Research demonstrates how small amounts of strain can be used to control a material's properties

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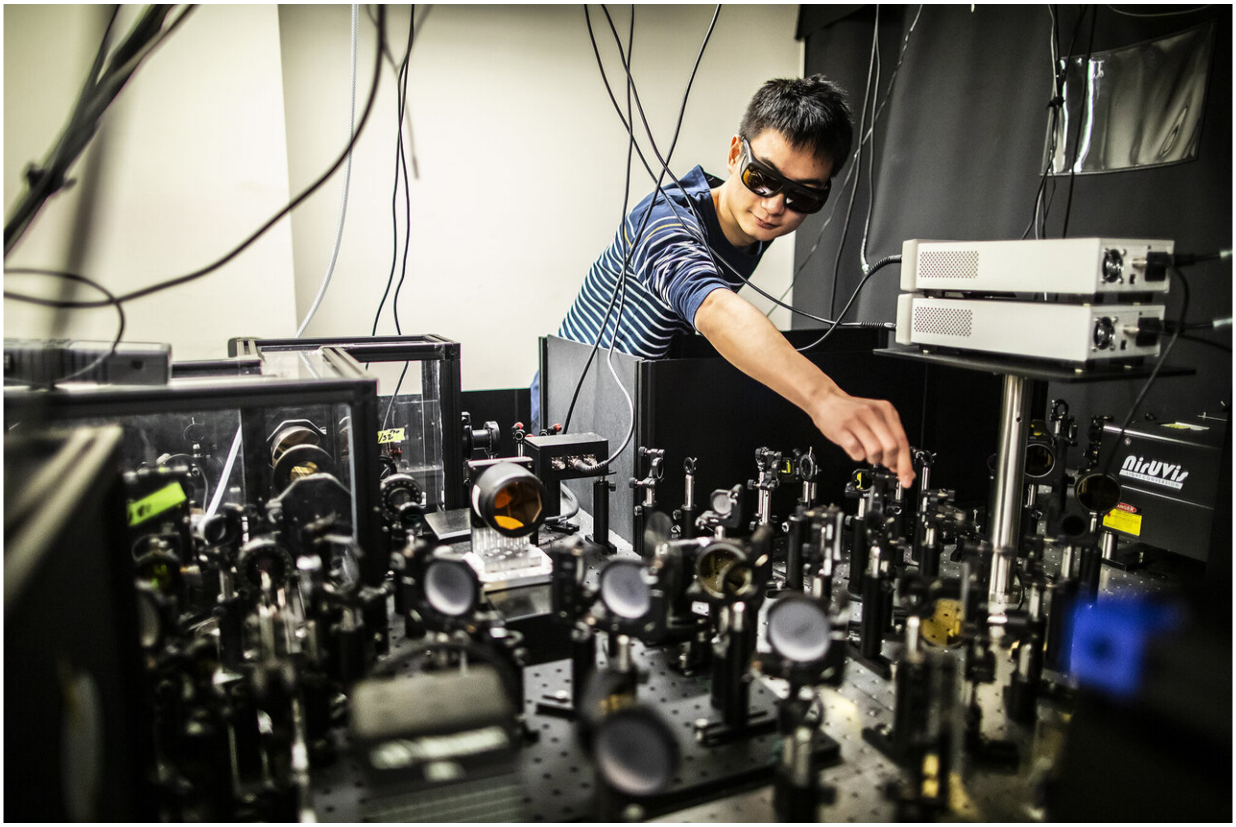

Graduate student Zhuoliang Ni, who works in the lab of assistant professor Liang Wu, is the first author on a new study using an atomically-thin semiconductor and how a material's magnetism can be controlled using small amounts of strain. (Pre-pandemic image). Credit: University of Pennsylvania

New research on an atomically-thin semiconductor demonstrates how a material's magnetism can be controlled using small amounts of strain. Published in *Nature Nanotechnology*, this study provides key insights for applications ranging from new spintronic devices to faster hard drives. This research was conducted by graduate student Zhuoliang Ni and led by assistant professor Liang Wu in collaboration with Penn's Charlie Kane and Eugene Mele, as well as researchers from the University of Tennessee, Knoxville, Texas A&M University, the University of Fribourg, and Oak Ridge National Laboratory.

Wu's lab is primarily focused on experiments with topological materials. But, with recent studies on the photogalvanic effects of two metal alloys and the discovery of exotic particles in cobalt monosilicide, the lab's latest paper on manganese phosphorus triselenide (MnPSe3), a semiconducting material, delves into concepts around symmetry, a physical or mathematical feature of a system that does not change when subjected to certain transformations. Symmetry is a key idea in physics, from the laws of conservation to the behavior of particles, and is central in understanding materials that have controllable, or switchable, magnetic states such as MnPSe3.

There are different types of magnets. For materials that are ferromagnetic, electrons all spin in the same direction and imbue the material with spontaneous magnetism that allows them to adhere to certain types of metals. In contrast, antiferromagnetic materials, like MnPSe3, have a pattern with an equal number of electrons with up and down spins in an antiparallel arrangement. This cancels out their overall magnetic moments, meaning that they don't have an external stray field like ferromagnetic materials; however, they still have electrons with varying spin orientations.

Existing hard drives rely on ferromagnetic materials, where changes in the directions of electron's spin represent the bits, or the zeroes and ones, that make up memory, but there is interest in developing memory devices from antiferromagnetic materials. For example, the information stored in ferromagnetic devices can be lost if there is another magnetic field present. These devices are also limited in how quickly they can operate by the time it takes to manually change a bit, in the nanosecond range. Antiferromagnetic materials, on the other hand, are able to switch their spin orientations much more quickly, in the picosecond range, and are also much less sensitive to external magnetic fields.

But while antiferromagnetic materials have some advantages, working with this type of material, especially one that is two-dimensional, is technically challenging, says Wu. In order to study this material, Ni and Wu had to first develop a way to measure minute signals without delivering too much power that would damage the atomically-thin material. "By using a photon counter, we were able to lower the noise," Wu says. "That's the technical breakthrough which made us able to detect the antiferromagnetism in the monolayer."

Using their new imaging approach, the researchers found that they could "switch" the material to be in an antiferromagnetic phase at low temperatures. They also found that the material had fewer states, akin to the bits used in computer memory, than expected. The researchers only observed two states even though, based on its rotational symmetry, it was predicted to have six states.

Wu turned to Kane and Mele to come up with a theory that could help explain these unexpected results, and through this collaboration realized the significant impact that lateral strain, such as stretching or shearing, could have on its symmetry. "A perfect sample has threefold rotational symmetry, but if something is pulling on it it's no longer the same if you rotate it 120°," says Kane. "Once Liang suggested that there could be strain, it was immediately obvious as a theorist that two of the six domains should be picked out."

After follow-up experiments that confirmed their hypothesis, the researchers were additionally surprised at how powerful a small amount of strain could be in changing the material's properties. "In the past, people did use strain to change spin directions, but in our case what's important is that a tiny amount of strain can control the spin, and that's because the role of the strain is really fundamental in the phase transition in our case," Wu says.

With this new insight, the researchers say this study could be a starting point for better controlling antiferromagnetic properties using small changes in strain. Strain is also a much easier property to control in this class of materials, which currently require a massive magnetic field—on the order of several tesla—to change electron spin direction and could be a sort of dial or knob that could change the magnetic order, or the pattern of the electron's spins.

"The absence of stray fields in antiferromagnetic materials means that you don't have a macroscopic thing that you can use to manipulate the moment," says Mele, "But there is some internal degree of freedom that allows you to do it by coupling directly to the ordering."

To study this material further, Ni is working on several follow-up experiments. This includes seeing if electrical fields and pulses can change spin direction and evaluating the use of terahertz pulses, the natural resonant frequency of antiferromagnetic materials, in controlling both electron spin direction and switching speed. "We can possibly use terahertz to control the spins," Ni says about this system, which is also a regime of expertise for the Wu lab. "Terahertz is much faster than gigahertz, and for the antiferromagnetic spins it's possible that we can use terahertz to control ultrafast switching from one state to another."

"Antiferromagnetic materials provide new exciting opportunities for creating faster spintronic devices for information processing as well as new ways for efficiently generation of terahertz radiation, which is the part of the electromagnetic spectrum for beyond 5G wireless communications," says Joe Qiu, program manager for Solid-State Electronics and Electromagnetics at the Army Research Office, which funded this study. "All of these are important technologies for future Army electronic systems."

More information: Zhuoliang Ni et al. Imaging the Néel vector switching in the monolayer antiferromagnet MnPSe3 with strain-controlled Ising order, *Nature Nanotechnology* (2021). DOI: 10.1038/s41565-021-00885-5

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