Moving Majorana Fermions Around

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Majorana fermions, also referred to as Majorana particles, are particles that are their own anti-particles. They were hypothesized by Ettore Majorana in 1937 and were considered only as a mathematical possibility in theoretical physics for more than 70 years. About ten years ago, however, it was realized that Majorana's concept is ubiquitous, and Majorana fermions are central to the work not only in neutrino physics (as Majorana originally proposed), super-symmetry and dark matter, but also for some exotic states of ordinary matter [1]. If realized and manipulated, their exotic behaviour – or, to put it in technical language, the non-abelian statistics – is anticipated to make Majorana fermions ideally suited to be fault-tolerant quantum bits of information process in a quantum computer [2]; if the unit information is carried non-locally by two Majorana fermions, the computer should be robust to any local de-coherence.

There are already a number of interesting proposals on how to use Majorana fermions to perform fundamental quantum gate operations [3], which inevitably involve the movement of Majorana fermions. Unfortunately, while the properties of Majorana fermions at rest are understood to some extent, their fate (i.e., existence) while moving/traveling is less well known. Writing in *Physical Review Letters* [4], Peng Zou, Xia-Ji Liu and Hui Hu from the Centre for Quantum and Optical Science at Swinburne University of Technology, Australia, and Joachim Brand from the Dodd-Walls Centre for Photonic and Quantum Technologies at Massey University, New Zealand, discuss what happens if one moves Majorana fermions around.

The underlying system considered in their work is an interacting ultracold atomic Fermi gas with both spin-orbit coupling and large Zeeman field, confined in one dimension (see Fig. 1, the upper panel). At incredibly low temperatures, i.e., a billionth of a degree Kelvin, the Fermi gas is expected to condense into a superfluid state. It behaves like a completely frictionless fluid with

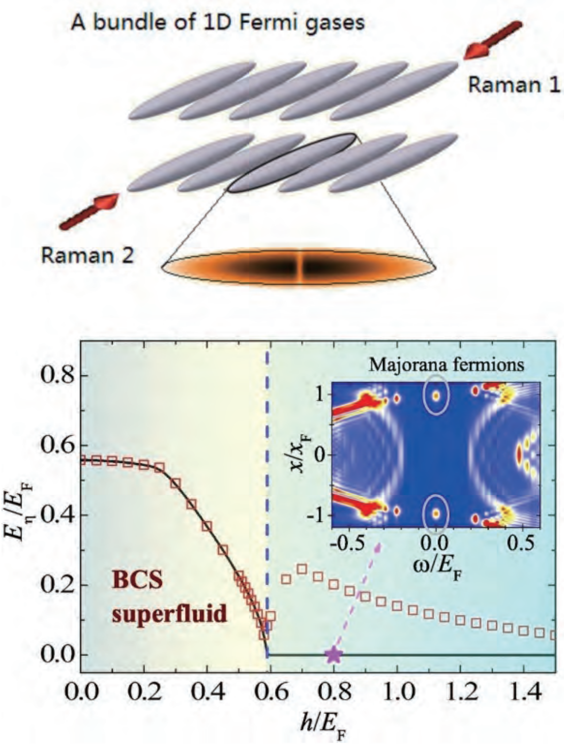

Fig. 1: Top: Sketch of an experimental configuration for creating Majorana fermions. A bundle of one-dimensional Fermi gases can be realized in cold-atom experiments. Bottom: In the presence of spin-orbit coupling (engineered via two Raman laser beams) and sufficiently large Zeeman field h, at low temperature a Fermi gas turns into a topological superfluid that supports Majorana fermions at the superfluid-normal interface, such as the two edges (see the inset, where $x = \pm x_F$), or at the soliton core (not shown).

additional non-trivial properties due to its topological nature. The groundwork for understanding topological materials was laid by the recipients of the 2016 Nobel Prize in Physics. In particular, the topological superfluid can host Majorana fermions at the boundaries where it fails to be superfluid (Fig. 1, the inset in the lower panel). As recently suggested in two works [5,6], Majorana fermions also appear at the position of stationary/dark solitons, where the Fermi gas locally becomes normal.

This suggestion is useful since in cold-atom experiments dark solitons can be generated by phase imprinting techniques. The problem now is, if one boosts the dark solitons to let them travel, what happens to the Majorana fermions located at the soliton core?

Dark solitons are generally characterized by a sharp phase jump π and a vanishing order parameter at the soliton core. When solitons are allowed to move, the phase jump decreases from π and the order parameter becomes nonzero. In other words, solitons can be *greyed* by their motion. This turn-to-grey feature is typical for non-topological solitons in superfluids, including dark solitons in atomic Bose-Einstein condensates (BECs) with and without optical lattices, as well as dark solitons in interacting Fermi gases at the crossover from BECs to Bardeen-Schrieffer-Cooper (BCS) superfluids. If this feature continues to hold in topological superfluids, then, one must anticipate that the soliton core is filled by superfluid when the solitons travel and therefore Majorana fermions should disappear at infinitely small velocity of travel, since they can exist only at the superfluid-normal interface. This would definitely be a disaster for potential applications of Majorana fermions, as they are destroyed immediately by any movement/manipulation.

Luckily, in their work, Peng *et al.* found that a finite velocity of travel does not grey the soliton in topological superfluids [4]. Both time-independent calculations (in the co-moving frame) and time-dependent simulations (in the laboratory frame) reveal a universal, constant π phase jump across the soliton, irrespective of the velocity of travel (see Fig. 2, the top right figure and the inset in the bottom figure). Correspondingly, Majorana fermions at the soliton core survive up to a threshold velocity, which is smaller than the Landau critical velocity, at which the soliton decays. These unusual properties of the traveling soliton in topological superfluids (referred to as a *Majorana soliton* in the work) may provide a new way to manipulate Majorana fermions for fault-tolerant topological quantum computations. Further calculations and simulations in different setups, such as two-dimensional spin-orbit coupled Fermi superfluids and *p*-wave Fermi superfluids, also confirm the existence of Majorana solitons [4], indicating that it is indeed a *universal* state of matter ensured by the nontrivial topological properties of topological superfluids.

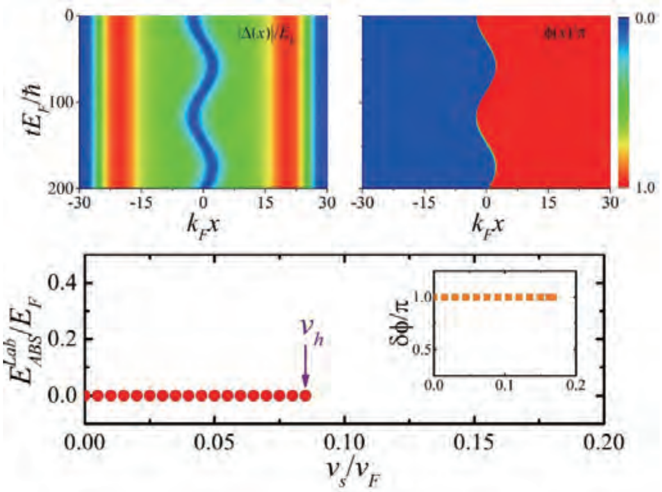

Fig. 2: Upper panel: time evolutions of the magnitude (left) and the phase (right) of the order parameter for a Majorana soliton oscillating in a trapped topological superfluid. Lower panel: The energy of the lowest-lying vortex state of the Majorana soliton (i.e., the energy of Majorana fermions) as a function of the traveling velocity. The inset shows the phase jump of the Majorana fermions at different traveling velocities.

References

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