Advanced X-ray technique enables first direct observation of magnon spin currents

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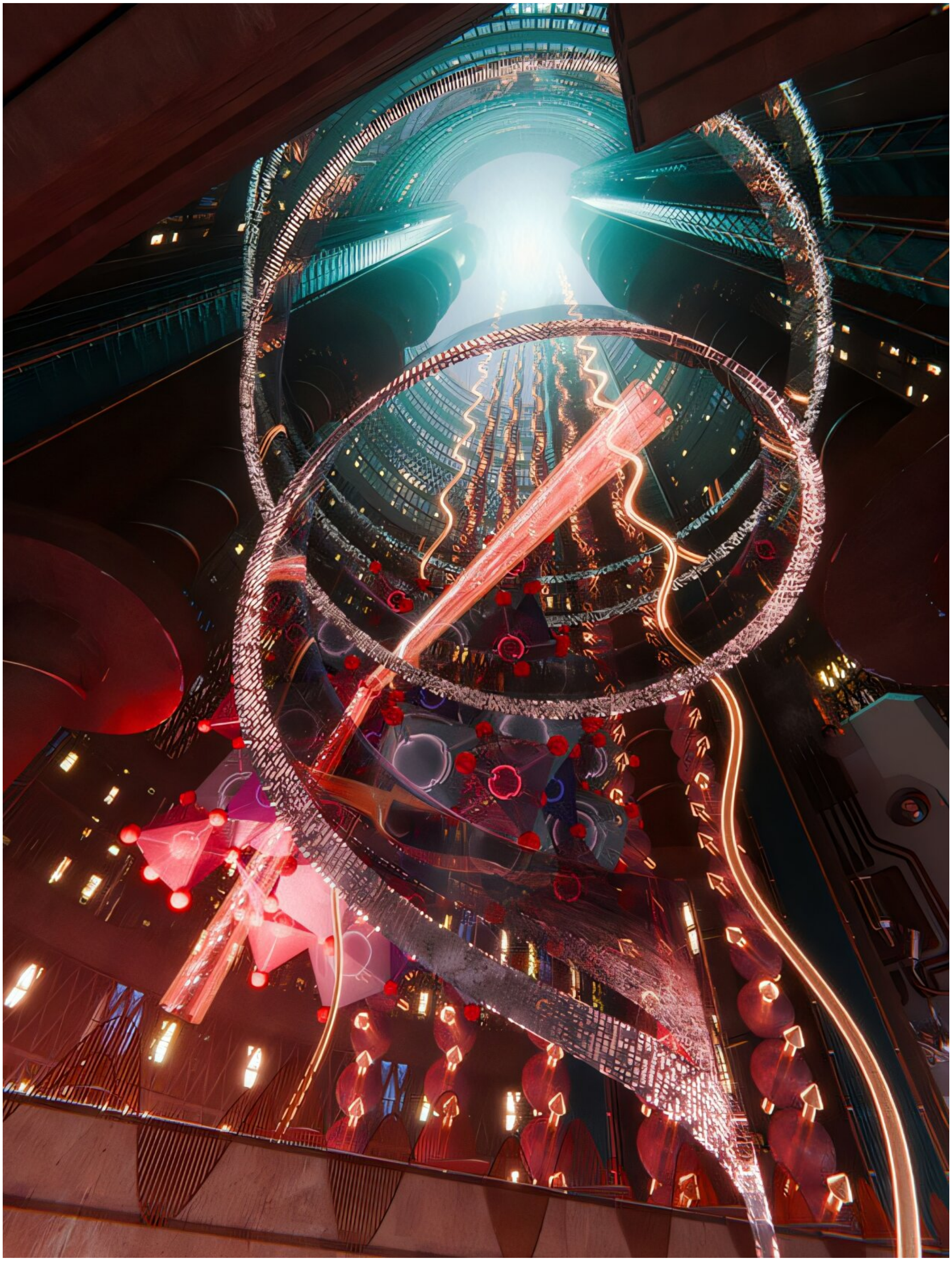

An artist's representation of the spin current generated in yttrium iron by the spin Seebeck effect and probed with resonant inelastic X-ray scattering at the Soft Inelastic X-ray Scattering (SIX) beamline at the National Synchrotron Light Source II. Credit: Valerie A. Lentz/Brookhaven National Laboratory

Spintronics is an emerging field that leverages the spin, or the intrinsic angular momentum, of electrons. By harnessing this quantum-relativistic property, researchers aim to develop devices that store and transmit information faster, more efficiently, and at higher data densities, potentially making devices much smaller than what is possible today. These advances could drive next-generation memory, sensors, and even quantum technologies.

A key step toward this future is the control of "spin currents," the flow of angular momentum through a material without an accompanying electrical charge current. However, spin currents have proven notoriously difficult to measure directly—until now.

In a new study, a research team led by scientists at the National Synchrotron Light Source II (NSLS-II)—a U.S. Department of Energy (DOE) Office of Science user facility at DOE's Brookhaven National Laboratory—used a technique called resonant inelastic X-ray scattering (RIXS) to detect a current formed by the flow of magnons, quantized spin-wave excitations in a material's magnetic structure.

By applying a temperature gradient across a magnetic insulator, where heat moves from hot to cold, a spin current was induced by magnon transport, and these spin excitations were observed as they propagated under non-equilibrium conditions. Using this novel technique, the team can delve deeper into key transport properties, like how long magnons last before they scatter. These results were published today in *Nature*.

Measuring in uncharted territory

Spin currents have been studied for decades; however, this has primarily been through macroscopic techniques that only offer indirect insights. To detect a magnon spin current, scientists typically convert it into an electrical signal, a process that involves multiple interfaces and conversion steps, obscuring direct spin information.

"Those steps can be modeled, but not perfectly," explained Valentina Bisogni, lead beamline scientist for the Soft Inelastic X-ray Scattering (SIX) beamline and lead author on this research. "There are many unknowns and assumptions that can't be fully verified in this process. While these methods lay solid groundwork to prove the existence of spin currents, trying to derive accurate microscopic models from such indirect probes has been challenging."

"Our goal was to reveal the magnons involved in spin currents," said Yanhong Gu, former postdoctoral fellow in Bisogni's group. "These are not moving spins, but moving angular momenta forming a spin wave, while the electron charges remain still."

Conventional methods, like X-ray magnetic circular dichroism, offered some spin sensitivity, but not to the momentum distribution of the excitations within the spin current. "Magnons carry both energy and momentum. Identifying which magnon modes contribute to the current is essential for constructing a detailed, microscopic understanding," said Gu.

"It's a bit like looking at the ocean here on Long Island," said Johnny Pelliciari, a beamline scientist at SIX and a co-author on this research. "You can see the waves, but that doesn't mean you understand what water is made of. It's made up of countless tiny particles working together.

"Similarly, in magnon spin transport, you can detect the overall current, or the conversion process, but that doesn't necessarily mean you understand the underlying mechanisms: the energy and momentum of the fundamental magnetic excitations, like magnons, that give rise to it."

One of the critical parameters in this study is the magnon relaxation time. If the excitation decays too quickly, effective transport cannot occur due to dissipation. Many of these parameters are currently estimated, not measured, which motivated Bisogni and her team to pursue a more precise method for probing and characterizing spin currents using RIXS.

If the right tool doesn't exist, build it

A challenge the team was tasked with was developing an experimental setup to combine RIXS measurements with transport measurements. They created a device that produces magnon spin current using the spin-Seebeck effect, a phenomenon that generates spin conductivity through a temperature gradient, within the sample environment of the SIX experimental endstation.

The sample chosen for this experiment was yttrium iron garnet (YIG), an electrically insulating ferrimagnet and one of the most promising materials for spintronic applications. Integrating the magnon spin current device into the endstation chamber presented another challenge, but persistence and innovation led the team to design exactly what they needed.

When the scientists applied a temperature difference across their sample, the magnons started moving, creating a spin current. RIXS proved sensitive enough to detect even very small imbalances in the magnon intensity, reflecting the underlying changes in magnon distributions. The team was able to observe which specific excitations were carrying the spin current and at what momentum, offering a true microscopic picture.

Using a mathematical model called the Boltzmann equation, the team was also able to calculate how long the magnons lasted and how they moved, important details for developing magnon-based spintronic devices in the future. This collaboration didn't just assemble a novel experimental device, though; it brought together the expertise of several key players in a very niche field.

For theoretical support, the team collaborated with Gerrit Bauer, a professor and principal investigator at the Advanced Institute for Materials Research at Tohoku University, and Joseph Barker from the University of Leeds. Bauer, a leading voice in the field, challenged some of the team's initial ideas, which only strengthened the team's resolve.

"Many doubted that RIXS would ever turn out a useful spectroscopic method, but the development of powerful X-ray sources and high-resolution detectors proved the philistines wrong," said a spirited Bauer. "The present results provide only a glimpse, be it a spectacular one, into the potential of the method to image non-equilibrium bosonic distribution functions in reciprocal space. You haven't seen anything yet!"

"It was amazing to see something that we have relied on as a theoretical concept for so long be measured directly," added Barker.

This research not only brought together researchers from across the country and the world but it also benefited from nearby collaboration with the Center for Functional Nanomaterials, a DOE Office of Science user facility at Brookhaven Lab. Technical associate Kim Kisslinger and scientist Fernando Camino were instrumental in preparing and supporting the device and sample used for this work alongside Takashi

Kikkawa of the Japan Atomic Energy Agency, Eiji Saitoh of the University of Tokyo, and Dmitri Basov of Columbia University.

From an ambitious proposal to an exciting future

The result of this experiment reflects a key goal of Bisogni's DOE Early Career Research proposal: using RIXS to access non-equilibrium phenomena, ultimately guiding the path towards the next generation of electronics. Observing a magnon spin current is just the beginning.

"We can now detect changes in the excitation spectral weight as we drive a material out of equilibrium," said Bisogni. "That opens many other research directions, including other forms of non-conventional, charge-less transport, like phonons, orbitals, or plasmons, which hold promise of being faster and resilient to magnetic fields."

The group at the SIX beamline also developed a novel sample environment that replicates the working conditions of electrical devices called "Opera." This system came together thanks to the hard work and insight of Daniel Bacescu, a Mechanical Engineer at NSLS-II who helped engineer Opera.

An immediate follow-up is to replicate the results at various momenta and in thin films to compare with bulk crystals. In the longer term, they intend to use RIXS to study other forms of unconventional transport. They hope to find applications in systems like graphene and magnetic van der Waals materials.

More information: Valentina Bisogni, Observing differential spin currents by resonant inelastic X-ray scattering, *Nature* (2025). DOI: 10.1038/s41586-025-09488-9.
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