Researchers discover superconductive images are actually 3D and disorder-driven fractals

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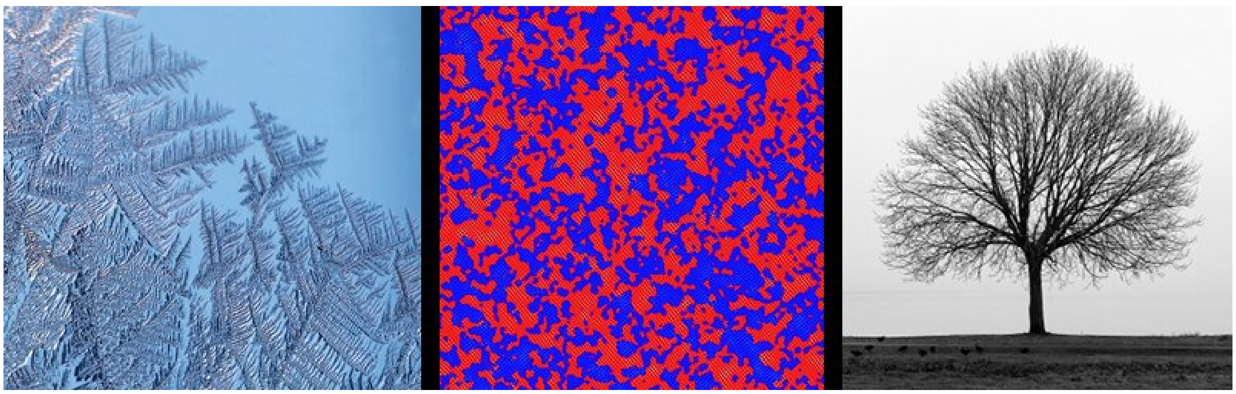

Fractals are a never-ending pattern that you can zoom in on and the image doesn’t change. Fractals can occur in two dimensions, like frost on a window, or in three dimensions like the limbs of a tree. A recent discovery from Purdue University researchers has established that superconducting images, seen above in red and blue, are actually fractals that fill a three-dimensional space and are disorder driven, rather than driven by quantum fluctuations as expected. Frost and tree images by Adobe. Superconducting image (center) from "Critical nematic correlations throughout the superconducting doping range in $Bi_{2-x}Pb_zSr_{2-y}La_yCuO_{6+x}$" in *Nature Communications*. Credit: *Nature Communications* (2023). DOI: 10.1038/s41467-023-38249-3

Meeting the world's energy demands is reaching a critical point. Powering the technological age has caused issues globally. It is increasingly important to create superconductors that can operate at ambient pressure and temperature. This would go a long way toward solving the energy crisis.

Advancements with superconductivity hinge on advances in quantum materials. When electrons inside of quantum materials undergo a phase transition, the electrons can form intricate patterns, such as fractals. A fractal is a never-ending pattern. When zooming in on a fractal, the image looks the same. Commonly seen fractals can be a tree or frost on a windowpane in winter. Fractals can form in two dimensions, like the frost on a window, or in three-dimensional space like the limbs of a tree.

Dr. Erica Carlson, a 150th Anniversary Professor of Physics and Astronomy at Purdue University, led a team that developed theoretical techniques for characterizing the fractal shapes that these electrons make, in order to uncover the underlying physics driving the patterns.

Carlson, a theoretical physicist, has evaluated high resolution images of the locations of electrons in the superconductor $Bi_{2-x}Pb_zSr_{2-y}La_yCuO_{6+x}$ (BSCO), and determined that these images are indeed fractal and discovered that they extend into the full three-dimensional space occupied by the material, like a tree filling space.

What was once thought of as random dispersions within the fractal images are purposeful and, shockingly, not due to an underlying quantum phase transition as expected, but due to a disorder-driven phase transition.

Carlson led a collaborative team of researchers across multiple institutions and published their findings, titled "Critical nematic correlations throughout the superconducting doping range in $Bi_{2-x}Pb_zSr_{2-y}La_yCuO_{6+x}$," in *Nature Communications.*

The team includes Purdue scientists and partner institutions. From

Purdue, the team includes Carlson, Dr. Forrest Simmons, recent Ph.D. student, and former Ph.D. students Dr. Shuo Liu and Dr. Benjamin Phillabaum. The Purdue team completed their work within the Purdue Quantum Science and Engineering Institute (PQSEI). The team from partner institutions includes Dr. Jennifer Hoffman, Dr. Can-Li Song, Dr. Elizabeth Main of Harvard University, Dr. Karin Dahmen of the University of Illinois at Urbana-Champaign, and Dr. Eric Hudson of Pennsylvania State University.

"The observation of fractal patterns of orientational ('nematic') domains—cleverly extracted by Carlson and collaborators from STM images of the surfaces of crystals of a cuprate high temperature superconductor—is interesting and aesthetically appealing on its own, but also of considerable fundamental importance in coming to grips with the essential physics of these materials," says Dr. Steven Kivelson, the Prabhu Goel Family Professor at Stanford University and a theoretical physicist specializing in novel electronic states in quantum materials. "Some form of nematic order, typically thought to be an avatar of a more primitive charge-density-wave order, has been conjectured to play an important role in the theory of the cuprates, but the evidence in favor of this proposition has previously been ambiguous at best. Two important inferences follow from Carlson et al.'s analysis: 1) The fact that the nematic domains appear fractal implies that the correlation length—the distance over which the nematic order maintains coherence—is larger than the field of view of the experiment, which means that it is very large compared to other microscopic scales. 2) The fact that patterns that characterize the order are the same as those obtained from studies of the three dimensional random-field Ising model—one of the paradigrmatic models of classical statistical mechanics—suggests that the extent of the nematic order is determined by extrinsic quantities and that intrinsically (i.e. in the absence of crystalline imperfections) it would exhibit still longer range correlations not just along the surface, but extending deep into the bulk of the crystal."

High resolution images of these fractals are painstakingly taken in Hoffman's lab at Harvard University and Hudson's lab, now at Penn State, using scanning tunneling microscopes (STM) to measure electrons at the surface of the BSCO, a cuprate superconductor. The microscope scans atom by atom across the top surface of the BSCO, and what they found was stripe orientations that went in two different directions instead of the same direction. The result, seen above in red and blue, is a jagged image that forms interesting patterns of electronic stripe orientations.

"The electronic patterns are complex, with holes inside of holes, and edges that resemble ornate filigree," explains Carlson. "Using techniques from fractal mathematics, we characterize these shapes using fractal numbers. In addition, we use statistics methods from phase transitions to characterize things like how many clusters are of a certain size, and how likely the sites are to be in the same cluster."

Once the Carlson group analyzed these patterns, they found a surprising result. These patterns do not form only on the surface like flat layer fractal behavior, but they fill space in three dimensions. Simulations for this discovery were carried out at Purdue University using Purdue's supercomputers at Rosen Center for Advanced Computing. Samples at five different doping levels were measured by Harvard and Penn State, and the result was similar among all five samples.

The unique collaboration between Illinois (Dahmen) and Purdue (Carlson) brought cluster techniques from disordered statistical mechanics into the field of quantum materials like superconductors. Carlson's group adapted the technique to apply to quantum materials, extending the theory of second order phase transitions to electronic fractals in quantum materials.

"This brings us one step closer to understanding how cuprate superconductors work," explains Carlson. "Members of this family of superconductors are currently the highest temperature superconductors that happen at ambient pressure. If we could get superconductors that work at ambient pressure and temperature, we could go a long way toward solving the energy crisis because the wires we currently use to run electronics are metals rather than superconductors. Unlike metals, superconductors carry current perfectly with no loss of energy. On the other hand, all the wires we use in outdoor power lines use metals, which lose energy the whole time they are carrying current. Superconductors are also of interest because they can be used to generate very high magnetic fields, and for magnetic levitation. They are currently used (with massive cooling devices!) in MRIs in hospitals and levitating trains."

Next steps for the Carlson group are to apply the Carlson-Dahmen cluster techniques to other quantum materials.

"Using these cluster techniques, we have also identified electronic fractals in other quantum materials, including vanadium dioxide (VO2) and neodymium nickelates (NdNiO3). We suspect that this behavior might actually be quite ubiquitous in quantum materials," says Carlson.

This type of discovery leads quantum scientists closer to solving the riddles of superconductivity.

"The general field of quantum materials aims to bring to the forefront the quantum properties of materials, to a place where we can control them and use them for technology," Carlson explains. "Each time a new type of quantum material is discovered or created, we gain new capabilities, as dramatic as painters discovering a new color to paint with."

More information: Can-Li Song et al, Critical nematic correlations throughout the superconducting doping range in $Bi_{2-x}Pb_zSr_{2-y}La_yCuO_{6+x}$, *Nature Communications* (2023). DOI: 10.1038/s41467-023-38249-3

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