New density waves uncovered in fermion liquids

In spite of their exotic name, fermion liquids are common in nature: metals, atomic nuclei and neutron stars are made out of strongly interacting particles named **fermions**, a group that includes quarks, electrons, protons and neutrons. Fermion particles obey the Pauli Exclusion Principle, which states that two identical fermions cannot occupy the same quantum state. The other class of quantum liquids, composed of **bosons** like gluons and photons, is well understood, but fermion liquids remain mysterious.

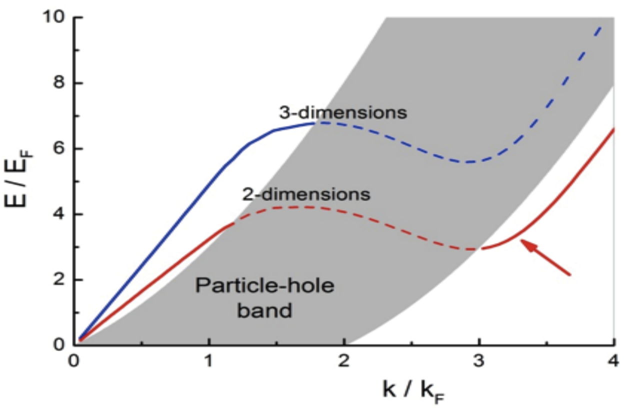

Fig. 1: Collective excitations in matter, where many particles oscillate together, are characterized by the dependence of their energy on the wave-vector k (=2π/wave-length). The linear behaviour seen at low wave-vectors is similar to what is observed for usual sound waves; in liquid ^{3}He, it corresponds to "collision-less sound", also called "zero-sound". At higher wave-vectors k, within the grey area shown in the figure, the sound waves are strongly damped, because they can create other excitations characteristic of a Fermi liquid, named "particle-hole excitations". In 3-dimensional Fermi liquids like bulk liquid ^{3}He, the zero-sound mode (blue curve) is always damped at high wave-vectors, and disappears. Here we show that in two-dimensional Fermi liquids, like a liquid Helium-3 film of atomic thickness, zero-sound (red curve) may, surprisingly, reappear beyond the particle-hole band as a well-defined collective mode (indicated by the red arrow). The mode displays a minimum in energy similar to the "roton" of liquid Helium-4.

A team of researchers from the Institut NEEL and the Institut Laue-Langevin (ILL) in Grenoble, Aalto University in Finland, Oak Ridge National Laboratory and SUNY University at Buffalo in the US, and Johannes Kepler University in Linz, Austria has carried out the first direct investigation of very short wave-length elementary excitations in a two-dimensional fermion liquid. The fluid under investigation consisted of Helium-3 atoms (the He^3 nucleus, a rare isotope of helium made up of two protons and one neutron, is a fermion). The atoms were deposited onto a graphite substrate, where they remain confined at very low temperatures, forming a remarkable two-dimensional Fermi liquid.

Since fermions cannot exist in the same state as each other, the quantum ground state (the minimum energy state, at the absolute zero of temperature) of a Fermi liquid is obtained by placing the particles in successive states of increasing energy, up to the "Fermi energy". Matter can be "excited" above its ground state; the corresponding quanta of energy are named "elementary excitations". The density excitations of a Fermi liquid, analogous to sound waves, are called plasmons (for charged particles) or "zero-sound" (for neutral particles).

The excitations can be created by a beam of neutrons, which also provides us with a privileged tool (neutron diffraction) to determine the excitations' energy and velocity. However, observing these excitations on just a one-atom-thick layer of helium-3 atoms is particularly difficult. For this reason, the experiment was done in the very high neutron fluxes available at the ILL reactor. Extremely low temperatures, less than a tenth of a degree above the absolute zero of temperature, are needed in order to clearly detect the elementary excitations of the liquid.

Much to our surprise, contrarily to the broad signal we had previously observed in bulk liquid helium-3, the two-dimensional liquid displayed sharp modes of oscillation. These unexpected experimental results lie beyond the scope of the standard theory, Landau's 1957 theory of Fermi liquids. They agree very well however with a new, Dynamical Many-Body theory developed by our co-workers in Linz and show that, in two-dimensions, zero-sound waves reappear at large momentum (short wave-lengths) beyond the "particle-hole band", the range in energy and momentum where they are strongly damped, see Fig. 1.

The discovery of short wave-length collective oscillations in Helium-3 is particularly interesting, as it is thought that they should be observable in other fermion liquids. For instance, short wave-length plasmons (or magnons, the corresponding magnetic density wave) could provide a mechanism for high temperature superconductivity. Understanding these properties is a challenge for modern physics.

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FURTHER READING

OBSERVATION OF A ROTON COLLECTIVE MODE IN A TWO-DIMENSIONAL FERMI LIQUID
H. Godfrin, M. Meschke, H-J. Lauter, A. Sultan, H. M. Böhm, E. Krotscheck and M. Panholzer
Nature 483, 576 (2012)