Behavior of 'trapped' electrons in a one-dimensional world observed in the lab

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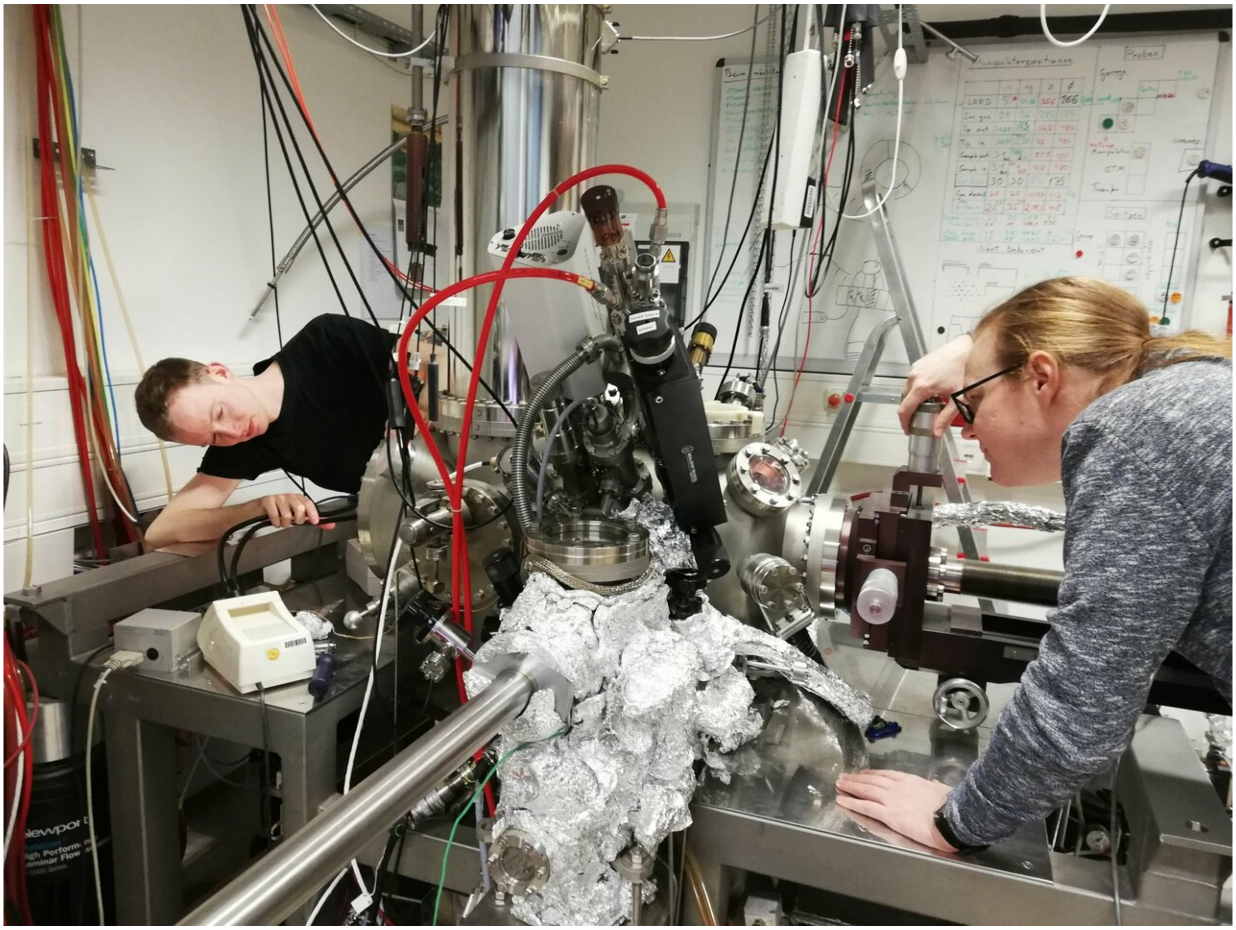


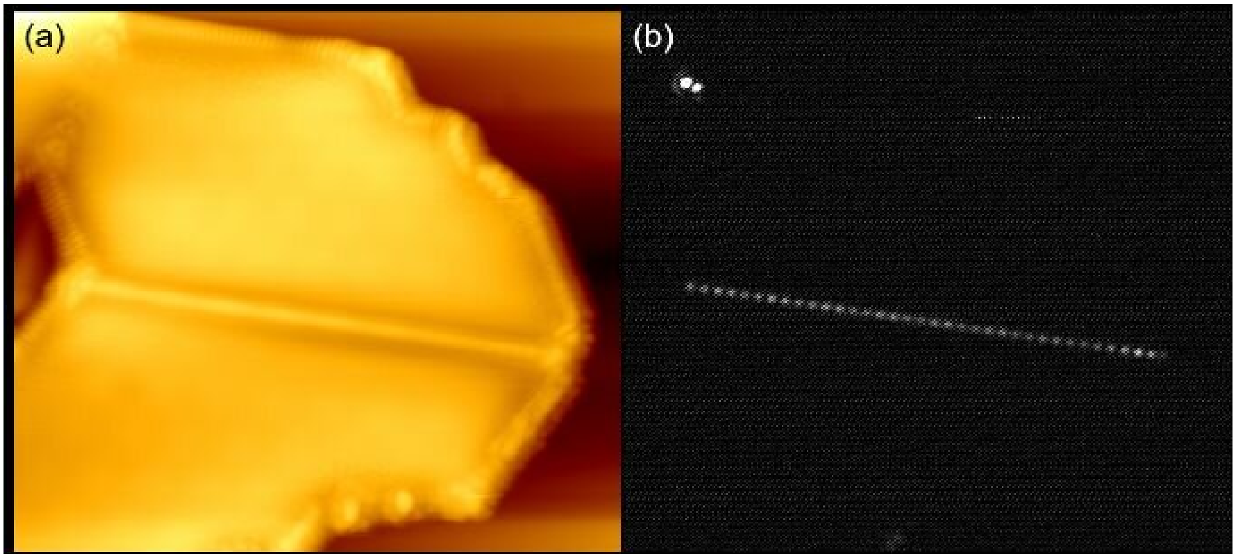
Wouter Jolie and Clifford Murray at the scanning tunneling microscope instrument for low temperatures, with which they investigate the electrons in a box that form the Tomonaga-Luttinger liquid. Credit: Jeison Fischer

A team of physicists at the University of Cologne has, for the first time, seen a particularly exotic behaviour of electrons on an atomic scale. Electrons normally move almost freely through three-dimensional space. However, when they are forced to move in only one dimension, i.e., in a chain of atoms, they begin to act strangely. The Tomonaga-Luttinger liquid theory predicted this decades ago. In the lab, however, this phenomenon has so far only been shown indirectly.

An international research team led by Professor Dr. Thomas Michely at the University of Cologne's Institute of Physics II has now produced one-dimensional wires, allowing them to witness the behaviour of trapped electrons in 1-D with the scanning tunneling microscope. They report on their discovery in the journal *Physical Review X*.

"In 1950, Japanese physicist and later Nobel laureate Shin'ichiro Tomonaga imagined what electrons would do in a metal reduced to one dimension, that is, a chain of single atoms," said Michely. "The remarkable consequences that ensue when electrons can no longer avoid each other are particularly fascinating for us physicists. In a real 3-D crystal, their interaction is rather weak because they are quite free to move around in such an 'open' system. In 1-D, however, the electrons simply cannot avoid each other and begin to interact strongly."

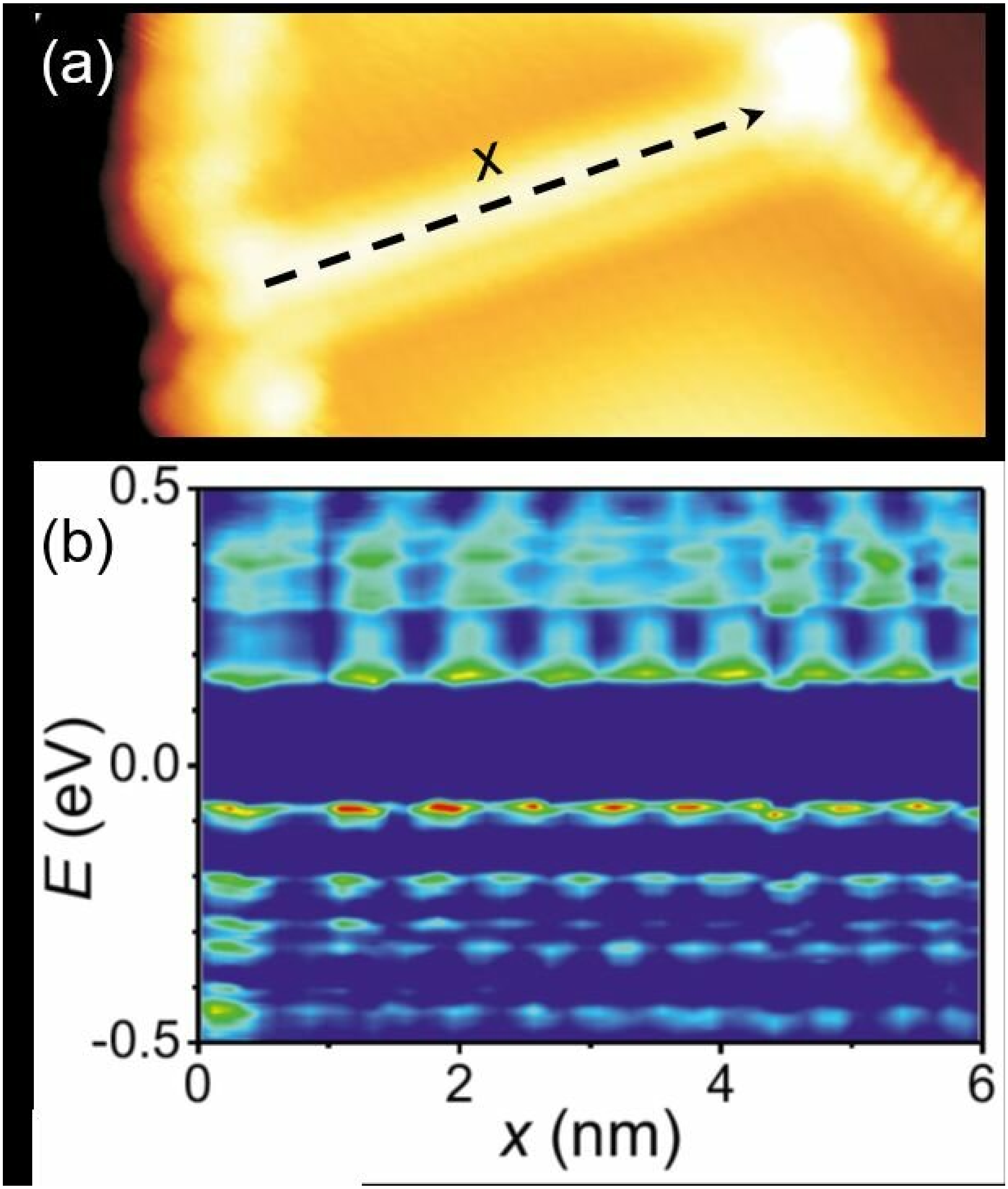
Electrons normally carry a charge and a spin, a quantum mechanical angular momentum. However, in 1-D, they stop behaving like normal electrons due to their strong interaction. Instead, they divide into two types of quasi-particles that have either spin or charge. Here electrons are better described as two independent waves: a spin density wave and a charge density wave. This phenomenon is called spin-charge separation and is the crux of the Tomonaga-Luttinger liquid theory, named after Tomonaga, who first formulated it in 1950, and the American theoretical physicist Joaquin Mazdak Luttinger, who developed the theory further.



The straight, almost horizontal line across the middle of the image shows a 1D wire, formed at the interface of two islands of molybdenum disulfide (MoS2). The wire is about 70 atoms long. The image or topograph was recorded with a scanning tunneling microscope at -268°C. (b) A scanning tunneling spectroscopy map of the same area shows a standing wave in the 1D wire. Credit: Wouter Jolie, Clifford Murray, Thomas Michely

To be able to see this spin-charge separation locally for the first time, the researchers from Cologne trapped the so-called Tomonaga-Luttinger liquid in wire of finite length, essentially locking it in a cage. Due to the wire's finite length, standing electron waves with discrete energies form, as required by quantum mechanics. This makes it possible to explore the limits of Luttinger and Tomonaga's theories with a precision unfathomable during their time.

The research group at the Institute of Physics II specializes in the production and exploration of 2-D materials such as graphene and monolayer molybdenum disulfide (MoS_2). They found that at the interface of two MoS_2 islands, one of which is the mirror image of the other, a metallic wire of atoms forms. The researchers were able to visualize the standing waves along the wire and their discrete energies with the help of their scanning tunneling microscope at a temperature of -268 degrees C (5 Kelvin).



The dashed black line across the middle of the image indicates the position of a 1D wire, formed at the interface of two islands of molybdenum disulfide (MoS2). The wire is about 20 atoms long. The image or topograph was recorded with a scanning tunneling microscope at -268°C. (b) A spectroscopic image of the standing spin- and charge-density waves along the wire, which have discrete energies. Credit: Wouter Jolie, Clifford Murray, Thomas Michely

To their surprise, the scientists discovered two sets of standing waves in the wire, while for 'normal' independent electrons, only one set would have been expected. The key to explaining the phenomenon came from the theoretical physicists around Professor Dr. Achim Rosch, also University of Cologne: The two sets of standing waves represent the spin density and the charge density waves, as Tomonaga and Luttinger predicted a half-century ago.

The scientists are now planning to investigate the behaviour of the electrons in one-dimensional cages even more closely. To test the limits of the Tomonaga-Luttinger liquid theory, they want to conduct new experiments at temperatures more than 10 times lower (0.3 degrees Kelvin) and in an improved "cage."

More information: Wouter Jolie et al, Tomonaga-Luttinger Liquid in a Box: Electrons Confined within MoS2 Mirror-Twin Boundaries, *Physical Review X* (2019). DOI: 10.1103/PhysRevX.9.011055

Provided by University of Cologne

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