Helical electron and nuclear spin order in quantum wires

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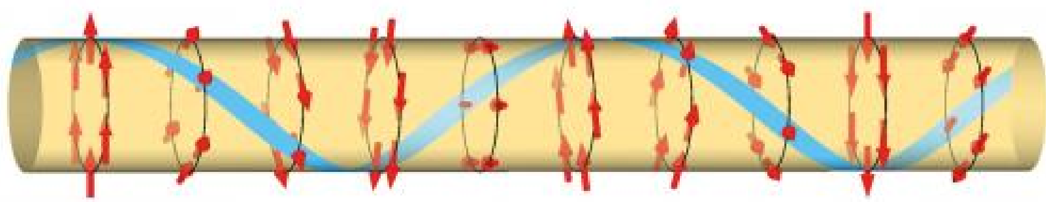

Helical order: The spins of the electrons and nuclei (red arrows) take the form of a helix rotating along the axis of the quantum wire. The blue ribbon is a guide to the eye for the helix. Credit: B. Braunecker, P. Simon, and D. Loss, Phys. Rev. B 80, 165119 (2009)

Physicists at the University of Basel have observed a spontaneous magnetic order of electron and nuclear spins in a quantum wire at temperatures of 0.1 kelvin. In the past, this was possible only at much lower temperatures, typically in the microkelvin range. The coupling of nuclei and electrons creates a new state of matter whereby a nuclear spin order arises at a much higher temperature. The results are consistent with a theoretical model developed in Basel a few years ago, as reported by the researchers in the scientific journal *Physical Review Letters*.

The researchers, led by Professor Dominik Zumbühl from the University of Basel's Department of Physics, used quantum wires made from the semiconductor gallium arsenide. These are one-dimensional structures in which the electrons can move in only one spatial direction.

At temperatures above 10 kelvin, the quantum wires exhibited universal, quantized conductance, suggesting that the electron spins were not ordered. However, when the researchers used liquid helium to cool the wires to a temperature below 100 millikelvin (0.1 kelvin), the electronic measurements showed a drop in conductance by a factor of two, which would suggest a collective orientation of the electron spin. This state also remained constant when the researchers cooled the sample to even lower temperatures, down to 10 millikelvin.

Electron-nuclear spin coupling

The results are exceptional because this is the first time that nuclear spin order has been measured at temperatures as high as 0.1 kelvin. Previously, spontaneous nuclear spin order was observed only at much lower temperatures, typically below 1 microkelvin; i.e. five orders of magnitude lower in temperature.

The reason why nuclear spin order is possible already at 0.1 kelvin is that the nuclei of the gallium and arsenic atoms in these quantum wires couple to the electrons, which themselves act back on the nuclear spins, which again interact with the electrons, and so on. This feedback mechanism strongly amplifies the interaction between the magnetic moments, thus creating the combined nuclear and electron spin magnetism. This order is further stabilized by the fact that the electrons in such quantum wires have strong mutual interactions, bumping into each other like railcars on a single track.

Helical electron and nuclear spin order

Interestingly, in the ordered state, the spins of the electrons and nuclei do not all point in the same direction. Instead, they take the form of a helix rotating along the quantum wire. This helical arrangement is predicted by a theoretical model described by Professor Daniel Loss and collaborators at the University of Basel in 2009. According to this model, the conductance drops by a factor of two in the presence of a nuclear spin helix. All other existing theories are incompatible with the data from this experiment.

A step closer to the development of quantum computers

The results of the experiment are important for fundamental research, but are also interesting for the development of quantum computers based on electron spin as a unit of information (proposed by Daniel Loss and David P. DiVincenzo in 1997). In order for electron spins to be used for computation, they must be kept stable for a long period. However, the difficulty of controlling nuclear spins presents a major source of error for the stability of electron spins.

The work of the Basel physicists opens up new avenues for mitigating these disruptive nuclear spin fluctuations: with the nuclear spin order achieved in the experiment, it may be possible to generate much more stable units of information in the quantum wires.

In addition, the nuclear spins can be controlled with electronic fields, which was not previously possible. By applying a voltage, the electrons are expelled from the semiconductor, which dissolves the electron-nucleus coupling and the helical order.

More information: C. P. Scheller, T.-M. Liu, G. Barak, A. Yacoby, L. N. Pfeiffer, K. W. West, and D. M. Zumbühl. "Possible Evidence for Helical Nuclear Spin Order in GaAs Quantum Wires." *Physical Review Letters*, published 10 February 2014 DOI: 10.1103/PhysRevLett.112.066801

B. Braunecker, P. Simon, and D. Loss. "Nuclear magnetism and electron order in interacting one-dimensional conductors." *Physical Review B*, published 16 October 2009 DOI: 10.1103/PhysRevB.80.165119

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