Beyond equilibrium: Scientists investigate Floquet Fermi liquids

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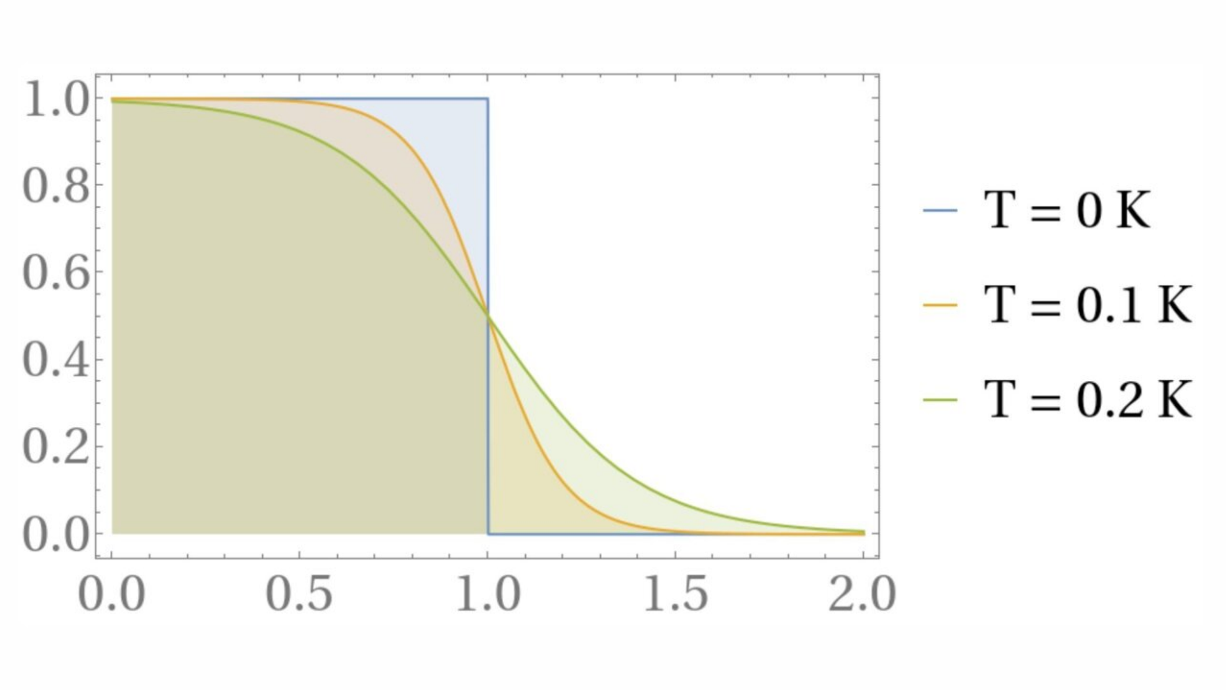

The Fermi-Dirac distribution at three different temperatures including absolute zero (blue line). Credit: Lauro B. Braz/Wikimedia Commons. https://commons.wikimedia.org/wiki/File:FermiDist.png

Researchers from Germany and Singapore have studied a non-equilibrium state of Fermi liquids called the Floquet Fermi liquid (FFL), which is formed when Fermi liquids are subjected to a periodic driving force and kept in contact with a fermionic bath.

Fermi liquids are quantum mechanical systems where fermions (like electrons in a metal) collectively behave predictably at absolute zero temperature, equivalent to 0 Kelvin or -273.15°C.

Fermions are one of the two fundamental classes of particles in the universe, and they obey Fermi-Dirac (FD) statistics. This describes their distribution when the system is in thermal equilibrium.

This is where we encounter an interesting quantum system called a Fermi liquid. The term "Fermi liquid" comes from the idea that similar to how a liquid flows freely and can change shape, the fermions in a Fermi liquid move relatively freely within the material due to their collective behavior.

For Fermi liquids, the behavior of fermions is characterized by a Fermi surface. The Fermi surface marks a separation in the Fermi liquid's energy states, indicating filled and empty energy states occupied by the fermions.

The researchers were motivated to understand what happens to electrons when a periodic driving force is applied to them while coupled with a fermionic heat bath.

The study, published in *Physical Review Letters*, was conducted by Dr. Li-kun Shi and Dr. Inti Sodemann Villadiego from the Universität Leipzig in Germany and Dr. Oles Matsyshyn and Dr. Justin C. W. Song from Nanyang Technological University in Singapore.

Phys.org spoke to the researchers, who cited a bigger question they were hoping to answer: Do photocurrents (currents resulting from illuminating a material) exist in pure bulk crystals (like metals and semiconductors) even when the material doesn't absorb light?

This question led them to the Floquet Fermi liquid.

The Floquet Fermi liquid

In a Fermi liquid, the energy states are continuous, with filled energy states below the Fermi energy and empty states above it. The Fermi energy level marks the energy level at which the probability of finding a fermion state transitions from nearly 100% occupied to nearly 0% occupied.

At absolute zero, all states up to the Fermi energy are filled and all the states above it are empty. This energy level effectively defines the Fermi surface in momentum space: a theoretical concept that helps to visualize what is happening inside matter.

When we apply a periodic force on a Fermi liquid, its normal energy levels are modified to Floquet bands, which are the modified energy levels of the Fermi liquid due to the driving force. Think of it as ripples forming on the surface of water.

The researchers now wanted to understand what happens if this system is driven far from equilibrium. To do so, the researchers introduced a fermionic bath, which is a reservoir or environment composed of fermions.

The researchers found that the resulting Fermi liquid is in a nonsteady trivial state, termed a Floquet Fermi liquid. They found that the resulting liquid did not follow the typical FD statistics.

FD staircase and nested surfaces

In this case, the FFL state is considered non-trivial because it emerges as a result of the interplay between periodic driving forces, fermionic interactions, and the surrounding environment.

Instead of a smooth transition in energy states, resembling a single jump typically observed in equilibrium FD distributions, the occupation of energy states showed a staircase-like pattern with multiple jumps.

"Each of these jumps leads to the appearance of a new Fermi surface (the Floquet Fermi surface)," explained Dr. Shi.

"The Floquet Fermi surfaces that appear in the FFL state, are enclosed inside each other," added Dr. Matsyshyn.

Think of it as layered Fermi surfaces, similar to a Russian nesting doll situation. These Floquent Fermi surfaces affect the overall system's behavior, giving rise to specific phenomena.

Beating patterns in quantum oscillations and controlling electronic behavior

Quantum oscillations are periodic changes in a material's properties, such as resistance, as a function of external parameters like magnetic field or pressure.

The researchers observed beating patterns in the quantum oscillations under the influence of an external magnetic field in the case of FFLs.

These patterns arise due to the interference between different-sized Floquet Fermi surfaces, which are nested within each other. The presence of multiple Floquet Fermi surfaces leads to constructive and destructive interference effects, resulting in oscillations in the resistance.

"The beating patterns in the quantum oscillations are consistent with observed microwave-induced resistance oscillations (MIRO) experiments in two-dimensional electron systems," explained Dr. Song.

They also provide a means to engineer and tailor the electronic behavior of the system.

Dr. Villadiego said, "The presence of multiple Fermi surfaces allows for greater control over the electronic properties of the system. By tuning the light frequency or intensity, we can manipulate the shape and separation of the Floquet Fermi surfaces."

This offers new possibilities for controlling electronic behavior.

Potential applications and insights

One of the most interesting lessons that the researchers point out is that the steady state shouldn't be seen, as Dr. Shi put it, as "a kind of boring, slightly hotter version of the equilibrium FD distribution."

"Instead, the system approaches a steady state, which has higher energy density than the equilibrium state, but this excess energy is not stored as some kind of featureless heat but instead leads to a very precise re-arrangement of the occupation of states that retains a precise quantum nature," said Dr. Matsyshyn.

The researchers also provided conditions or criteria to be met for realizing the FFL experimentally. They also listed several potential avenues for future work, one of which is the original question of photocurrent in bulk materials.

"Using our Floquet Fermi liquid state, one can rigorously demonstrate that it is indeed possible for even purely monochromatic light to drive a net rectified current, even when its frequency is inside the gap," said Dr.

Villadiego.

"These ideas could be relevant for the development of novel optoelectronic technologies such as light amplifiers, sensors, solar cells, and energy harvesting devices," concluded Dr. Song.

More information: Li-kun Shi et al, Floquet Fermi Liquid, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.132.146402. On *arXiv*: DOI: 10.48550/arxiv.2309.03268

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