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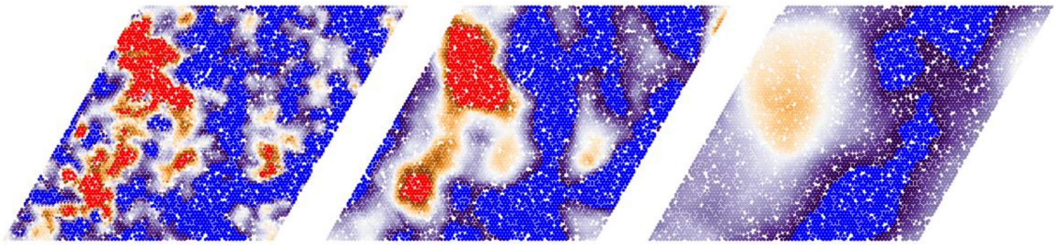
PRESS RELEASE

Topological materials and critical phenomena: the unexpected connection between two worlds

Topological materials can display local behaviours similar to those observed in water turning into ice or metals becoming magnetised. This is the central finding of a new study published in Physical Review Letters and led by Antimo Marrazzo from SISSA.



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Phase transitions in "conventional" materials – such as water turning into ice or a metal becoming magnetised – and topological phase transitions have long been treated as fundamentally distinct, governed by different physical principles and lacking a shared conceptual framework. This study, however, published in Physical Review Letters, challenges that notion. Antimo Marrazzo, assistant professor at SISSA, together with Roberta Favata and Nicolas Baù, PhD students at the University of Trieste, have shown that—even in topological phase transitions—certain local markers can exhibit behaviours analogous to those of conventional local order parameters. Just like in a magnet near its critical temperature, these systems exhibit significant local fluctuations. The researchers also identified universal critical exponents, i.e. numerical values that describe how a topological phase transition unfolds and that remain consistent across different materials, as seen in conventional phase transitions. According to the authors, this discovery builds a conceptual bridge between the world of topology and the physics of phase transitions.

What makes topological materials so peculiar

Symmetry, local order parameters, critical fluctuations: these are the key concepts traditionally used in physics to describe phase transitions. While they provide a powerful theoretical framework, they are not universally applicable: certain exotic materials simply do not follow these rules. “These are the so-called topological materials," explains Antimo Marrazzo, who coordinated the study. "They typically behave as insulators in the bulk, while remaining conductive at the surface. These materials defy many of the usual rules. For instance, they are not distinguished by any particular symmetry, as is normally the case, but by global properties known as "topological invariants": integer numbers that remain unchanged unless the material undergoes a fundamental transformation. This is why it was long believed that topological phase transitions could not be described using the same tools as conventional ones". These properties remain stable even in the presence of moderate disorder, the authors explain, until Anderson localisation occurs and destroys the topological phase. A typical example of disorder is the presence of so-called vacancies: i.e. sites in the atomic lattice where an atom is missing, creating a local defect in the otherwise ordered crystalline structure. Interestingly, disorder can also induce a topological phase – known as a topological Anderson insulator – starting from an initially disorder-free phase. Beyond their scientific appeal, topological materials also offer promising avenues for technological innovation, from energy-efficient electronics to the development of quantum computers.

Things are not always what they seem

Through numerical simulations carried out on a CINECA supercomputer in Bologna, the researchers uncovered a series of striking features. "While topological properties have traditionally been regarded as global – pertaining to the system as a whole – our research shows that it is also possible to use local topological markers to probe the system point by point, especially in the presence of disorder. Remarkably, these markers exhibit behaviours analogous to conventional order parameters, meaning they can act as genuine local indicators of topological phase transitions. For instance, if a sufficient amount of disorder is introduced, a topological insulator can transition into a trivial insulator". The team observed that during this topological phase transition, local topological markers undergo short-range fluctuations, which disappear when the system is viewed at a larger scale – much like zooming out with a camera. This occurs in all cases except near the critical point, where the behaviour at one point influences distant regions and long-range fluctuations persist. This is precisely what one expects to see in a conventional (non-topological) phase transition. To analyse this behaviour, the researchers introduced a topological correlation function, describing how the value of the local topological order parameter at one point affects the value at another, as a function of the distance between them. To their surprise, the researchers found that the correlation function exhibits critical exponents that appear to be universal across disorder types and microscopic configurations, yet remain sufficiently sensitive to discriminate among distinct topological phases. Such universal critical exponents are a hallmark of conventional phase transitions and a cornerstone of the theory of critical phenomena.

Implications of the research

The core message of this work is that topological phase transitions are, in the end, not so different from conventional ones. “This discovery is crucial in that it builds a bridge between topology and the physics of phase transitions,” the authors say, “opening new possibilities to apply powerful tools from statistical physics – and perhaps even quantum information theory – to study these fascinating and technologically relevant materials”. Understanding how topological materials behave in the presence of microscopic disorder and defects is crucial, they add, since such imperfections are inevitably present even in the purest materials used in real-world technologies.

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IMAGE
Crediti: A**ntimo Marrazzo**

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