SUPERFLUIDS

Surprising entropy transport

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A superfluid is a macroscopic system with zero viscosity and where entropy is reversibly transported by waves. An unexpected transport phenomenon has now been observed between two superfluids, where irreversible entropy transport is enhanced by superfluidity.

When cooled down to very low temperatures, some fluids see their viscosity falling to exactly zero. This phenomenon, known as superfluidity, was first observed in liquid ^{4}He [1,2], and can be described by the "two-fluids model" introduced by Landau[3]. According to this model, a superfluid comprises a "normal" component with standard viscosity and entropy, and a "superfluid" component, with zero viscosity and almost zero entropy. Now, writing in *Nature Physics*, Philipp Fabritius and colleagues report new and unexpected entropy transport phenomena between two superfluid reservoirs of ultracold Fermi gases[4].

In bosonic ^{4}He, the superfluid component arises from Bose-Einstein condensation, where all atoms occupy the same energy state, namely the ground state of the macroscopic system. The picture is more complex for fermions since the Pauli exclusion principle prohibits the Bose-Einstein condensation of identical fermions. However, in two-component Fermi systems, with for example two different spin states, interactions between the two components can lead to pairing and a superfluid transition at low temperature. This phenomenon was first shown in ^{3}He, which becomes superfluid below 2.6 millikelvin, and it is also observable with ultracold Fermi gases.

Ultracold gases are composed of dilute samples of 10^4-10^7 atoms cooled down to temperatures in the nanokelvin range, where the quantum nature of the particles governs their behavior. They have been extensively studied over the past 30 years, and their equilibrium properties are now relatively well understood. In particular, the equation of state of strongly interacting Fermi gases has been measured accurately[6], and thermodynamic quantities such as the local temperature or the entropy can be extracted from absorption images providing the atomic density.

Ultracold gases also play a major role as quantum simulators, owing to the numerous degrees of freedom that are accessible, particularly in terms of energy landscape or interactions. For instance, using tailored optical potentials, it is possible to create a unique system composed of two reservoirs connected by a narrow channel[5], containing a strongly interacting two-component Fermi gas in the superfluid regime (see Fig. 1).
Fabritius and coworkers applied these tools to monitor the evolution of the thermodynamic entropy and number of particles in the two reservoirs.

The team created an imbalance in the number of atoms and/or entropy between the two reservoirs, for different channel geometries: a one-dimensional channel deep in the superfluid regime, or a two-dimensional channel with normal regions at the edges. The imbalance induced a flow of particles and/or entropy, in principle progressing towards an equilibrium steady state of the two reservoirs where the difference in the number of particles and the difference in entropy would both become zero.

In the case of an initial particle and entropy imbalance, the difference in entropy remained proportional to the difference in the number of particles throughout the relaxation to equilibrium. This behavior indicated an advective entropy transport, independent of the channel geometry used. In this far-from-equilibrium regime, the usual hydrodynamic description of entropy transport within a superfluid as reversible waves of “second sound” breakes down, leading to the emergence of a resistive entropy flow.

In the case of an initial nearly pure entropy imbalance, particle and entropy currents were generated, behaving in an advective manner at early times but becoming diffusive at long times. This diffusion process could be strongly suppressed by adjusting the geometry of the channel towards a one-dimensional configuration. Under such conditions, the system reached a non-equilibrium steady state, with non-vanishing particle and entropy imbalances between the reservoirs. Although this non-equilibrium steady state had been previously observed by the group[7], this is the first time that it has been reported in the superfluid regime of an ultracold Fermi gas.

These unexpected results were captured by a phenomenological model based on the formalism of generalized gradient dynamics — a generalization of Onsager’s theory for irreversible processes — that Fabritius and coworkers used to perform fits to both experiments. The analysis showed that nonlinear advection of the superfluid increased irreversible entropy transport. Nonetheless, a complete microscopic theory that fully encompasses this conceptually simple system remains to be developed.

The work by Fabritius et al. sheds light on our understanding of out-of-equilibrium and transport phenomena in quantum systems. This is an important topic whose exploration has been enabled by recent fundamental and technological advancements, and one that holds great significance for future applications of quantum technologies. The findings of this article could guide and inform more complete theoretical descriptions, further refining our grasp of non-equilibrium transport of superfluids.

References

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Competing interests

The author has no competing interests.

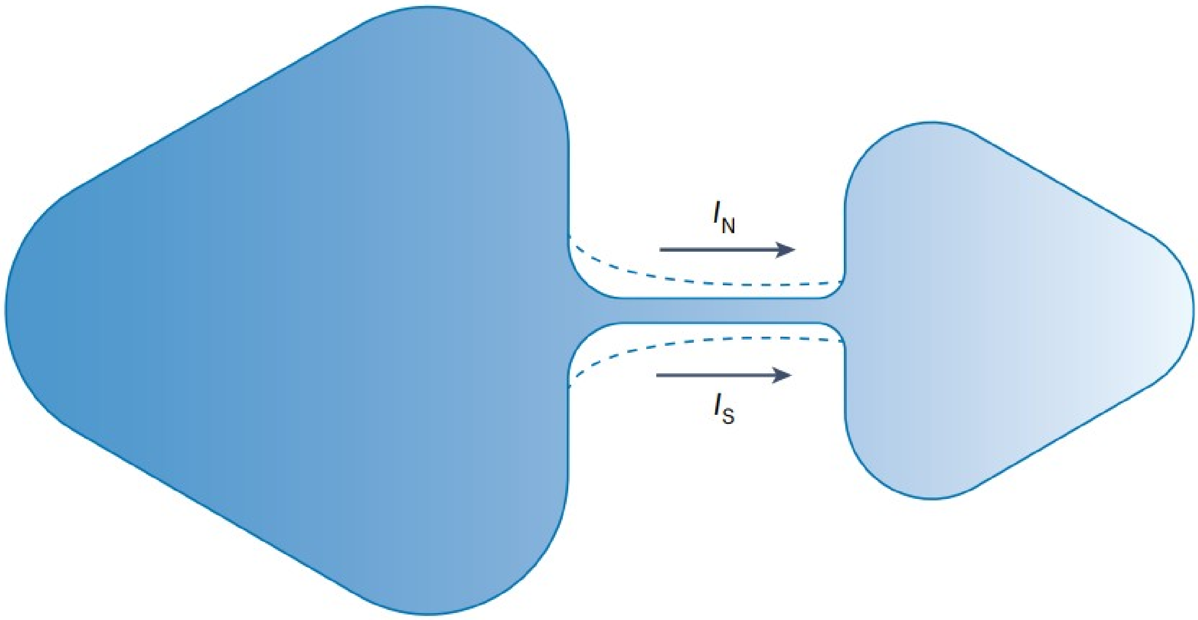

Fig.1: Entropy transport between two reservoirs of superfluid Fermi gases. The system is composed of two reservoirs, connected by a narrow channel. The geometry of the channel can be adjusted from 1D (solid lines) to 2D (dashed lines). A particle and/or entropy imbalance between the two reservoirs leads to particle (resp. entropy) current I_N (resp. I_S).