When a doughnut becomes an apple

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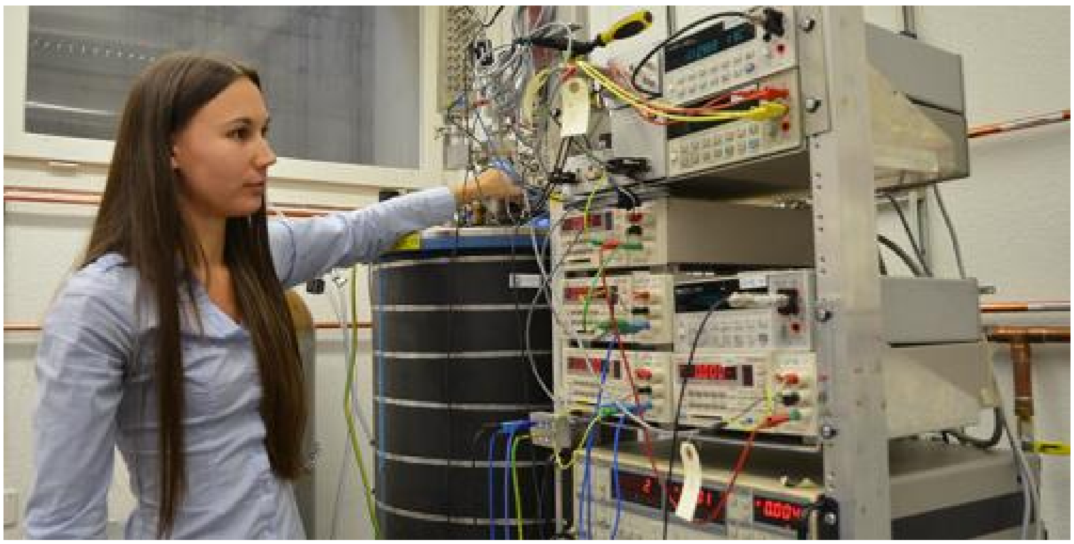

Anastasia Varlet is preparing an experiment close to absolute zero. Credit: Peter Rüegg / ETH Zürich

In experiments using the wonder material graphene, ETH researchers have been able to demonstrate a phenomenon predicted by a Russian physicist more than 50 years ago. They analyzed a layer structure that experts believe may hold unimagined promise.

Anastasia Varlet works as a doctoral candidate in the research group headed by ETH Professor Klaus Ensslin in the Laboratory for Solid State Physics and has had two research papers published consecutively in the renowned American scientific journal *Physical Review Letters*. Both works are based on measurements made on the same electronic component, a sandwich construction using graphene – a material made of carbon with a honeycomb structure that is only a single atom thick. A single layer of graphene is extremely stable, elastic and conductive. This wonder material is of particular interest in electronic applications when two layers are on top of one another, as it becomes a semiconductor that can be used to engineer electronic switches.

The quality of Varlet's double-layer graphene sample was so good that the researcher obtained completely unexpected results from her measurements. "We were able to prove the existence of a Lifshitz transition," she says. The physicist uses the example of a coffee cup and water glass to explain what this means. A cup has a handle with a hole. Using mathematical functions, it is possible to transform a geometrically designed object from the form of a cup to that of a doughnut, given that a doughnut also features a hole. A glass, on the other hand, can not be reshaped into a doughnut because it does not have a hole. Mathematically speaking, a cup has the same topology as a doughnut. "A glass is topologically the same as an apple," explains Ensslin.

Changing the topology of an object can improve its usefulness; e.g. by transforming a beaker into a cup with handle. In reality, this should not be possible at all; nevertheless, the ETH researchers have achieved exactly that by using a double layer of graphene. Named after a Russian physicist who predicted it in 1960, a Lifshitz transition is a transformation from one topology to another. However, it does not apply to objects in our normal environment; rather, the physicists are researching an abstract topology of surfaces with which the energy state of electrons is described with electronic materials. In particular, the researchers examined surfaces of constant energy, as these determine the conductivity of the material and its application potential.

Three islands in a lake

Ensslin makes another comparison to demonstrate the mathematical concept behind these energy surfaces: "Imagine a hilly landscape in which the valleys fill up with electrical charges, just as the water level rises between the hills when it rains." This is how a conductive material is formed from an initial isolator – when it stops raining, the water has formed a lake from which the individual hilltops emerge like islands. This is exactly what Varlet observed when experimenting with the double layer of graphene: at a low water level, there are three independent, but equivalent lakes. When the water level increases, the three lakes join to form a large ocean. "The topology has changed altogether," Varlet concludes. In other words, this is how a doughnut is transformed into an apple.

Until now, scientists have lacked the right material to be able to demonstrate a Lifshitz transition in an experiment. Metals are not suitable and initially the ETH team was unaware it had found the material that others had been looking for. "We observed something strange in our measurements with the graphene sandwich construction that we were not able to explain," says Varlet. A Russian theoretician, Vladimir Falko, was able to interpret these measurements in discussions with the team.

Low-cost raw materials

To produce the sandwich construction, Varlet enclosed the double layer of graphene in two layers of boron nitride, a material otherwise used for lubrication and which has an extremely smooth surface. Although both materials are cheap, a lot of work is required in the cleanroom – the carbon flakes must be exceptionally clean to produce a functioning component. "A significant part of my work consists of cleaning the graphene," says Varlet. The special feature of the samples, says Varlet's boss, is that they are able to withstand enormously strong electrical fields, enabling the work published in *Physical Review Letters* to be carried out.

At present, a practical use for the phenomenon is speculation only. The topology of quantum states, for example, offers a way of decoupling them from their environment and perhaps achieving extremely stable quantum states that can be used for information processing. In the meantime, however, the researchers will focus on gaining a better understanding of the structural elements of double-layered graphene.

More information: Varlet A, Bischoff D, Simonet P, Watanabe K, Taniguchi T, Ihn T, Ensslin K, Mucha-Kruczyński M, Falko VI: "Anomalous Sequence of Quantum Hall Liquids Revealing a Tunable Lifshitz Transition in Bilayer Graphene." *Physical Review Letters* 2014, 113: 116602. DOI: 10.1103/PhysRevLett.113.116602

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