Nature Reviews Materials | https://doi.org/10.1038/s41578-019-0082-7 | Published online 21 January 2019

Credit: Getty images/Nacivet

MAJORANA FERMIONS

Into the vortex

Majorana fermions — particles that are their own antiparticles — have never been observed in the context of high-energy physics in which they were originally proposed, but have been realized as quasiparticles in condensed-matter systems. Being able to study such quasiparticles in different materials is useful to fully characterize them and to learn how to manipulate them: an Fe-based superconductor can now be added to the list of systems in which Majorana quasiparticles have been observed, as Dong-Lai Feng, Tong Zhang, Zhi-Ping Yin and colleagues report in *Physical Review X*.

Majorana bound states, also called Majorana zero modes (MZMs), are attracting considerable attention because they do not behave as fermions or bosons — the two types of elementary particles that make up matter and light — but as a special type of particle, anyons. Anyons only exist in 2D systems and have the exotic ability to encode quantum information. MZMs are thus potentially useful as qubits for quantum computers. Because MZMs are topological in nature and thus robust against perturbations, a quantum computer based on them would have the advantage of being error protected.

MZMs have been realized in several materials platforms, including vortices in topological superconductors; however, much remains to be done in the field. In particular, to be used as qubits, MZMs need to be exchanged in space, an operation called braiding that has not been demonstrated yet.

Although MZMs in other materials systems, such as superconductor–semiconductor heterostructures and magnetic atomic chains, have been studied in more depth, investigating MZMs in vortex cores in superconductors has the advantage that the quasiparticles can be directly accessed using a scanning tunnelling microscope, allowing a detailed analysis of their properties, and that vortices can be moved around, which might be useful for braiding operations. In these systems it's challenging to obtain clear Majorana signatures because impurities are often present and there are non-topological electronic states with spectroscopic signatures that tend to overlap with those of MZMs. However, the observation of MZMs in vortex cores has been recently achieved in the Fe-based superconductor FeTe$_{1-x}$Se$_x$.

Feng and colleagues now demonstrate that the superconducting material (Li,Fe)OHFeSe also hosts MZMs. The ideal material to realize MZMs in vortex cores has to satisfy four conditions: have a small Fermi energy, so that MZMs are well separated from the non-topological states; have as few impurities as possible; present a high superconducting critical temperature, to avoid the need for manipulation in ultracold conditions; and exhibit topological surface states. "There are not many superconductors that match all these conditions," says Feng. "We knew that (Li,Fe)OHFeSe matches the first three. The group of Xiaoli Dong and Zhongxian Zhao made some high-quality thick films, and we started looking for, and found, topological surface states with angle-resolved photoemission spectroscopy, while Zhiping Ying proved theoretically that such states should indeed be present." The advantages of this material with respect to the FeTe$_{1-x}$Se$_x$ samples studied previously include a higher superconducting critical temperature (42 K as opposed to 14.5 K), MZMs surviving at higher magnetic fields without disturbing each other and a stoichiometric composition of the FeSe layers, which improves the sample quality — a key feature, because if a vortex is pinned by a defect, the superconductivity is suppressed and an MZM cannot be obtained.

The next steps will include a more detailed characterization of the MZMs in the vortex cores, studying their spin polarization, quantized conductance and interactions with impurities and with each other. Then, the priority will be to move the vortices and try to achieve braiding, which will certainly be challenging. "We have talked with a few theorists, and we still have no scheme to detect the encoding of information by switching two or more vortices," explains Feng. "Another problem is the timing: it takes time to move a vortex mechanically, so the question arises of whether it exceeds the decoherence time and if the encoded information would be disturbed. The only way to have an answer is to try to do it."

Giulia Pacchioni

ORIGINAL ARTICLE Liu, Q. et al. Robust and clean Majorana zero mode in the vortex core of high-temperature superconductor (Li$_{0.84}$Fe$_{0.16}$)OHFeSe. *Phys. Rev. X*, **8**, 041056 (2018)
FURTHER READING Wang, D. et al. Evidence for Majorana bound states in an iron-based superconductor. *Science* **362**, 333–335 (2018)