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Majorana modes in artificial atomic chains: a new hope

1. **Topological Shiba bands in artificial spin chains on superconductors**
   Authors: L. Schneider, P. Beck, T. Posske, D. Crawford, E. Mascot, S. Rachel, R. Wiesendanger, J. Wiebe
   Nat. Phys. (2021)
2. **Controlled length-dependent interaction of Majorana modes in Yu-Shiba-Rusinov chains**
   Authors: L. Schneider, P. Beck, J. Neuhaus-Steinmetz, T. Posske, J. Wiebe, R. Wiesendanger
   arXiv:2104.11503

Recommended with a Commentary by Anton Akhmerov, Kavli Institute of Nanoscience, Delft University of Technology

Contrary to the impression a superficial reading of these manuscripts may give, I am going to explain why the two highlighted works demonstrate the absence of Majorana modes. At the same time, I believe that these works resolve a long-standing limitation of the field of atomic structures on metal surfaces and present data of unparalleled quality. Also before I delve into the details, I have to make a disclaimer: while I am an expert on Majorana modes, I am certainly an outsider to scanning tunneling microscopy, and my perspective on that field is likely limited.

The main goal of the search reported in the two highlighted works is the creation of Majorana modes. I will not attempt to give justice to Majorana modes in a few sentences, instead leaving the reader with just a definition: Majorana modes are zero energy "half-fermions"—particles with non-Abelian exchange statistics and a potential building block of a protected quantum computer. The approach chosen by the authors—and by their predecessors—is to deposit a chain of magnetic atoms on top of a superconductor. A single magnetic atom, due to its local breaking of time-reversal symmetry, forms fermionic orbitals, known as Shiba states, within the superconducting gap. Once one creates a chain of multiple overlapping Shiba states, these states couple and create Majorana modes at the edges, provided that:

- the total number of partially filled spin-polarized modes is odd,
- the system is gapped, which may require either helical magnetic order or spin-orbit interaction.

Using such atomic chain-based Majorana modes for quantum computation or topological many-body physics remains an open conceptual challenge: it requires Coulomb interaction of multiple isolated Majoranas—something that is usually possible using superconducting circuits on micron rather than atomic scales. Despite this complication, already creating Majoranas in a Shiba chain as well as any other system is an exciting and worthy research goal by itself.

With this background in mind, let us examine the new findings of the two works. The authors explore a new material combination: Mn atoms on top of Nb superconductor. Furthermore, the atoms are arranged into a chain by using a scanning tunneling microscope (STM) tip for picking them up and positioning them one by one. Compared to the more easily scalable but less controlled catalytic growth of atomic chains, this allows to create chains with length controlled down to a single atom, align the chain along any crystallographic direction, or arrange atoms into a more complex structure than a simple chain. By combining the precise control over the chain size with the enhanced energy resolution accommodated by a superconducting STM tip, the authors identify two Shiba orbitals: α-orbital and δ-orbital that form bands once atoms are appropriately arranged into a chain. Both of the bands are spin-polarized, and therefore suitable to host Majorana modes. The dispersions of the bands reveal that the α-band has a sizeable gap of about $0.2\,\text{meV}$, the δ-band is gapless within the experimental resolution. Furthermore, by varying the chain length, the authors observe nearly perfect particle-in-a-box oscillations of both the α-band and the δ-band energies, and even find the specific lengths of 14 and 16 Mn atoms when the gapless δ-band has a zero-energy state. Unfortunately, these observations prove that the chain is incompatible with Majorana modes:

- it has two spin-resolved bands in the first place (and it would need to have an odd number)
- one of these two bands is gapless.

Still, despite the lack of Majorana modes, I consider these two works the most important achievement in the field of Shiba chains up to date. Examining the data presented in preceding works, we could only conclude that Shiba bands play some role. While there were multiple observations of zero energy peaks in the tunneling density of states near the chain edges, the Shiba chain itself had no superconducting gap, leaving only the community optimism as a justification for calling these zero energy peaks 'Majorana modes'. Up to now, we were unable to answer any of the critical questions required for understanding what is happening in these systems. We had no idea how many Shiba bands are there in the superconducting gap. There was no evidence allowing to confirm that the disorder in the atomic chains is sufficiently low to even hope to obtain Majorana modes. Finally, there was no observation of the dispersion relation of the Shiba bands. The new experiments demonstrate that it is possible to confidently answer these questions at least in a specific system, and I cannot overstate the importance of having a complex material system that *just makes sense*.

Given the new observations, it is natural to wonder what are the possible next steps. Can we utilize what we learned from these experiments to engineer Majoranas? I believe that there is indeed a clear path forward: because Majoranas require a single partially filled band, the desired topological chain has to have the δ-band gapped out and emptied. Because the combination of Mn atoms and the Nb superconductor allows single-atom manipulation, engineering a more complex unit cell is within reach. It is also likely that a chain with a more complicated unit cell—for example, dimerized by introducing gaps between neighboring pairs of atoms—would gap out the δ-band. An argument in favor of staggering the interatomic distances is also the Fermi wavelength of the δ-band, which is measured to be very close to twice the unit cell size. I am, however, confident that the applications of the new platform extend much broader than Majoranas in Shiba chains. Thanks to our precise knowledge of what is happening with each Shiba orbital and the ability to controllably couple them, I expect that this platform can be exploited to engineer many more electronic band structures, especially if one turns to the 2D systems, where the opportunities are essentially endless.