Majorana zero modes (MZMs) are non-Abelian anyons that emerge as localized zero-dimensional end states of 1D topological superconductors. Unlike fermions and bosons, anyons are quasiparticles, and interchanging two identical anyons modifies the quantum-mechanical ground state of the host system. The ground state of a system with non-Abelian properties has multiple degenerate configurations, which are not uniquely specified by the spatial locations of the MZMs. Adiabatic ‘braiding’ of MZMs provides the means to perform qubit operations within the subspace of the degenerate quantum state manifold, and the ‘fusion’ of MZMs can be used as a means of qubit readout. In qubits based on MZMs, the quantum information is stored non-locally and protected by a topological energy gap of the system, therefore such qubits would be more resilient to local perturbations that can cause quantum decoherence.

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A key experimental tool is scanning tunnelling microscopy (STM). STM experiments combine the ability to visualize the atomic structure of condensed matter systems with the capability of studying their electronic structure with high resolution in both energy and space.

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Despite the tremendous progress and achievements in research on topological superconductivity, scepticism exists in the research community about the interpretation of localized ZPBs as signatures of MZMs. The debate on possible trivial origins of the observed ZPBs and lack of consistency of experimental results in some studies emphasizes the key question of how to experimentally distinguish topological ZPBs from trivial ZPBs that imitate the MZM but are of different origin.

In this Review, we survey the state of research on topological superconductivity and MZMs using STM experiments. We describe the pivotal role of STMs in exploring
Majorana modes in 1D chains

Kitaev model for topological superconductivity in spinless 1D systems. The idea of a 1D topological superconductor hosting MZMs was introduced in a simple and elegant model proposed by Alexei Kitaev in 2001 [REF 1]. It describes spinless electrons hopping on a 1D lattice in the presence of a nearest-neighbour $p$-wave superconducting pairing interaction. Depending on the model parameters, the system exhibits two distinct ground states [BOX 1], which can be best understood by decomposing the electronic states into pairs of MZMs. In the trivial regime, the system simply consists of ordinary fermions — that is, pairs of MZMs — located on each lattice site. In the topological regime, pairing between the MZMs of neighbouring sites results in an unpaired localized MZM at the opposite ends of the chain. The emergence of these edge excitations at zero-energy cost represents a distinct localized signature of MZM that can be detected with the STM. In these experiments, this signature would appear in the measured differential tunnel conductance ($dI/dV$) spectrum as a peak at zero bias voltage, the so-called ZBP. We note that the bias-voltage-dependent $dI/dV$ spectrum is proportional to the energy-dependent local density of states of the sample, where energy ($E$) maps to bias voltage ($V$) as $E = eV$.

The main challenge for realizing the Kitaev model is to make electrons behave as spinless fermions and to induce superconducting pairing among them. A fully spin-polarized system that breaks time-reversal symmetry (TRS) can be considered as having spinless electrons; however, intrinsic pairing instability between such spin-polarized electrons, known as $p$-wave pairing, has been elusive in nature. Various concepts have been proposed for engineering a 1D superconductor with an effective $p$-wave pairing via the proximity effect from a conventional $s$-wave superconductor. The central idea is built on the combination of Rashba spin–orbit coupling (SOC) with TRS breaking, such as induced by an external magnetic field or ferromagnetism, to lift the spin degeneracy at the Kramer’s point.

One approach to realize this concept is shown in BOX 1, which depicts the normal-state band structure of a 1D ferromagnet under the influence of Rashba SOC. Owing to the ferromagnetic exchange splitting, the minority and the majority bands are energetically separated and SOC imprints a spin texture. When the Fermi level lies in the minority band, only one spin species is populated. The system is considered spinless, because its physical description is reduced by the spin degree of freedom. This combination of magnetism, Rashba SOC and superconductivity therefore realizes a 1D topological superconducting state with $p$-wave pairing symmetry that can host zero-dimensional MZMs at its ends.

A related approach using the interplay between magnetism and superconductivity that arrives at the Kitaev model considers the in-gap Shiba states induced by magnetic atoms in a superconductor. If the limit that overlaps between the magnetic atoms is weak (unlike the band picture described above), considering only the overlap between the Shiba states, theoretical analysis shows that a topological superconductor with MZMs can be created, provided that there is helical order in the 1D magnetic chain. The stability of such helical order in this limit has been the subject of considerable theoretical studies; however, the combination of ferromagnetism with strong SOC is found to be equivalent to helical magnetic order and has proven so far to be a more feasible pathway for realizing topological $p$-wave superconductivity.

Ferromagnetic Fe chains on Pb. Chains of magnetically coupled atoms on the surface of a superconductor [BOX 1; FIG. 1] have been used to realize the 1D Kitaev model and have been established as a platform to study topological superconductivity and to directly visualize the presence of MZMs with STM. In these experiments, localized ZBPs within the superconducting gap were observed at the chain ends and were interpreted as the spectroscopic signature of MZMs. FIGURE 1a shows an STM topography of an Fe chain on a Pb(110) substrate. The regularly shaped Fe chain was realized through self-assembly of evaporated Fe atoms that arrange themselves in a linear zigzag structure (inset of FIG. 1b). Spin-polarized STM experiments were used to demonstrate the ferromagnetic nature of the Fe chains.
in a regime for topological superconductivity to emerge. Calculations provide evidence that these Fe chains, and their comparison with theoretical results, highlight the important role of hybridization between electronic states of chain and substrate, which can be understood in terms of coherence length, which can be understood in terms of a topologically non-trivial state with nearest-neighbour pairing of Majorana quasi-particles (part b of the figure). Intuitively, in the topologically non-trivial case, two individual Majorana quasi-particles remain localized at the chain ends.

Material realization of the Kitaev model of 1D topological superconductivity can be achieved by considering the normal-state band structure of a 1D ferromagnet under the influence of Rashba spin–orbit coupling (SOC) with amplitude $E_{\text{SO}}$ (part c of the figure). Here, $N$ is the lattice constant; $E$, energy; $k$, wave vector. Ferromagnetic exchange splitting of strength $J$ separates minority and majority bands. When the Fermi level lies in the minority band, only one spin species is populated, and the system can be regarded as spinless. Rashba SOC imprints a momentum-dependent spin texture on these 1D states, which facilitates proximity-induced pairing by an s-wave superconductor of the electrons in the otherwise fully spin-polarized minority band. This combination of magnetism and superconductivity therefore realizes a 1D topological superconducting state with $p$-wave pairing symmetry that can host zero-dimensional Majorana zero modes (MZMs) at its ends.

Scanning tunnelling microscopy (STM) experiments are ideally suited to study topological superconductivity and MZMs across nanoscopic material platforms (part d of the figure). In addition to the study of topographical sample properties, STM experiments can visualize localized MZMs at the ends of 1D topological superconductors, such as ferromagnetic chains of atoms placed on top of a superconducting surface. MZMs would appear as zero-energy states inside a superconducting gap in the measured conductance ($dI/dV$) spectrum of scanning tunnelling spectroscopy measurements. The use of functional tips diversifies the spectroscopic toolbox of STM measurements, aiding the measurement of electron–hole symmetry or spin signatures of MZMs, as discussed in the section on distinguishing trivial and topological zero-bias peaks.

Visualizing Majorana zero modes with scanning tunnelling microscopy

The Kitaev model describes the hopping (with strength $t$) of spinless electrons between sites of a 1D chain in the presence of $p$-wave superconducting pairing, $a$, Fractionalizing the fermionic modes into pairs of Majorana quasi-particles, the system can assume topologically distinct ground states: a topologically trivial state with on-site pairing (part a of the figure) and a topologically non-trivial state with nearest-neighbour pairing of Majorana quasi-particles (part b of the figure). Intuitively, in the topologically non-trivial case, two individual Majorana quasi-particles remain localized at the chain ends.

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strong Fermi velocity renormalization induced by chain–substrate hybridization. These conclusions were further supported by experiments on Fe chains that were covered with a monolayer of Pb; STM measurements revealed a clear MZM signature in this overlayer.

**Other atomic chains.** A crucial figure of merit for systems hosting MZMs is the size of their $p$-wave gap, which is $\Delta E_{SO}/J$, where $\Delta E_{SO}$ is the spin–orbit splitting and $J$ is the ferromagnetic exchange interaction in atomic chains. The topological gap protects the MZM...
from poisoning through quasiparticles in its vicinity, and it is key to the application of MZMs for topologically protected quantum computation. Experimentally, one practical way to estimate a lower bound of the \( p \)-wave gap size is to consider the energy of the peak in a tunnelling spectrum, which appears at the smallest energy above zero bias. In the case of the Fe chain platform, this energy is found to be at a modest value of around 150 \( \mu \)eV for a peak in the chain centre (corresponding to \( T < 2 \) K)\(^{34}\). Comparably small gap values are found for the semiconducting nanowire platform\(^{32,37}\), putting the MZM at risk of being poisoned through thermally excited quasiparticles\(^{37}\). Hence, a strong motivation exists for discovering other material platforms beyond the Fe chain, with the potential to stabilize the larger \( p \)-wave gaps.

Following the approach of synthesizing Fe chains on Pb(110) (REF\(^{24}\)), Co chains on Pb(110) have been studied\(^{24}\). However, in stark contrast to the Fe chains, the zero-energy mode appears delocalized along the Co chain, and no ZBP was found at the chain ends, possibly owing to an even number of bands crossing the Fermi energy. The contrasting experimental outcomes on the Fe and Co chain platforms\(^{24,50}\) raise questions about the best strategy to engineer 1D topological superconductors. Guidance may come from earlier models\(^{11,24}\), which outline that an increased number of magnetic atoms in the unit cell results in a larger number of energy bands and can reduce the size of the topological phase space. It is therefore desirable to tailor atomic chains with preferably simple lattice structures that admit the largest topological phase space.

In this direction, linear chains of Fe atoms on a Re substrate have been assembled using atomic manipulation with an STM tip\(^{38}\) (FIG. 1). Spin-polarized measurements with different tip magnetization directions reveal the spin-spiral arrangement of these Fe atoms (FIG. 1g), a structure that is suitable to induce topological superconductivity, as outlined in an earlier proposal\(^{38}\). Spatially dependent STS measurements on chains with more than 12 atoms display an enhanced zero-bias local density of states (LDOS) at the chain end (FIG. 1h), consistent with a topological superconducting phase and MZM. However, the small superconducting gap of Re, \( \Delta_s = 0.28 \) meV, renders the clear detection of a distinct ZBP difficult. The presence of MZM in this system is thus debatable.

More recent efforts have focused on extending such atomic manipulation experiments to materials that combine a larger superconducting gap with a longer Fermi wavelength than Re and strong SOC. Such a system can be obtained by the epitaxial growth of Bi(110) thin films on the surface of a Nb substrate\(^{38}\). In this platform, the interplay between the Ruderman–Kittel–Kasuya–Yosida interaction, SOC and surface magnetic anisotropy stabilizes different types of spin alignments, which also depend on the separation between spins. The spin alignments influence the hybridization of the in-gap Shiba states (FIG. 1a–c) and show promise as a means of engineering the band structure of such states for creating topological phases. Spin–spin interaction can be tuned on length scales longer than interatomic distances in the presence of a large proximity gap from the Nb substrate, thereby providing the possibility of creating helical spin chains atom-by-atom in the presence of robust superconductivity.

**Majorana modes in 2D systems**

*From 1D chains to 2D islands.* The idea of combining magnetism, superconductivity and strong Rashba SOC to engineer topological superconductivity can naturally be extended to two dimensions\(^{26,50,60}\). A 2D topological superconductor is predicted to harbour propagating Majorana edge modes along its 1D boundary\(^{41,62}\). Such a chiral 1D Majorana mode is characterized by a linear (that is, massless) quasiparticle energy–momentum dispersion, which connects the edges of the topological superconducting gap. It is expected to give rise to a flat d\(I/dV\) signal inside the superconducting gap, by which it can be detected in STS measurements.

Such a system has been realized in a monolayer of superconducting Pb covering Co islands on an Si(111) substrate\(^{24}\) (FIG. 2a). Although the presence of the Pb film hinders the structural characterization of the underlying Co islands, their locations can be identified by inspecting the influence of the Co on the superconducting electronic states of Pb. A conductance map taken at zero bias inside the superconducting gap of the monolayer Pb film on the same area reveals a concentric ring-like pattern of high d\(I/dV\) amplitude (FIG. 2b). This 1D edge mode is dispersive in character (FIG. 2c), and its spatial evolution across the centre of the Co island has been examined (FIG. 2d). The observation of dispersive and gapless edge modes on this and a similar sample platform\(^{11}\) suggests that such samples realize a 2D topological superconductor using arrays of magnetic atoms, and potentially host chiral MZMs.

Two-dimensional islands of the magnetic insulator EuS, which are deposited on top of Au nanoribbons, were also explored as a means of engineering topological superconductivity in the Au(111) surface state\(^{72}\) (FIG. 2d,e). This concept is motivated by the large SOC of the Au(111) surface state, \( E_g = 110 \) meV (REF\(^{69}\)), which may favour the realization of very large topological gaps. Superconductivity in the Au nanoribbons is induced by the V substrate on which they are grown. When an in-plane magnetic field is applied, localized ZBPs at the island edges have been detected in STS measurements\(^{32}\) (FIG. 2f). The appearance of ZBPs at specified island edge positions is also linked to the magnetic field direction. Unlike other 2D platforms hosting 1D chiral edge modes, theoretical modelling suggests that the directional in-plane magnetic field in concert with a magnetic exchange field underneath the EuS island could stabilize zero-dimensional MZMs instead.

In addition to these material systems, van der Waals (vdW) heterostructures fabricated from transition-metal dichalcogenides are promising candidates for realizing 2D \( p + i p \) topological superconductivity. Platforms based on vdW heterostructures are desirable because they permit the controlled assembly of designer quantum materials\(^{64,65}\) by stacking layers of vdW-coupled 2D materials with various properties. Following this approach, islands of the magnetic insulator CrBr\(_3\) have been deposited on the surface of superconducting bulk
Majorana quasiparticles in 2D systems with ferromagnetism. a | Scanning tunnelling microscopy (STM) topography of the Pb/Co/Si(111). b | Conductance (dI/dV) map of the same area, measured at a bias-voltage set point of 1.30 meV. c | Line-cut of the deconvoluted local density of states (LDOS) along the white arrow in part b, showing the spatial dispersion of the in-gap state. The edge states display a X-shape at the interface of the cluster. d | Large-scale STM topography of an Au(111) nanowire (NW) array. e | STM topography of the black rectangle region in part d, showing a two-monolayer (ML) EuS island deposited on top of an Au nanowire. f | Zero-bias peaks emerge in the dI/dV spectra, which were measured at specific edge positions, 1 and 8, of the EuS island as indicated in part e. g | STM topography of a CrBr₃ ML deposited on the surface of NbSe₂. h | dI/dV spectra recorded with the STM tip located at different spatial positions, which are indicated by the corresponding numbered dots in panel g. i | Top row, left panel: STM topography of a CrBr₃ ML. All of the other panels show dI/dV maps recorded at different indicated energies.

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Majorana vortex core states in 2D topological superconductors. One-dimensional and two-dimensional topological boundary states of TRS topological insulators (TIs) provide alternative pathways to realize MZMs in condensed matter systems. Owing to the non-trivial bulk topology, they appear as TRS singly degenerate helical states. These states therefore provide a natural platform for realizing TRS topological superconductivity via the proximity effect from adjacent bulk s-wave superconductors. The helicity of the topological boundary modes favours the realization of large topological s-wave gaps with sizes comparable to the gap size of the host superconductors, of the order of millielectronvolts. These large gaps offer a clear advantage over the p-wave superconductors discussed above, in which the gap size is reliant on the strength of the SOC and may be far smaller than the gap of s-wave superconductors used for the proximity effect. However, the challenge in realizing topological superconductivity in material platforms that host TRS topological boundary modes lies in isolating the effect of superconductivity on the bulk of such materials as compared with their boundary modes, where it is expected that superconductivity has a topological nature.

An early proposal for realizing TRS topological superconductivity is based on the 2D topological surface state of 3D topological insulators, in which proximity-induced pairing of the helical surface Dirac electrons stabilizes a p+ip 2D topological superconducting phase.

NbSe₂ [REF. 49] (Fig. 2g). Low-temperature STM experiments found a ZBP localized to the CrBr₃ island edge (Fig. 2h), and spectroscopic imaging with the STM revealed the 1D character of this ZBP (Fig. 2i). Modelling supports the interpretation of this edge state as a signature of a chiral Majorana mode, and it was argued that the ferromagnetic CrBr₃ layer induces a 2D topological superconducting phase with Chern number 3 in the topmost layer of the bulk NbSe₂ substrate. However, 1D chiral Majorana modes with approximate linear dispersion around zero energy are expected to produce a flat but not a peaked LDOS inside the superconducting gap. Further experiments will therefore be necessary to address the deviating spectral characteristics of the edge state LDOS and to elucidate its inhomogeneous spatial pattern (Fig. 2i), which is unlike the results from STM experiments on other candidate material platforms.
Applying an external magnetic field results in the formation of a vortex core that locally breaks TRS. The vortex core represents a topological defect and can host an MZM at its centre (Fig. 3a). Early experimental efforts to realize this proposal focused on heterostructures of epitaxially grown Bi$_2$Se$_3$ (REFS 92–95) thin films on the surface of superconducting bulk NbSe$_2$ (REFS 96–98). Spectroscopic measurements with the STM and complementary spin-resolved STM experiments on this material platform reported a ZBP inside the vortex cores at moderate magnetic fields (Fig. 3b), with properties consistent with the presence of a localized MZM (REFS 92–98). However, spectroscopic imaging experiments revealed a continuous ZBP splitting into a pair of finite-energy states over a range of 40 nm away from the vortex core (Fig. 3c). Although such characteristics could result from other trivial low-lying in-gap states (REFS 97,98,99) that exhibit a spatial distribution different from that of the ZBP, they challenge the interpretation of the ZBP as a charge signature of an MZM. In addition, the interpretation of these sub-gap states is complicated because the superconducting gap is a soft gap, resulting from a weak superconducting proximity effect in the quintuple layered structure of Bi$_2$Se$_3$ (REFS 44,45).

In this regard, a major leap forwards was achieved by the possibility of finding intrinsic superconductivity with a hard superconducting gap in the 2D topological surface states of FeTe$_{0.55}$Se$_{0.45}$ and Li$_{0.84}$Fe$_{0.16}$OHFeSe (REFS 92–94). Ensuing low-energy STM experiments on the surface of these materials (Fig. 3d for FeTe$_{0.55}$Se$_{0.45}$) reported the observation of a sharp and spatially homogeneous ZBP inside the vortex core states (REFS 30,93) (Fig. 3e,f). Although the properties of the ZBP, such as its spatial extent, spectral width and temperature dependence, have been reported to be consistent with those of an MZM, trivial vortex core states inside the superconducting gap, known as Caroli–de Gennes–Matricon (CdGM) states (REFS 84,87,88), would exhibit similar characteristics; this is discussed further in the section on MZM spin signature. Only a fraction of vortices were actually found to host a ZBP, whereas the others host CdGM states at finite energy. Hence, open questions about the origin of the ZBP and the role of the substantial surface disorder remain. In the case of FeTe$_{0.55}$Se$_{0.45}$, disorder was also found to induce trivial surface states in some regions of the sample surface, and other experiments even reported the entire absence of any vortex core ZBP (REF 99).

The debate on the origin of the ZBP may partially be resolved by a high-resolution study of the vortex core sub-gap states on the surface of FeTe$_{0.55}$Se$_{0.45}$, which was performed at a temperature of 80 mK (REF 98). This experiment first reproduced the experimental observation of a vortex core ZBP. In addition, the trivial CdGM states appeared as distinct peaks at finite energy, well separated from the vortex core ZBP (Fig. 3g). Interestingly, it was also reported that the relative occurrence of ZBP states inside vortex cores decreases with increasing strength of an externally applied magnetic field (Fig. 3h). This intriguing observation hints at hybridization of MZMs residing in neighbouring vortices, by which their energy is shifted to a finite value (REF 98).

Other studies addressed the origin of vortex core ZBP on Li$_{0.84}$Fe$_{0.16}$OHFeSe and FeTe$_{0.55}$Se$_{0.45}$ surfaces (REFS 90,91) by...
investigating their spectral properties as function of tip–sample distance (FIG. 5). Theory predicts that tunnelling into a localized MZM via resonant Andreev reflection results in quantized conductance of the ZBP, which assumes universal value of the conductance quantum, \( G_0 = 2e^2/h \) [REF. 102]. This quantized conductance value would be independent of the tunnel junction conductance and yield a ‘conductance plateau’ when the tip–sample distance is changed.

In the context of charge tunnelling into a superconductor, it is instructive to consider that, in general, varying the tip–sample distance changes the tunnel contact conductance\(^{103}\) and can realize various tunnel regimes in which charge transport is dominated by different mechanisms. At relatively large tip–sample distances, such as those commonly used for topographical imaging and STS measurements, tunnelling of individual quasiparticles dominates and gives rise to a superconducting gap, \( \Delta \), and coherence peaks at energies \(|E| = \Delta \) in the tunnelling spectrum (FIG. 5). At the same time, Cooper-pair-breaking effects, which can result from finite temperature, magnetic adatoms or vortex cores, for example, result in a finite quasiparticle density of states at \( E < \Delta \). Such ‘soft’ gaps provide relaxation pathways for quasiparticles\(^{104}\) and they aid tunnelling into sub-gap states, such as MZMs, Shiba states and CdGM states, even at \( E < \Delta \). In the presence of a ‘hard’ gap, by contrast, such tunnelling processes of individual quasiparticles would be suppressed. In the case of relatively small tip–sample distances, charge tunnelling at \( E < \Delta \) is dominated by Andreev reflections that give rise to rich spectral features inside the superconducting gap\(^{199}\). By injecting and extracting an electron and hole to form a Cooper pair, this tunnel process between tip and sample is mediated by Andreev bound states in the barrier and influences the spectral characteristics of charge tunnelling into sub-gap states such as MZMs, Shiba states and CdGM states\(^{102,106}\).

In the case of tunnelling into the vortex core ZBP on the \( \text{FeTe}_{0.55}\text{Se}_{0.45} \) surface, the ZBP amplitude is reported to be independent of tunnel contact conductance when the tip–sample distance is decreased\(^{100}\) (FIG. 5). Similar observations of plateau-like behaviour were reported for tunnelling into one vortex core on the surface of \( \text{Li}_{0.88}\text{Fe}_{1.16}\text{OHHSe} \) [REF. 100]. Whereas the appearance of a conductance plateau at zero bias voltage is qualitatively consistent with resonant Andreev reflection into an MZM\(^{102}\), the reported plateau amplitude assumes non-universal values below the theoretically expected quantized value \( G_0 \) [REF. 105] or even exceeds \( G_0 \) when the tip is continuously lowered towards the sample surface\(^{106}\). These tunnelling characteristics cast doubt on the interpretation of the appearance of the plateau as the signature of Andreev tunnelling into an MZM. In fact, comparable experiments on quasiparticle tunnelling into trivial Shiba states at \( E < \Delta \) yield similar results\(^{104}\).

In that case, the plateau behaviour can be unambiguously assigned to a tunnelling blockade that arises from a suppressed quasiparticle relaxation rate at low temperatures. Hence, the conductance plateau can be considered as a rather generic property of quasiparticle tunnelling into localized sub-gap states, challenging its suitability as a tool to distinguish trivial from non-trivial zero-energy states in STM experiments.

Beyond the search for MZMs in the vortex cores created by an externally applied magnetic field, the surface of \( \text{FeTe}_{0.55}\text{Se}_{0.45} \) has also inspired other concepts in which an MZM could localize at structural defects. STM experiments on 1D line defects in monolayer \( \text{FeSe}_{0.69}\text{Te}_{0.31} \) reveal ZBP pairs, which are localized at the ends of 1D line defects\(^{107}\), and it has been conjectured that these states could be the signatures of a Majorana Kramer’s pair. Further STM experiments on structural domain walls that appear on the surface of \( \text{FeSe}_{0.69}\text{Te}_{0.31} \) observed a filling of the superconducting gap with an energetically flat quasiparticle density of states along the 1D domain-wall trajectory\(^{199}\). Because such a flat \( \text{d}I/\text{d}V \) amplitude inside the domain-wall superconducting gap can arise from a linearly dispersing 1D quasiparticle state, this phenomenon is interpreted as a signature of a 1D chiral Majorana mode.

**MZMs in 1D topological edge states.** Two-dimensional topological insulators host 1D helical edge states\(^{108,109}\). It has been proposed that proximity-induced s-wave superconductivity in these states can realize a TRS topological superconducting phase. Its combination with segments of ferromagnetic material can realize an interface at which a localized MZM emerges\(^{110,111}\). Magnetism and superconductivity each induce their respective gaps on the topological edge states, giving rise to a topological mass domain wall that separates a region with a topologically non-trivial superconducting gap from a region with a topologically trivial magnetic gap. At this mass domain wall, an MZM is expected to be localized (FIG. 4a). Several transport experiments have already reported superconducting pairing in the topological edge states of \( \text{HgTe} \) quantum wells, and \( \text{InSb} \) and \( \text{Bi} \) nanowires\(^{112-114}\). Whether an MZM can be realized in these materials by using a domain wall with magnetism, however, has remained an open question, possibly owing to the challenge that arises when coupling these states to suitable magnetic materials.

The topological edge state of \( \text{Bi} \) [REFS.\(^7,111\)] is a promising alternative, because it appears on the edges of bilayers on the surface of \( \text{Bi}(111) \), where their properties can be explored with STM experiments\(^{116-118}\). Moreover, high-quality \( \text{Bi}(111) \) thin films can be grown epitaxially\(^{119}\), which facilitates the observation of superconducting pairing inside the edge states of \( \text{Bi}(111) \) thin films grown on \( \text{Nb}(110) \) [REF. 31]. The challenge of inducing the topological mass domain wall for localizing an MZM was overcome by decorating the bilayer edges with self-assembled ferromagnetic Fe clusters (FIG. 4a), which were found to induce a trivial magnetization gap inside the edge-state band structure\(^{113,114}\).

High-resolution spectroscopic measurements with the STM demonstrated the emergence of a localized ZBP at the interface between an Fe cluster and topological edge state (FIG. 4d–g), confirming the early theoretical proposals for the emergence of \( \text{MZM} \) on such a platform\(^{116,117}\). Additionally, the presence of the ZBP showed a characteristic dependence on the Fe cluster magnetization (FIG. 4e), justifying its interpretation as a
charge signature of an MZM. We note that this observation could provide avenues to manipulate MZMs with nanoscale magnetic switches, in which the cluster magnetization could be tuned with external magnetic fields or spin-polarized currents from the STM tip. Although the reported ZBP properties were consistent with results from models, only one cluster–edge state interface at the so-called A edge (Fig. 4a) was reported to show a prominent ZBP, whereas the other interface of the cluster with the B edge revealed an enhanced zero-bias conductance. This observation can be accounted for by the hybridization of the topological edge state with the bulk states along the B edge. However, it would be desirable to make further experiments in which the ferromagnetic cluster decorates the centre of an A edge and a pair of distinct ZBPs emerges on both sides of the cluster.

Also in the context of 2D topological insulators, vdW heterostructures have been established as an attractive platform to study proximity-induced s-wave superconductivity with large topological gaps in the 1D helical edge state of monolayer transition-metal dichalcogenides. Superconducting pairing in the topological edge state of monolayer 1T'-WTe$_2$ (REFS 120,121) has been realized by depositing a micrometre-sized flake of this compound on top of the surface of bulk NbSe$_2$ (REF 122) (Fig. 4f). Spectroscopic measurements with the STM on the edge of this flake reveal the presence of a

Fig. 4 | Topological superconductivity and Majorana zero mode in 1D topological edge states. a | A topological hybrid structure to realize Majorana zero modes (MZMs), based on the helical hinge states of a Bi bilayer. Proximity-induced superconductivity $\Delta_{\text{sc}}$ is realized by growing a Bi(111) thin film on top of the bulk superconductor Nb(110). A ferromagnetic Fe cluster adsorbed to the bilayer edge can induce a trivial magnetization gap $\Delta_m$. The topological mass domain realized at the interface between these regions localizes an MZM, which can be probed via local spectroscopy with a scanning tunnelling microscope (STM) tip. b | Close-up STM topography of an Fe cluster decorating the bilayer edge. c | A spectroscopic line-cut along the black dashed line in part b demonstrates the emergence of a localized ZBP at the interface of the edge state with the Fe cluster. d | Individual point spectra at different points of spectrum in part c. e | Magnetization components of several Fe clusters as reconstructed from spin-polarized STM experiments ($M_1$ points along the bilayer edge, $M_2$ perpendicular in-plane to the edge and $M_3$ out of plane). f | STM experiment on a van der Waals heterostructure assembled from NbSe$_2$ and 1T'-WTe$_2$ monolayer (ML) flakes deposited on an Au electrode, which serves as a drain for the tunnel current, $I_t$ at an applied bias voltage $V_{\text{sample}}$, TSC, topological superconductor. g | STM topography (top) and topographical line-cut (bottom) of the edge of a WTe$_2$ monolayer flake on the surface of NbSe$_2$. h | The conductance (dI/dV) spectrum (blue line) recorded on the WTe$_2$ monolayer edge displays a soft superconducting gap, which can be separated into dI/dV contributions arising from the local density of states of the WTe$_2$ edge state and the NbSe$_2$ substrate. $E$, energy; $E_F$, Fermi energy. Parts a–e adapted with permission from REF 121; AAAS. Parts f–h adapted from REF 122; Springer Nature Limited.
superconducting gap in the LDOS of the topological edge state (FIG. 4g.h). This observation opens an avenue to explore topological superconductivity and MZM in experiments on other heterostructures, including flakes of 2D ferromagnets or local gates that have the potential to engender topological superconductivity through the intrinsic proximity effect.[23]

**Distinguishing trivial and topological ZBPs**

This Review illustrates that ZBPs have been sighted in STM experiments across a range of material platforms that have been proposed to realize various theoretical concepts for topological superconductivity. Although several control experiments are commonly performed, such as the suppression of the ZBP in the absence of superconductivity, studies of the temperature and magnetic-field dependence, the interpretation of the observed ZBP as a charge signature of an MZM rests on the assumption that a ZBP is detected when the parameters of the system make it most likely to be in a topological superconducting phase. An accidental trivial zero-energy state, such as a Shiba state fine-tuned to zero bias, will, however, result in experimental characteristics similar to those of an MZM. Sighting of a ZBP on a suitable material platform by itself does not, therefore, constitute sufficient evidence to justify its interpretation as a charge signature of an MZM. STM experiments with functional tips have the ability to probe other predicted MZM properties, such as its spin and electron–hole symmetry, and they were established as a way out of this predicament of distinguishing trivial from topological ZBP, as we discuss in this section.

**MZM electron–hole symmetry.** The intrinsic electron–hole symmetry of an MZM, which is imposed by its Bogoliubov-quasiparticle character, can be probed in tunnel spectroscopy experiments with superconducting STM tips. The presence of a superconducting tip gap, $\Delta_s$, facilitates a separate measurement of the electron and hole sectors of a ZBP at different energies, by shifting their spectral weight to finite voltages. An electron–hole symmetric ZBP will be mapped to a pair of peaks with equal amplitude appearing at $V = \pm \Delta_s/e$. Although thermally excited resonances can render the detection of this symmetry challenging, high-resolution STS performed at dilution-refrigerator temperatures has observed electron–hole symmetry of the ZBP at the end of the ferromagnetic Fe chain on Pb(110) (REF. [4]). In these experiments, trivial Shiba states appeared as pairs of asymmetric peaks at $V > \Delta_s$, reflecting their intrinsic electron–hole asymmetry, and a pair of peaks with equal amplitude was measured at $\Delta_s$. This observation further consolidated the MZM interpretation of the ZBP on the Fe chain platform and underscored the potential of functional STM tips for the study of MZM.

**MZM spin signature.** Theoretical investigations have proposed that MZMs can leave unique fingerprints in spin-sensitive measurements, therefore providing the means to distinguish topological MZMs from trivial zero-energy states. STM experiments with magnetic tips, also called spin-polarized spectroscopy (SPS), can measure a sample’s spin polarization with atomic resolution. Such experiments are particularly well suited for studies attempting to identify topological MZMs (FIG. 5).

When tunnelling occurs between a ferromagnetic tip and sample, the tunnel conductance at a given bias voltage depends on the relative magnetization of the tip and sample. This effect is also called tunnel-magneto resistance, and it allows calculation of the spin polarization of the tunnel current, giving direct access to a sample’s magnetic properties. If the distance between tip and sample is adjusted so as to maintain a constant current set point, the spin-dependent contribution to the tunnel current, which arises from unequal normal-state spin densities, is compensated. The same measurement in the superconducting state opens a possibility to detect any spin polarization of the in-gap states beyond that caused by the ferromagnetism of the atomic chains in the normal state.

Model calculations of spin-dependent tunnelling into localized sub-gap states of a magnetic impurity on a superconducting surface reveal that the spin polarization of a pair of Shiba states at $\pm E$ is asymmetric about zero energy and that the Shiba state spin-density of states is bound by $\rho_N^{1/4}$ outside the superconducting gap. Accordingly, a trivial Shiba state tuned to zero energy is expected to show no spin polarization in SPS experiments, because the spin densities are offset by the

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**Fig. 5 | Detection of Majorana zero modes using superconducting and spin-polarized scanning tunnelling microscope spectroscopy.** a | Individual conductance (dI/dV) spectra, recorded with a superconducting scanning tunnelling microscope (STM) tip on a bare Pb substrate, at the Fe chain centre (Mid.) and at the Fe chain end. The end spectrum shows electron–hole symmetric peak amplitude at substrate, at the Fe chain centre (Mid.) and at the Fe chain end. The end spectrum shows electron–hole symmetric peak amplitude at substrate, at the Fe chain centre (Mid.) and at the Fe chain end. The end spectrum shows electron–hole symmetric peak amplitude at substrate, at the Fe chain centre (Mid.) and at the Fe chain end. The end spectrum shows electron–hole symmetric peak amplitude at substrate, at the Fe chain centre (Mid.) and at the Fe chain end.

b | Spectra measured on an Fe chain at 100 mT with up-polarized and down-polarized tips, showing the compensation of the unequal spin densities of the ferromagnetic Fe chain in the dI/dV spectrum by the STM set point effect (see also FIG. 1a). c | Spectra at the end of chain (left) and at the centre of chain (right) and their corresponding polarization. Red arrows mark the zero-energy end state; black arrows mark the van Hove singularity of the Shiba band. $\Delta_{\text{Shiba}}$, superconducting gap of Pb. Part a reprinted from REF. [4], Springer Nature Limited. Parts b and c reprinted with permission from REF. [4], AAAS.
set point effect of the tunnel current. By contrast, the MZM spin densities are, to first order, only dependent on the magnetic exchange interaction, and an MZM is expected to show a finite spin polarization despite the set point effect. Hence, a topological ZBP can be distinguished from a trivial ZBP by measuring its spin polarization in SPS experiments.

This hypothesis was confirmed in spin-polarized STM experiments on the sub-gap states appearing in Fe chains on Pb, using Fe-coated Cr tips. Consistent with the model calculations, the Shiba states within the chain exhibit an energy-asymmetric spin polarization. Comparable results were also reported in similar experiments on Co chains on Pb(110) (REF 39) and single magnetic impurities 134. More importantly, additional measurements at the Fe chain end revealed a distinct spin-polarized signal of the ZBP. By virtue of the above considerations, this observation directly demonstrates its non-trivial origin and establishes the MZM interpretation of the ZBP in the platform of the Fe chain on Pb(110). Similar SPS measurements have been used to confirm the MZM nature of the ZBP observed in the proximitized topological edge state of Bi (REF 31). The observed strong spin polarization of the ZBP was found to be of opposite sign to that of the Shiba state on top of the Fe cluster. This finding is consistent with analytical and numerical model calculations, which predict that MZM and Shiba state spins point along different spatial axes.

Additional results from recent spin-polarized STM experiments on Fe adatoms adsorbed to the surface of FeSe0.45Te0.55 underscore the relevance of diagnostic tools that probe MZM properties other than the presence of a ZBP by itself. Initial spectroscopic measurements on top of the adatoms revealed the presence of a sharp ZBP, which was interpreted as a signature of an MZM occurring inside a quantum anomalous vortex core 136. We note that similar results and conclusions were reported for Fe adatoms deposited on the surface of LiFeAs and PbTaSe4 (REF 136). However, a recent study using spin-polarized measurements demonstrated the absence of finite spin polarization for the ZBP observed on top of Fe adatoms on FeSe0.45Te0.55 (REF 134). The conflicting outcome of these two studies clearly precludes the interpretation of the ZBP on this platform as a signature of an MZM. More broadly, this result emphasizes that tracking the temperature dependence and field dependence of a ZBP alone does not provide sufficient information to draw conclusions on its topological origin.

Other proposals exist to use STM experiments to probe the MZM origin of ZBPs. These proposals involve microwave radiation coupled to the tunnel junction to accurately test spectral properties of ZBP, and a shot noise analysis of the tunnel current to discriminate tunnelling into an MZM from tunnelling into trivial states 138. Finally, we anticipate that Josephson STM measurements could present a valuable tool to scrutinize the presence of topological p-wave superconducting pairing in the bulk of 1D and 2D systems. Josephson STM focuses on measurement of a Cooper-pair current near zero bias voltage, through which it has the ability to quantify the superconducting order parameter amplitude with atomic resolution. Because tunnelling of Cooper pairs between spin-singlet (s-wave) superconductivity in the STM tip and spin-triplet (p-wave) superconductivity in the sample cannot occur, the Cooper-pair current between tip and sample would be locally suppressed. Such local variations can be detected with Josephson STM, resulting in a clear experimental signature for p-wave superconductivity.

Outlook and potential future experiments

The diversity of results from STM experiments presented in this Review illustrate the important role that STM has played in exploring topological superconductivity and visualizing the presence of MZMs across a variety of material platforms. More recently, various STM experiments have also succeeded in establishing material platforms that lend themselves to integration into electron transport experiments. Noteworthy examples of such material platforms include the hinge state of Bi, the properties of which can be studied in quantum transport experiments based on Bi nanoribbons, and the topological edge state of monolayer 1T’-WTe2 in vdW heterostructure devices. These developments close the gap between microscopic studies of MZM properties with the STM and measurements of global material properties in device transport, and they provide avenues to explore more complex MZM braiding experiments in the future.

At the same time, theoretical studies of the atomic chain platform have proposed STM measurements to test the two essential properties of MZMs that are key to their application as topologically protected qubits — their non-Abelian exchange statistics and anyonic character. Here we outline the future direction of research on MZM with STM experiments.

Possibly the simplest demonstration of control of MZMs occurring at the ends of magnetic atomic chains on a superconducting surface is the study of their properties as a function of the relative angle of an in-plane magnetic field to that of the chain direction (FIG. 6a). Theory predicts that a spin chain with helical magnetic order would be driven out of the topological phase as a function of this angle (FIG. 6b). Hence, in a situation in which the chain displays a semicircle-like geometry, trivial and topological segments can coexist; the MZM would be localized at the boundary between these phases along the chain, the location of which depends on the local angle of the field with respect to the chain. Spatially resolved STM spectroscopy as a function of position along the chain and the applied magnetic field at different angles would enable testing of this approach for manipulating the chain topology.

An extension of this proposal considers the properties of a T-junction chain as a function of a rotating in-plane magnetic field. Examining the influence of the magnetic field on a tri-junction geometry with a 120° angle, theoretical analyses predict that the magnetic field rotation can drive each arm of such tri-junctions sequentially in and out of the topological phase. At each orientation of the applied field, precisely one pair of MZM appears at the ends of two out of three chains in the tri-junction
and can be detected by the ZBP at the respective locations [Fig. 6d]. The process by which MZMs in these tri-junctions are fused and created sequentially as a function of field rotation results in their exchange at a rotation angle of $\pi$ and a single braid at $2\pi$. A real-space manipulation of an MZM pair, following this pattern, corresponds to a braiding process, which is at the heart of the complex physics of MZMs. Such manipulation could be visualized in STS measurements with the STM.

We propose that chains of magnetic atoms may also serve as a suitable testbed to demonstrate the ground-state degeneracy of a system containing more than two MZMs. Theoretical analyses of MZM quantum dot devices propose that coupling three (out of two pairs of) degenerate MZMs to metallic leads constitutes an effective spin-1 particle, which gives rise to the topological Kondo effect\(^{146}\). In a similar manner, we envisage an atomic-scale platform with two atomic chains placed on a superconducting film, each of which hosts a pair of MZMs [Fig. 6d]. If a thin electrically insulating layer isolates the superconductor from a normal metallic substrate, the superconductor forms a Coulomb island. We conjecture that the coupling, $t_{c}$, of the MZM with the conduction electrons in the substrate could mediate a Kondo-type interaction governed by $t_{c}$ and the Coulomb energy, displaying non-Fermi liquid behavior. The resulting Kondo screening cloud, which arises in the metal substrate surrounding the island, can be detected in STS measurements\(^{147}\) [Fig. 6d]. The emergence of the topological Kondo effect requires the existence of more than two degenerate MZMs. The experimental detection of the Kondo cloud would therefore provide direct evidence for the anyonic character of MZMs. We envisage that such a sample platform could be realized on the basis of vdW heterostructures, by assembling monolayer and few-layer flakes of suitable materials, such as superconducting monolayer NbSe$_2$, insulating hexagonal boron nitride and metallic graphene\(^{65}\).

The demonstration of atom-by-atom assembly with an STM tip of magnetic nanostructures on the surface of different superconducting substrates\(^{12,48,100}\) increases the likelihood of these studies occurring. These experiments are challenging because they require atomically clean superconducting surfaces\(^{12,48,100}\) that permit atomic assembly of elaborate atomic structures, and the right material combination to realize 1D topological superconductivity with MZM end states. These developments will, ultimately, be driven by the realization of material platforms and concepts, such as those based on higher-order topological superconductors\(^{490–151}\) or quantum-spin liquids\(^{152–154}\). Nevertheless, STM experiments — which combine the ability to visualize, investigate and potentially manipulate MZMs with atomic-scale precision — will continue to be at the forefront of research on topological superconductivity and MZMs in condensed matter systems.

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