control of magnetization offers many potential applications. For example, in an all-magnon device, spin waves could modulate the transmission of subsequent ones by moving the domain wall. Or they could be detected through changes in the magnetization rather than through small changes in the electrical resistance.

But first, the process of creating spin

waves in a material needs to become more efficient. According to Liu, the solution for efficiently inducing spin waves will come down to developing easy-to-fabricate materials with the right properties, such as low damping and high magnetic anisotropy, and new techniques, such as voltage-controlled magnetic anisotropy.

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A broad acoustic bandwidth helps listeners understand fragmented speech

High-frequency audibility is critical for understanding speech in crowded social settings.

Fortunately for the 50 million Americans who experience hearing loss, hearing aids have improved since the cumbersome, hand-held trumpets of the late 18th century. Back then, mechanically amplifying any and every sound frequency was the only option.

Today, audiologists know that loss of sensitivity to sound first becomes measurable at frequencies around 4000–8000 Hz—much higher than the dominant frequencies in normal speech, which range from around 100–1000 Hz. Most modern hearing aids work by providing frequency-dependent amplification based on the severity of an individual's loss at each frequency. That approach works well in quiet settings.

However, in noisy settings, listeners also need to distinguish competing talkers and interpret speech based on a few heard fragments—a problem that extends beyond amplification alone. (See the article by Emily Myers, *PHYSICS TODAY*, April 2017, page 34.) Even for people with normal hearing, understanding a conversation in a noisy train station

or a crowded bar can be challenging. For those who can no longer make out high-frequency sounds, it's even more difficult.

The importance of extremely high-frequency sounds may not be immediately apparent in daily life, but even mundane speech contains important information at high frequencies. For example, the fricative consonants “th,” “s,” and “f” have energy beyond 4000 Hz when spoken, so words containing those consonants may be difficult to distinguish for someone who is beginning to experience high-frequency hearing loss. Luckily, speech is a highly redundant signal; robust information in one frequency band can compensate for lost information in another, and the brain can often fill in the gaps from what's left.

How the brain uses high-frequency cues to understand speech in noisy settings remains a puzzle. However, Virginia Best and colleagues at Boston University have made a new and significant observation: Systematically removing sound energy at high frequencies can have

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