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Visualizing Majorana fermions in a chain of magnetic atoms on a superconductor

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Visualizing Majorana fermions in a chain of magnetic atoms on a superconductor

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Abstract

A chain of magnetic atoms on the surface of a superconductor provides a versatile platform for realizing a one-dimensional topological superconductivity phase with edge-bounded Majorana fermions zero modes. This platform lends itself to spatial resolved measurements with scanning tunneling microscope (STM) that enables direct visualization of the presence of a localized Majorana zero mode. Experiments on self-assembled chains of Fe atoms on the surface of Pb show that such a system can be experimentally fabricated and studied using various high-resolution STM measurement techniques. Spatial and energy resolved STM experiments provide strong evidence for Majorana bound states that emerge due to the combination of Fe’s ferromagnetism and spin–orbit coupling of the superconducting Pb substrate. These studies provide a roadmap for optimizing topological superconductivity in this one-dimensional platform and its extension to realize chiral two-dimensional superconductors.

Keywords: topological quantum states, topological superconductors, Majorana fermions

Topological forms of electronic matter are identified by their novel boundary states. The recently discovered electronic states with a Dirac spectrum at the boundary of two or three-dimensional topological insulators are examples of such edge states that indicate the formation of a novel bulk topological phase [1, 2]. Although signatures of these boundary states were first detected by using electrical transport [3] and angle-resolved photoemission spectroscopy [4], scanning tunneling microscopy (STM) studies have provided a unique perspective of their properties. The spatially resolved capability of the STM combined with its high energy resolution spectroscopic mapping has not only allowed for direct visualization of these states, but has also been used to demonstrate the absence of backscattering for the boundary state of topological insulators [5–8]. These previous studies demonstrate the unique capabilities of STM techniques to probe topological phases of electrons and their associated boundary modes.

More recently, there has been a focus on finding topological superconducting phases that host Majorana fermions at their boundaries [9, 10]. Similar to free Majorana fermions proposed as elementary particles [11, 12], the condensed matter Majorana quasi-particles (MQPs) have the intriguing property of being their own antiparticles that obey non-Abelian statistics. In an ideal setting, the Hilbert space for such an edge-bounded MQP is non-local, hence any change to the MQP quantum state requires simultaneous interaction on pairs of MQPs at both ends of the 1D system—making MQPs immune to local perturbations. This property may make it possible to build topologically protected qubits using pairs of MQPs at the edge of a 1D topological superconductor [13].

One approach to the realization of topological superconductors was introduced by combining the proximity effect of a conventional superconductor and the helical surface or edge states of a topological insulator [14]. The spin–momentum locking of these states requires their pairing to have an odd symmetry with respect to momentum and hence p-wave in nature. While a superconducting proximity effect has been observed in these surface or edge states (see for example [15]), direct evidence for p-wave pairing and MQPs in such edge modes is currently lacking. Following this approach, it was realized that the combination of spin–orbit coupling with Zeeman energy in semiconductor nanowires, which are in proximity to a BCS superconductor, could also be used to engineer the desired band structure for topological superconductivity [16, 17]. Subsequent experiments with
semiconductor nanowires have shown zero-bias peak (ZBP) in tunneling measurements of such structures, which is consistent with the presence of MQPs [18–22]. However, the observation of ZBPs in such structures can also be due to the Kondo effect or caused by the presence of disorder [23, 24]. Another important shortcoming of the device-based searches for MQPs is the lack of spatially resolved measurements to ensure that the ZBPs that have been interpreted as evidence for MQPs are in fact associated with the boundaries of the system.

Recently, we have proposed chains of magnetic atoms on the surface of a superconductor as a new platform for the realization of a one-dimensional topological superconductor that can lend itself to high-resolution STM measurements (figure 1(a)) [25–27]. This approach followed earlier proposals in which magnetic textures were considered as an alternate approach to emulate spin–orbit coupling [28–30]. Model calculations for chains of magnetic Shiba impurities on a superconductor show that topological superconductivity in this platform can be realized with the impurities having either a ferromagnetic or helical spin texture, the former relying on spin–orbit coupling to induce p-wave pairing (figures 1(B) and (C)) [25, 27, 31, 32]. The appearance of topological superconductivity in such a model can be related to the band of Shiba states induced by magnetic impurities in a superconductor. For sufficiently strong exchange interaction and hopping, the electrons and hole Shiba bands near the Fermi level can overlap, thus opening up a topologically gapped state. The p-wave nature of pairings can be understood as onsite pairing is forbidden by the large exchange interaction at the impurity site, while the combination with a hopping term (in the presence of a spin texture or spin–orbit coupling) results in nearest-neighbor p-wave pairing.

An alternative approach to understanding the phase diagram for topological superconductivity in ferromagnetic chains of atoms on a superconductor is to consider the normal state band structure of such magnetic chains [26, 27]. For transition metal chains, the large exchange interaction (2 eV) would result in a fully occupied majority band, along with states near the chemical potential being due to a minority band (figure 1(B)). Proximity to a superconductor with strong spin–orbit coupling can induce superconductivity in such a band structure. More importantly, the low symmetry of this structure results in a band structure that almost always has an odd number of band crossings at the Fermi level, making such proximity-induced superconductivity guaranteed to be topological [26, 27]. The absence of the need to fine-tune the chemical potential to achieve topological conditions is an important advantage of a magnetic atomic chain platform over a semiconductor nanowire platform. Another advantage is that the Zeeman interaction is introduced locally from an atomic chain that does not suppress superconductivity away from the chain. The theoretical models described so far predict a induced p-wave pairing on the atomic chains with a strength $\Delta_p = \alpha \Delta_3 / J$, where $\alpha$ is the strength of spin–orbit coupling, $\Delta_3$ is the host s-wave gap, and $J$ is the strength of the exchange interaction.

To realize this proposed platform for topological superconductivity, we have carried out experiments on chains made of Fe atoms formed on the surface of Pb(110), which is a BCS superconductor with a large bulk spin–orbit interaction [26]. The Fe chains are created by the evaporation of Fe, followed by an annealing of the substrate that results in self-assembly of the Fe atoms into chains that form due to the anisotropic structure of the Pb surface (figure 2(A)). The chains appear to grow out of Fe islands on the surface that often remain in the middle of the chains. Detailed STM measurements and their comparison to density functional...
theory (DFT) calculations show the most likely structure of the Fe chains is that of a triple zigzag structure, which is partially submerged in between the rows of atoms on the Pb (110) surface (see [26]). The chains’ lattice structure appears to be incommensurate with the underlying Pb crystal, making the structure of these chains somewhat spatially non-uniform (figure 2(B)). The Pb substrate is strained to accommodate the zigzag. The Fe atoms appear to make a similar zigzag structure to that they would make in bulk body centered cubic structure along the diagonal direction. The DFT calculations of the chains’ magnetic properties show the ferromagnetic ground state to be the most likely ground state [26].

Studying the electronic and magnetic structure of the zigzag Fe chains on Pb using various STM techniques, we have found them to have properties that are consistent with those required for the formation of a topological superconducting phase. Tunneling between in situ prepared ferromagnetic tips and Fe chains shows a magnetic field dependence that is characteristic of tunneling between two ferromagnets, one of which can be switched with the application of the field (figures 2(C) and (D)). Remarkably, tunneling with the same tips on the Pb substrate also reveals a magnetic field dependence and the signatures associated with reversal of the tip’s magnetization with an external magnetic field (figure 2(D)). The shape of the tunneling magnetoresistance between ferromagnetic tips and the Pb substrate is very similar to those previously reported in semiconductor tunnel junctions where spin–orbit coupling influences the spin-polarized tunneling process [33]. The combinations of measurements on the chains and the substrate confirmed that the electrons on or near the chain experience both ferromagnetism from the chain and spin–orbit coupling of the substrate’s surface. Further information about the electronic properties of the chains obtained through spectroscopy measurements shows the electronic density of states (DOS) of such chains to have a double-peak structure near the Fermi level (figure 2(E)). Detailed calculations of the electronic structure of the suspended triple Fe chains with a tight-binding model, or DFT calculations (see [26, 27]) of similar chains submerged in Pb, reproduce this double-peak structure and attribute it to a structural band splitting of the spin-minority band near the Fermi level. Such a band splitting in the calculations is consistent with an odd number of band crossings at the Fermi energy for such chains, which is another indication that the experimental system of Fe/Pb(110) has favorable properties for realization of a topological superconducting phase.

To search for the presence of edge bounded MQPs on the Fe chains, we have carried out various spectroscopic measurements at 1.4 K. These measurements show that the BCS DOS of the Pb substrate to be modified in the vicinity of the Fe chains on the atomic scale. Energy resolved spectroscopic measurements in the middle of the chain (away from the disordered island structures from which the chains grow) show features consistent with Shiba states at energies within the Pb’s gap at around 1 meV (figures 3(A)–(E)). The electron–hole asymmetry of the intensity of these features is caused by the potential difference between the Fe chain and the Pb surface, which is indicated by the charge transfer between the substrate and chains in our DFT calculations. The incommensurability of the chain structure with the underlying Pb substrate results in a modulation of Shiba state features observed in the spectroscopic measurements along the chains.

Direct signatures for the MQPs are found in both STM spectra and conductance maps near the ends of the Fe chains. A pronounced ZBP, with a width that is consistent with thermal broadening (at 1.4 K), is detected within 10–20 Å from the end of the chains in the spectroscopic measurements (figures 3(A)–(E)). Similarly, energy resolved conductance maps show an atomically localized region of pronounced signal at zero bias near the end of the chains (figure 3(F)). Both of these features are consistent with the formation of MQPs at the edge of a 1D topological superconductor. A higher resolution data set of another Fe chain shown in figure 4 shows that the ZBP is clearly distinct at all positions along the chain from that of the Shiba state that are higher energies. Although Shiba states are influenced by proximity to the end of the chain, they do not evolve into the ZBP that is expected from the formation of a MQP.

A critical test for MQPs interpretation of the ZBP is to show that it is not caused by the Kondo effect or other phenomena that is unrelated to superconductivity [23, 24]. If the ZBPs reported here do not originate from MQPs but from the Kondo effect, they would persist beyond the superconductor-normal metal transition. To check this possibility, we have also performed measurements in a weak magnetic field of 100 mT at which superconductivity in Pb is suppressed. The comparison between measurements at zero field and 100 mT measurements on the same chain is shown in figure 4. As soon as superconductivity is suppressed, all the states, including ZBPs at the chain’s ends, disappear and the spectrum becomes featureless. Since the ZBPs are observed only in the superconducting state, we conclude that our peaks are not related to Kondo physics. This experimental check not only rules out Kondo physics in our system but also makes unlikely other scenarios, such as weak (anti-) localization in which superconductivity is not directly required for the formation of this ZBP [24]. Although we have found some long Fe chains (10–30% of chains examined to date) do not show clear evidence for a ZBP at their ends, the ZBP and other features described here have been reproduced on more than 30 Fe chains so far.

Search for evidence of a p-wave gap on the chain has been carried out using spectroscopic measurements with a superconducting tip, which because of the BCS singularity in its DOS can provide high-energy resolution. These measurements show an additional energy scale in the spectra at around 150–200 μeV, which appears to be on the energy scale anticipated from theoretical estimates for the p-wave gap for this system. However, more precise study of the p-wave gap requires future lower temperatures and higher energy resolution measurements. At 1.4 K there appears to be background DOS on the Fe chains that is either due to thermal broadening or the presence of ungapped channels. In this experiment so far, the MQPs appear to coexist with the background DOS in the bulk of the chain, which is
Figure 2. (A) Topograph of the Pb (110) surface after growth of Fe showing Fe islands and chains indicated by white arrows and atomically clean terraces of Pb (regions with the same color) with size exceeding 1000 Å. Upper-left insets show images of several atomic Fe chains and islands from which they grow (scale bar corresponds to 50 Å). (B) Fine-scale topograph. The scale bar corresponds to 20 Å. The arrow indicate evidence for strain in the Pb substrate. (C) Topography of the chain is colorized by the conductance at ±1 T from low conductance (dark blue) to high conductance (dark red). (D) Spatially averaged (over a region of about 100 Å) STM tunneling conductance as a function of an out-of-plane applied magnetic field H on the atomic chain and the substrate measured with a spin-polarized bulk Cr/Fe tip (inset shows a schematic of the measurement, set point $V = 30$ mV, $I = 0.75$ nA). Tip switching occurs at ±0.25 T. (E) STM point spectra of the atomic chain and the substrate. (From [26] with permission).
contributing to its visibility and might be influencing its energy width.

The experimental observation of strong spatial localization of ZBPs associated with MQPs in Fe chains has been the subject of considerable interest [27, 34–36]. Naively, the small estimated p-wave energy gap for this system would imply that the associated p-wave coherence length ($\hbar v_F/\Delta_P$) or the associated localization length of the MQPs would be very large as compared to the length of chains (longest at 200–300 Å) [36]. However, these considerations ignore the fact that this system is not strictly 1D, as it is essentially embedded into the surface of a thick superconducting crystal. Similar short length scale behavior appears to describe previous STM measurements of Shiba states for single magnetic impurities on the surface of the superconductor [37]. Recently, numerical calculations for spatial localization of MQPs for zigzag chains of Fe atoms on the surface of a Pb crystal show faster decay of the MQPs signature as compared to strictly 1D models and with similar localization to that observed in experiments [27]. Furthermore, other theoretical work suggests that this short length scale is associated with the avoided crossing between the Shiba band within the

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**Figure 3.** (A) STM spectra measured on the atomic chain at locations corresponding to those indicated in panels (B) and (C). For clarity, the spectra are offset by 100 nS. The red spectrum shows the ZBPs at one end of the chain. The gray trace measured on the Pb substrate can be fit using thermally broadened BCS DOS (dashed gray line, fit parameters $\Delta_s = 1.36$ meV, $T = 1.45$ K). (B), (C) Zoom-in topography of the upper end (B) and lower end (C) of the chain and corresponding locations for spectra marked [1–7]. (D), (E) Spectra measured at marked location as in (B) and (C). (F) Spatial and energy-resolved conductance maps of another Fe atomic chain close to its end, which shows similar features in point spectra as in (A). Conductance map at zero bias (middle panel) shows increased conductance close to the end of the chain. Scale bar corresponds to 10 Å. We note that the localization length of the MQPs observed here is a factor of 10 or smaller in length than the distance from the end to the islands that form in the middle of the chains. (From [26] with permission).
superconductor’s gap and band of d states originating from the chain of Fe atoms [35]. In this picture, the low energy electronic states relevant to the MQPs localization disperse rather weakly—reminiscent of a band of heavy quasi-particles created by hybridization of orbitals and a band with a broader dispersion. This composite model of a Shiba state and d-orbital appears to also reproduce the experimentally observed short length scale [35].

To better understand the background in the DOS, and to show that MQPs are not split in energy because of coupling through the chain STM studies at lower temperatures will be required. Potential avenues for improving the magnetic chains’ platform are also emerging from theoretical considerations of this system [27]. The modeling studies show that the straight chains, as opposed to the zigzag chains measured so far in the experiments, have a phase diagram with larger topological regions. They also suggest that to enhance the size of the p-wave gap in our chains, triple Fe chains may not be ideal, because of their large J. Other transition metals’ atoms, or even magnetic atoms with f-orbitals, that have a weaker exchange interaction with the superconductor, may provide a better opportunity to enhance topological superconductivity on these chains.

Overall, the platform of magnetic atoms on the surface of superconductor provides several unique opportunities to engineer exotic superconducting phases. In a 1D optimization of this system, by choosing different magnetic atoms, even ones with helical spin texture, may provide important new ways to extend the studies described here. Finally, recent studies show that extending this platform to two-dimensions using a 2D array of magnetic atoms on the surface of a superconductor with strong spin–orbit coupling can stabilize chiral two-dimensional p-wave superconducting phase [38, 39]. STM studies can also of such islands be used to provide direct evidence for propagating MQP at the edge of this proposed novel superconducting phase.

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