High-Temperature Superconductors: Playgrounds for Broken Symmetries.

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Studies of symmetries and the consequences of breaking them have lead to deeper understandings in many areas of science.

Superconductivity, a state classified by zero resistance (perfect conductivity) and the expulsion of magnetic fields (perfect diamagnetism) was discovered in metals at low temperatures in the early 1900's, and the mechanism was revealed approximately 50 years later. The transition from a normal to a superconducting state has been described as breaking a symmetry known as "gauge", which can be thought of as the superconductor transforming from the normal state where the electrons travel as unrelated waves, to the superconducting state where the phases of the electron waves are strongly correlated.

These metallic superconductors are now classified as "conventional", which means that that when a particle travels in any direction within the superconductor, it nominally experiences the same effects.

High-temperature superconductivity was discovered in 1986, but the mechanism remains elusive. These superconductors are classified as "unconventional" because the effects experienced by a particle moving within the material are dependent upon the direction of motion. This directional dependence in the unconventional superconductors indicates that they also break reflection symmetry.

There are fascinating ramifications of this extra symmetry breaking, including the sensitivity to disorder. There is also the possibility of time-reversal symmetry breaking, or the spontaneous appearance of magnetism.

The main problems still to be solved for unconventional superconductors include:

1. Finding the mechanism for superconductivity.
2. Finding reliable ways to measure if a superconductor is unconventional, and the symmetry of its pairing state.
3. Understanding the role of disorder, including interfaces. Conventional superconductors are typically metals or alloys, but the unconventional superconductors tend to be compounds. Therefore, they are more fragile, i.e., are more sensitive to structural disorder. In unconventional superconductors, even a small change in physical structure can cause a profound effect on their electronic structure, so this remains an important question, both for the basic understanding of the physical state, and for applications.
4. Finding reliable ways to measure if time-reversal symmetry is broken. This is a challenging, because the magnetism can occur in a very small fraction of the superconductor, and is buried within the superconducting state.