The evolution of skyrmions in Ir/Fe/Co/Pt multilayers and their topological Hall signature

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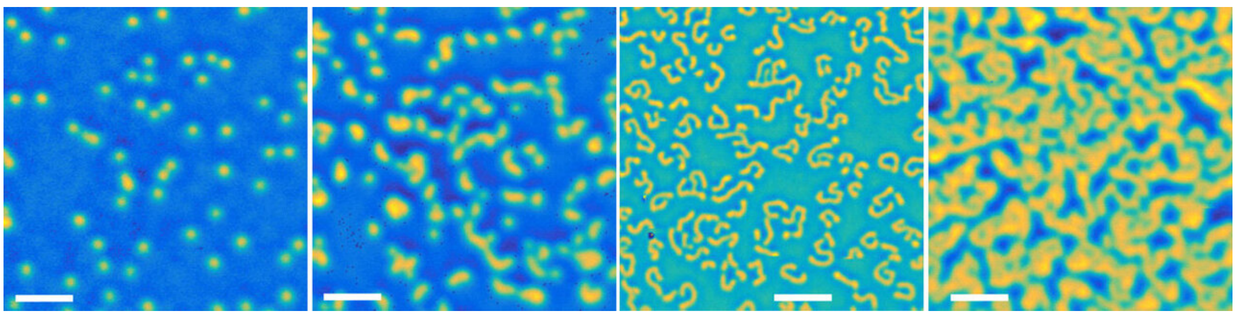

Magnetic measurement images showing how the number of skyrmions in a nanomaterial varies with magnetic field strength. These results were used to prove the influence of skyrmions on the Hall resistivity, a phenomenon called the Topological Hall Effect. Credit: M. Raju.

Magnetic skyrmions are tiny entities, manifesting in magnetic materials that consist of localized twists in the magnetization direction of the medium. Each skyrmion is highly stable because eliminating it requires untwisting the magnetization direction of the material, just as a knot on a string can only be untied by pulling the rest of the string out of the knot. Magnetic skyrmions are a promising candidate for next-generation magnetic storage devices because of their stability and tiny size—-with widths of 50 nanometers or less, they occupy only a fraction of the area of magnetic bits in current hard disks. For this reason, researchers have been intensively searching out materials that can contain magnetic skyrmions, and studying their electrical and magnetic properties.

Recently, an important breakthrough in understanding the behaviour of magnetic skyrmions has been announced by a team of scientists in Singapore and Israel. They have shown, for the first time, that the presence of magnetic skyrmions is unambiguously linked to a phenomenon known as the topological Hall effect, which describes how electric currents are diverted by an emergent magnetic field of a skyrmion. The work was published in March 2019 in the journal *Nature Communications*.

The team studied a synthetic nanomaterial optimized for hosting magnetic skyrmions, composed of consecutive layers of iridium, iron, cobalt, and platinum, each having thickness of a nanometer or less. In 2017, the same nanomaterial had provided the earliest evidence for the topological Hall effect at room temperature, observed by the research group of Christos Panagopoulos at Nanyang Technological University, Singapore (NTU Singapore), who also led the present work. Professor Panagopoulos and his co-workers showed that the nanomaterial's Hall resistivity—-the ratio of transverse voltage to electric current in the presence of a magnetic field—-contained anomalies that were difficult to explain except by the effect of magnetic skyrmions.

"The interesting thing about the way skyrmions influence the Hall resistivity is that it depends on how the magnetization twists around each skyrmion," explains Panagopoulos. "Mathematically, such twists are called 'topological' features, which is why the physical phenomenon is referred to as the 'topological Hall effect'."

However, some aspects of the 2017 experiments remained difficult to explain. The data seemed to indicate that the anomalies in the Hall resistivity were 100 times larger than theoretical predictions based on the topological Hall effect. To establish a definite connection, the electrical measurements needed to be carefully matched with direct observations of magnetic skyrmions. To accomplish this, the Panagopoulos group collaborated with the laboratory of Ophir Auslaender at Technion, the Israel Institute of Technology. Using a state-of-the-art low temperature magnetic force microscope, the Auslaender group obtained highly accurate images of the skyrmions in the nanomaterial. Notably, they found that certain "wormlike" magnetization patterns were formed by multiple skyrmions joined together.

By combining electrical Hall measurements and magnetic imaging, the collaboration managed to significantly narrow the discrepancy between theory and experiment. "The first thing we realized was that the number of magnetic skyrmions had been underestimated by a factor of ten," says M. Raju, a research fellow at NTU who is one of the lead authors of the study. "Digging deeper, we were able to show that the number of magnetic skyrmions is directly proportional to the topological Hall resistivity. This provides conclusive evidence that the skyrmions are responsible, not some other unaccounted-for phenomenon."

Despite this advance, Professor Panagopoulos notes that the topological Hall resistivity remains higher than theory predicts, and suggests that the remaining discrepancy may be a matter of theoretical limitations. "The topological Hall effect concept is based on assumptions, such as adiabaticity, that are theoretically convenient but may not be accurate for real materials," he notes. "With the aid of these improved experimental methods, we are building a more sophisticated understanding of how electrical charges interact with magnetic spin in these important and technologically-promising materials."

More information: M. Raju et al. The evolution of skyrmions in Ir/Fe/Co/Pt multilayers and their topological Hall signature, *Nature Communications* (2019). DOI: 10.1038/s41467-018-08041-9

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