Superconductivity that shouldn't exist: Physicists dissect the mind-boggling properties of a strange quantum material

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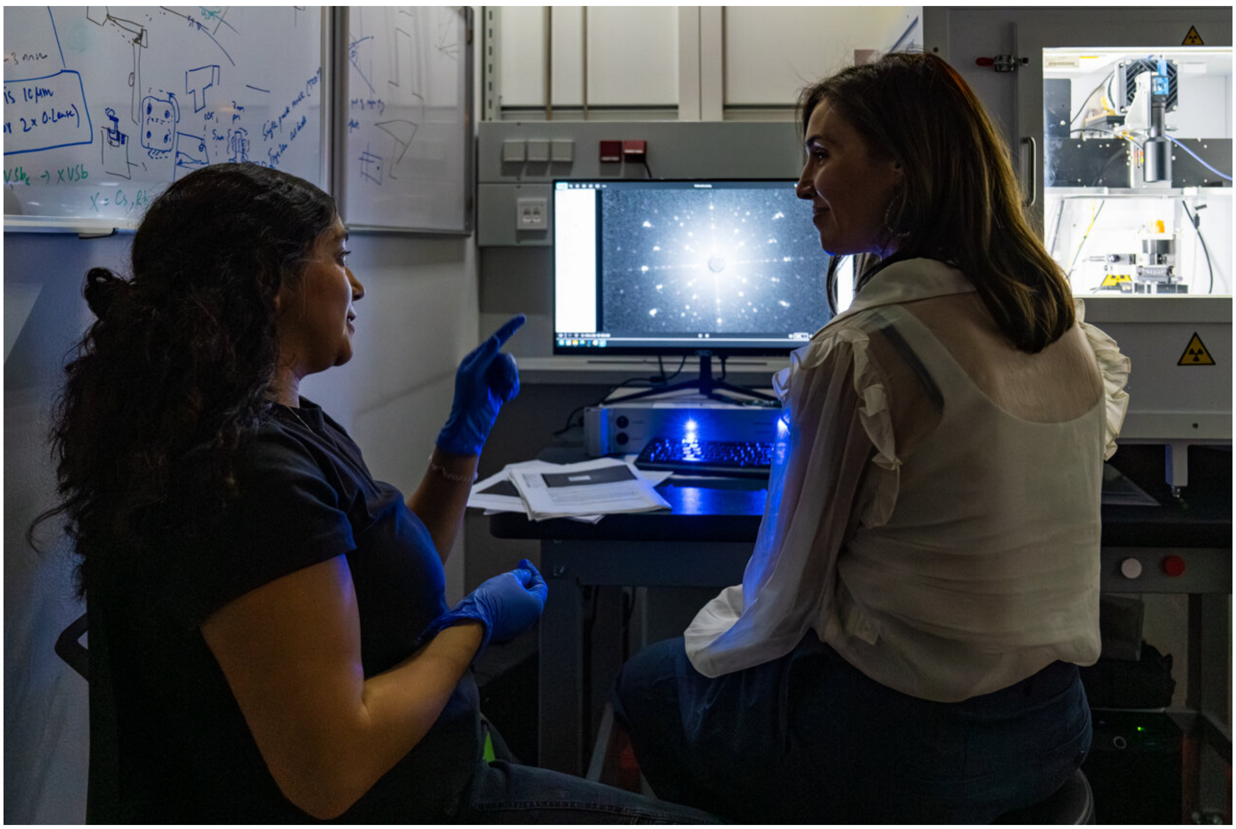


ISTA scientists examine a sample in the lab. Left to right: Ph.D. student and first author Valeska Zambra discusses the properties of a UTe_2 sample with Assistant Professor Kimberly Modic. Credit: ISTA

The material UTe_2 exhibits multiple forms of zero electrical resistance—a phenomenon known as superconductivity—and displays several puzzling properties. After UTe_2 loses its superconductivity at a certain magnetic field, it becomes superconducting again under much higher fields.

Using a new high-field measurement technique, researchers from the Institute of Science and Technology Austria (ISTA) have explained this unusual superconducting behavior in a paper in *Nature Communications*. Their method is now being adopted at high-field laboratories worldwide.

Quantum materials exhibit exotic properties that make them relevant for next-generation technologies. While some scientists researching quantum materials seek to uncover specific properties for targeted applications, such as quantum computing, other researchers are curiosity-driven, searching for knowledge that hasn't yet appeared in textbooks.

Such knowledge can take years or even decades to apply, but the process of discovery and understanding yields its own rewards.

One material that has tested scientists' textbook understanding is uranium ditelluride, which was discovered in 2019. Uranium ditelluride, also known as UTe_2, is a superconductor—a material that allows electric current to flow without any resistance.

However, not all superconductors are the same: some, like UTe_2, are called "unconventional superconductors." But even among these, UTe_2 seems to belong to a category of its own, with a hidden zero-resistance state that appears at extremely high magnetic fields after the material loses its original superconductivity at lower fields.

"It seems like each measurement on UTe_2 uncovers yet another mystery. Our work now presents evidence for the mechanism behind some of these mysteries," says Kimberly Modic, assistant professor at the Institute of Science and Technology Austria (ISTA).

Within her group, Ph.D. student Valeska Zambra has led the development of a new method to probe UTe_2's puzzling behavior, which has struck the interest of high-field scientists around the world.

Using a new high-field measurement technique, ISTA physicists have explained some of UTe_2's unusual properties. Their method is now being adopted at high-field laboratories worldwide. Credit: ISTA

How unconventional can a material be?

Conventional superconductors, which become superconducting only at extremely low temperatures, typically lose their zero-resistance state in magnetic fields. UTe_2, on the other hand, reenters a superconducting state at extreme magnetic fields between 40 and 70 Tesla after superconductivity disappears around 10 Tesla. For comparison, one Tesla is strong enough to lift a car in a scrapyard.

How superconductivity arises in conventional superconductors at such low temperatures is well understood: vibrations in the material structure lead to the binding of electrons into pairs that travel without resistance. This mechanism, however, does not explain the behavior of unconventional superconductors like UTe_2.

"So far, researchers have assumed that something magnetic must be behind superconductivity in unconventional superconductors," says Modic. In fact, UCoGe and URhGe, two unconventional superconductors related to UTe_2, are magnets themselves. Therefore, these materials have a reason to be superconducting.

"But the catch is that UTe_2 is not magnetic. So, at first glance, it's not obvious why this material exhibits such a special superconducting state."

Among UTe_2's three distinct zero-resistance states discovered to date, the phenomenon of "reentrant superconductivity," which describes how superconductivity reappears at extreme magnetic fields, is what has puzzled researchers the most.

Furthermore, this state exists only when the magnetic field is oriented in a very specific direction within the crystal, under temperatures colder than outer space.

"Although other unconventional superconductors exist, UTe_2 makes the word 'unconventional' almost sound like an understatement," says Modic.

ISTA Ph.D. student and first author Valeska Zambra inspects a sample. UTe_2 is a superconductor—a material that allows electric current to flow without resistance. It exhibits multiple forms of zero electrical resistance. Credit: ISTA

A small shake opens up a new world inside the material

To better understand how this unique superconductivity arises in UTe_2, the team sought to study what happens near the conditions where reentrant superconductivity emerges—meaning before the material becomes superconducting in high magnetic fields.

At pulsed field facilities, they can subject their samples to very short bursts of extreme magnetism, in which the magnetic field increases from 0 to 60 Tesla and back within a tenth of a second—as fast as one can blink. Their goal? To investigate whether this state could be due to magnetic fluctuations in the material, a phenomenon that, in theory, might explain high-field superconductivity.

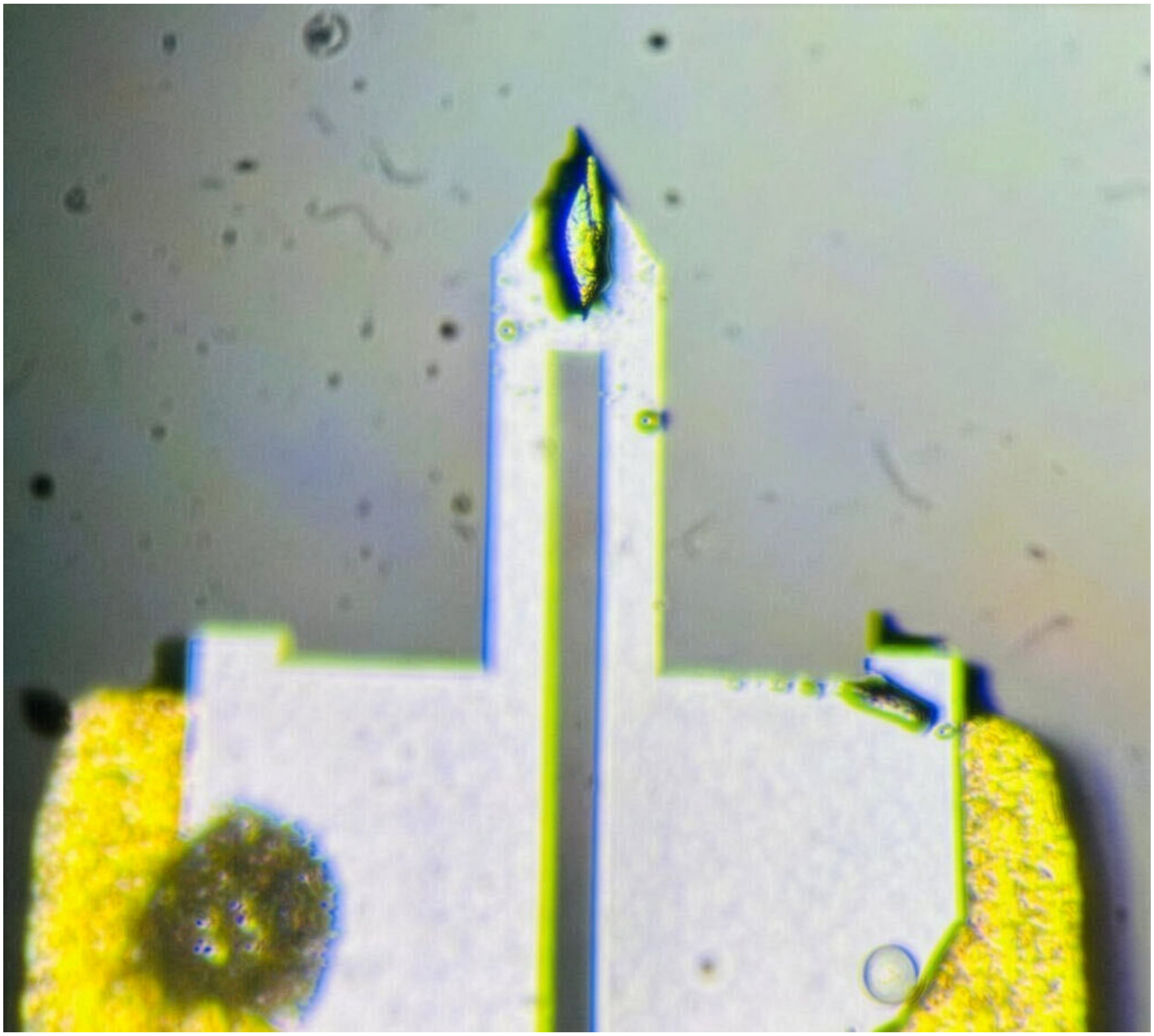
While extreme conditions allow strange quantum materials to exhibit their odd properties, understanding how these arise often requires a little push.

"We devised a method that allows us to interrogate the sample under extreme magnetic fields by giving it a controlled wiggle," says Zambra.

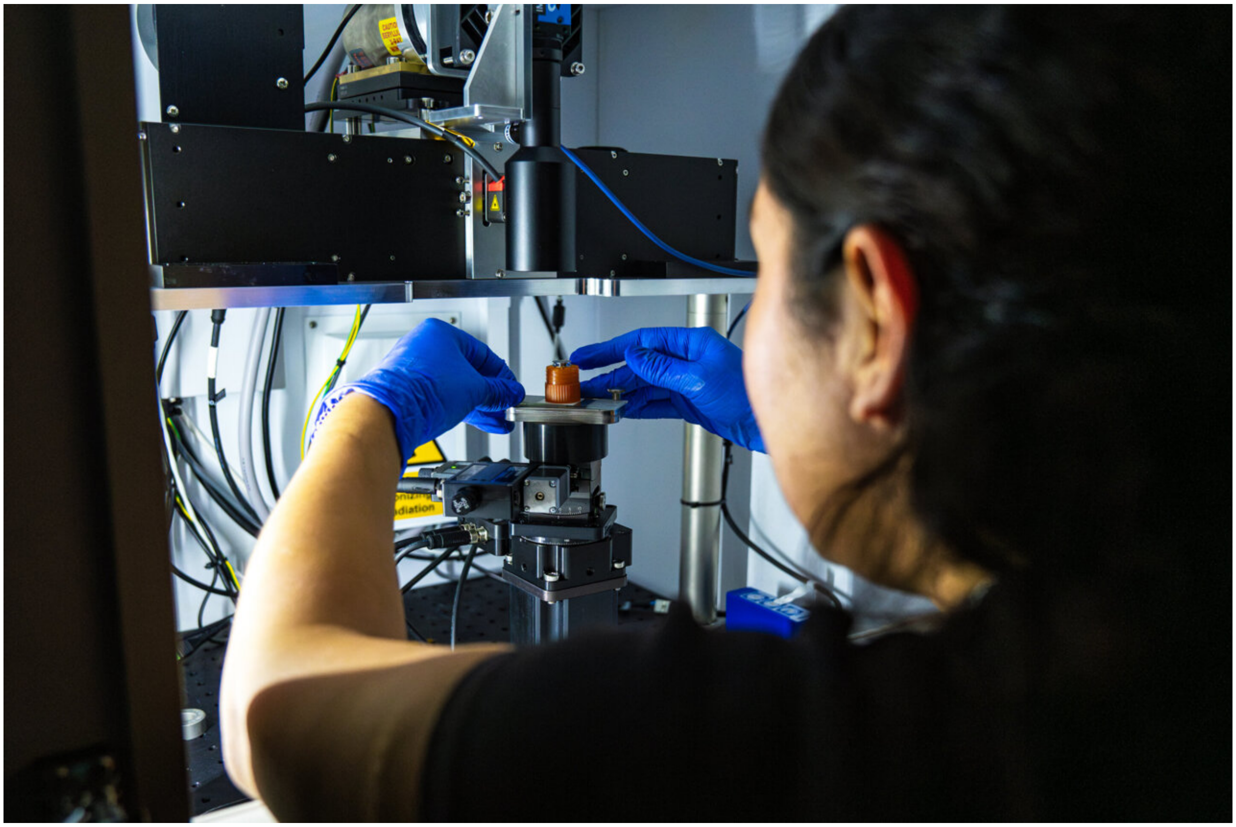
She further explains, "We place the sample on a cantilever—a sort of stick—to manipulate and shake it in the magnetic field. From the crystal's point of view, the shaking makes it look like the direction of the magnetic field oscillates in time, allowing for a fast check of the magnetization under that changing field.

"This allows us to measure an important property called 'transverse magnetic susceptibility' that no one has accessed under these conditions."

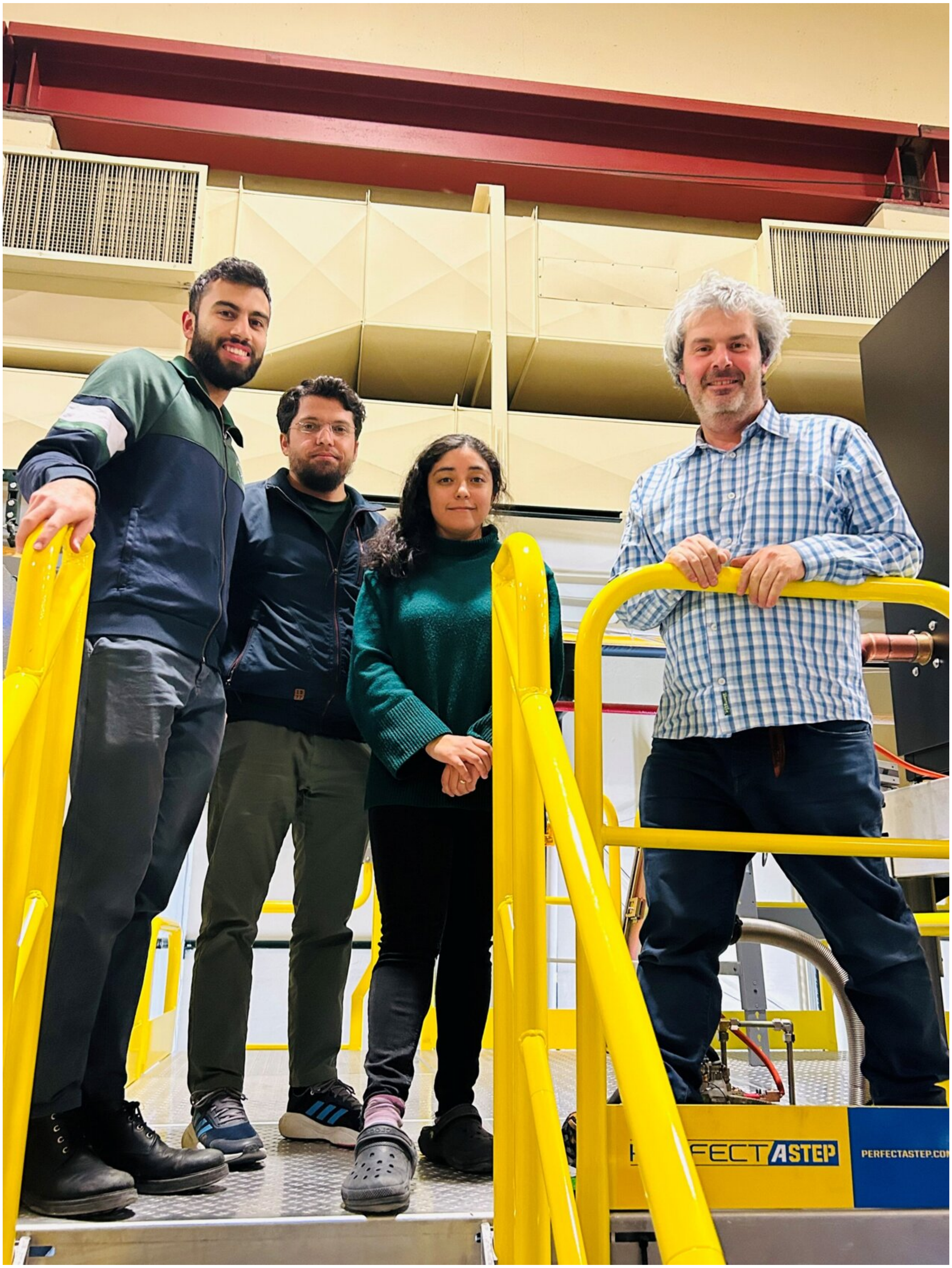
With this technique, the team uncovered a region of large transverse magnetic susceptibility in UTe_2 that likely acts as the "glue" between the material's electrons, providing a reason for the superconductivity under such high magnetic fields, Zambra and Modic explain.



Smaller than a grain of sand. A sample of UTe_2 mounted on a cantilever. This sample will be subjected to a magnetic field that increases from 0 to 60 Tesla and back within a tenth of a second, as fast as one can blink. Credit: Valeska Zambra | ISTA



UTe_2 has a hidden zero-resistance state that appears at extremely high magnetic fields after the material loses its original superconductivity at lower fields. Credit: ISTA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Co-authors at the Los Alamos National Laboratory pulsed field facility, United States. Left to right: ISTA alumni Amit Nathwani and Muhammad Nauman, ISTA Ph.D. student and first author Valeska Zambra, and co-author Arkady Shekhter. Credit: Valeska Zambra | ISTA

High-field facilities adopting an ISTA technique

The team emphasizes the importance of the method for dissecting the properties of this strange quantum material. In fact, they use samples smaller than a grain of sand, allowing them to measure defect-free pieces of the material. The group has expertise in fabricating samples at such small scales and unique capabilities to control how such small samples are integrated into the experiment.

"Measuring small samples roughly as large as the thickness of a human hair is especially challenging, but this is precisely what our group specializes in. While many techniques can only be applied to larger crystals, Valeska's method, developed in our group at ISTA, comes with the added advantage that it also works in high magnetic fields where the toolbox of available techniques is already very limited," says Modic.

"As such, high-field facilities have reached out to Valeska to collaborate on establishing this technique further at their facilities."

Zambra and Modic underscore the fundamental aspect of their research, arguing that they need to fully understand these new states of matter before exploring potential applications.

"Often, scientists realize the usefulness of a new finding years or decades later. The accidental discovery of superconductivity over a century ago eventually led to the development of the medical imaging technique MRI," says Zambra.

Modic concludes, "We might be looking at a completely new type of superconductivity for which we have not yet imagined applications. Will it be useful for something down the road? I don't know. But it's a mystery, and mysteries are worth going after."

More information: Valeska Zambra, et al. Giant transverse magnetic fluctuations at the edge of re-entrant superconductivity in UTe_2, *Nature Communications* (2026). DOI: 10.1038/s41467-026-71899-7

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