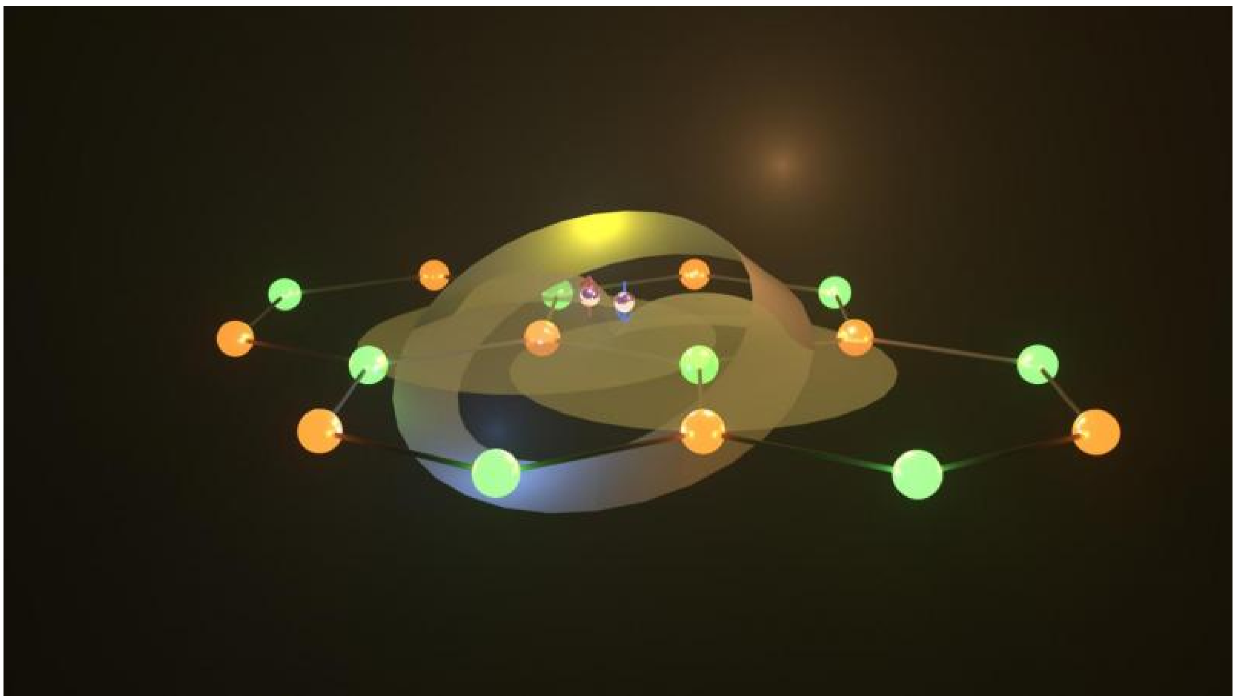
Superfluidity in topologically nontrivial flat bands

November 20 2015



Aalto researchers have discovered that superconductivity is possible even in a crystal where the apparent mass of the electrons is infinite.

Researchers at Aalto University have discovered that energy saving superconductors may be possible if the counterintuitive properties of electrons moving in "flat bands" are exploited.

Superconductors are marvellous materials that are able to transport electric current and energy without dissipation. For this reason, they are extremely useful for constructing magnets that can generate enormous magnetic fields without melting. They have found important applications as essential components of the Large Hadron Collider particle accelerator at CERN, levitating trains, and the magnetic resonance imaging tool widely used for medical purposes. Yet, one reason why the waiting list for an MRI scan is sometimes so long is the cost of the equipment. Indeed, superconductors have to be cooled down below one hundred degrees centigrade to manifest their unique properties, and this implies the use of expensive refrigerators.

An important open problem in modern materials science is to understand the mechanism behind superconductivity, and in particular, it would be highly desirable to be able to predict with precision the critical temperature below which the superconducting transition occurs. In fact, there are no currently available theories that can provide accurate predictions for the critical temperature of the most useful superconductive materials. This is unfortunate since a sound understanding of the mechanism of superconductivity is essential if we are interested in synthesizing materials that may one day achieve superconductivity at room temperature, without refrigeration.

A potential breakthrough has recently been put forward by researchers at Aalto University. Their study builds on the theory of the electronic motion in crystals developed by Felix Bloch in 1928. It is an interesting consequence of quantum mechanics that an electron that feels the electric charge of an ordered array of atoms (a crystal) can move as freely as it would in free space. However, the crystal has the nontrivial effect of modifying the apparent mass of the electron. Indeed, electrons appear to be heavier (or lighter) in a crystal than in free space, which means that one has to push them more (or less) to make them move.

This fact has very important consequences since electrons with a larger apparent mass lead to a larger critical temperature for superconductivity. Ideally to maximize the critical temperature, we should consider electrons with infinite apparent mass or, to use the jargon of physicists, electrons in a "flat band". Naively we could expect that electrons with infinite mass would be stuck in place, unable to carry any current, and the essential property of superconductivity would be lost.

"I was very intrigued to find out how a supercurrent, that is, electrical current, could be carried by electrons in a flat band. We had some hints that this is in fact possible, but not a general solution of this paradox" says Aalto physics Professor Päivi Törmä. Surprisingly in the world of quantum mechanics, an infinite mass does not necessarily prevent the flow of electric current. The key to this mystery is to remember that electrons are quantum mechanical objects with both particle- and wave-like features. Prof. Päivi Törmä and postdoctoral researcher Sebastiano Peotta have found that the mass alone, which is a property of particles, is not sufficient to completely characterize electrons in solids. We also need something called the "quantum metric".

A metric tells how distances are measured, for instance the distance between two points is different on a sphere than on a flat surface. It turns out that the quantum metric measures the spread of the electron waves in a crystal. This spread is a wave-like property. Electrons with the same apparent mass, possibly infinite, can be associated with waves that are more or less spread out in the crystal, as measured by the quantum metric. The larger the quantum metric, the larger the supercurrent that the superconductor can carry. "Our results are very positive," says Peotta, "they open a novel route for engineering superconductors with high critical temperature. If our predictions are verified, common sense will suffer a big blow, but I am fine with that."

Another surprising finding is that the quantum metric is intimately related to an even more subtle wave-like property of the electrons quantified by an integer number called the Chern number. The Chern number is an example of a topological invariant, namely a mathematical property of objects that is not changed under an arbitrary but gentle (not disruptive) deformation of the object itself. A simple example of a topological invariant is the number of twists of a belt. A belt with a single twist is a called a Möbius band in mathematics and is shown in the figure. A twist can be moved forward and backward in the belt but never removed unless the belt is broken. The number of twists is always an integer.

In the same way, the Chern number can take only integer values and cannot be changed unless a drastic change is performed on the electron waves. If the Chern number is nonzero, it is not possible to unknot the electron waves centred at neighbouring atoms of the material. As a consequence, the waves have to overlap, and it is this finite overlap that ensures superconductivity, even in a flat band. Aalto researchers have thus discovered an unexpected connection between superconductivity and topology.

Finland is a leader in this type of research, as flat band superconductivity was already predicted to occur at the surface of a certain kind of graphite, a result of the theoretical work of Grigory Volovik and Nikolai Kopnin (Aalto University) and Tero Heikkilä (University of Jyväskylä).

To launch the next stage of discovery, Peotta and Törmä's theoretical predictions could now be tested experimentally in ultracold atomic gas systems by collaborators. "The connections I made this summer as a guest professor at ETH Zurich will be very useful for our further research on the topic," reveals Törmä. "We are also intrigued by the fact that the physics we describe may be important for known superconductive materials, but it has not been noticed yet," adds Peotta.

More information: Sebastiano Peotta et al. Superfluidity in topologically nontrivial flat bands, *Nature Communications* (2015). DOI: 10.1038/ncomms9944

Provided by Aalto University