The Kavli ITS Workshop on Majorana Modes in Topological Superconductors

8-11 November 2019, Beijing, China

S201, Teaching Building, Zhong-Guan-Cun Campus, UCAS

No. 3, Zhong Guan-cun Nan Yi-Tiao, Haidian, Beijing

PROGRAM

8 January (Tuesday)

08:40-09:00 Registration

09:00-09:15 Opening **Fu-Chun Zhang**, Kavli ITS, UCAS

Tuesday Session A

Chair:	**Tetsuo Hanaguri**, RIKEN
09:15-10:15	**Roland Wiesendanger**, Univ. of Hamburg Emergence of Majorana States in Engineered Atomic-Scale Hybrid Systems
10:15-10:30	**Photo & Coffee/Tea break**
10:30-11:30	**Dong-Lai Feng**, Fudan Univ. Clean and robust Majorana zero modes in an iron selenide
11:30-12:30	**Lunch**
12:30-13:30	**The 1st Poster Session**

Tuesday Session B

Chair:	**Hao Zheng**, Shanghai Jiao Tong Univ.
13:30-14:30	**Hao Zhang**, Tsinghua Univ. Majorana nanowires: progress and challenges
14:30-15:30	**Xiao Hu**, NIMS Quest for Majorana Bound States in Topological Superconductors
15:30-15:50	**Coffee/Tea break**
15:50-16:50	**Jianping Hu**, IOP, CAS TBD
16:50-17:50	**Lingyuan Kong**, IOP, CAS Recent progress of Majorana in Fe (Te,Se)
18:30-20:30	**Banquet**

9 January (Wendesday)

Wednesday Session C

Chair:	**Tong Zhang**, Fudan Univ.
09:00-10:00	**Hai-Hu Wen**, Nanjing Univ.

Vortex bound states and Majorana mode in FeTe0.55Se0.45 and Bi2Te3/FeTe0.55Se0.45

10:00-11:00 **Tetsuo Hanaguri**, RIKEN

Nature of the Zero-Energy Vortex Bound State in Fe(Se,Te)

11:00-11:15 **Coffee/Tea break**

11:15-12:15 **Ching-Kai Chiu**, KITS, UCAS

Majorana lattice with disorder

12:15-13:30 **Lunch**

Wednesday Session D

Chair: **Dong Liu,** Tsinghua Univ.

13:30-14:30 **Jinfeng Jia**, Shanghai Jiao Tong Univ.

Majorana zero mode in the vortex

14:30-15:30 **Jun-Yi Ge**, Shanghai Univ.

Nanoscale assembly of superconducting vortices with STM tip

15:30-15:50 **Coffee/Tea break**

Wednesday Session E

Chair: **Fu-Chun Zhang**, Kavli ITS, UCAS

15:50- Discussion session focuses on problems of Majorana zero modes in vortices of topological superconductors

15-min talk: **Huan Yang,** Nanjing Univ.

Phase-referenced QPI and impurity effect in Bi2Te3/FeTe0.55Se0.45 heterostructures

10 January (Thursday)

Wednesday Session F

Chair: **Chun-Xiao Liu**, KITS/Delft

09:00-10:00 **Tong Zhang**, Fudan Univ.

STM study of the nematic superconductivity in CuxBi2Se3 and RbFe2As2

10:00-10:15 **Coffee/Tea break**

10:15-11:15 **Masatoshi Sato**, Kyoto Univ.

Multiple Topological Superconductivity in Iron-Based Superconductors

11:15-12:00 **Tadashi Machida**, RIKEN

How to identify the factors that govern the zero-energy vortex bound state in Fe(Se,Te)?

12:00-13:30 **Lunch**

Wednesday Session G

Chair: **Xin Liu,** Huazhang Univ. of Sci. and Tech.

13:30-14:30 **Xi Dai**, Hong Kong Univ. of Sci. and Tech.

	Quantum anomalous vortex and Majorana zero mode in iron-based superconductor Fe(Te,Se)
14:30-15:30	**Dong Liu**, Tsinghua Univ. Topologically protected quantum computation based on Majorana zero modes: A theory perspective
15:30-15:45	**Coffee/Tea break**
15:45-16:45	**Xiong-Jun Liu**, Peking Univ. Symmetry-protected non-Abelian Majorana braiding
16:45-18:00	**The 2nd Poster Session**

11 January (Friday)

Wednesday Session H

Chair:	**Ching-Kai Chiu**, KITS, UCAS
09:30-10:30	**Xin Liu**, Huazhang Univ. of Sci. and Tech. Lattice symmetry assisted second order topological superconductors and Majorana patterns
10:30-10:45	**Coffee/Tea break**
10:45-11:30	**Chun-Xiao Liu**, KITS/Delft Majorana qubit readout scheme in Coulomb blockaded topological superconductor for testing non-Abelian statistics
11:30-12:15	**Jun He**, RIKEN Platform of chiral Majorana edge modes and its quantum transport phenomena
12:15-	**Lunch**

Emergence of Majorana States in Engineered Atomic-Scale Hybrid Systems

Roland Wiesendanger

Interdisciplinary Nanoscience Center Hamburg, University of Hamburg, Germany

Majorana states in atomic-scale magnet-superconductor hybrid systems have recently become of great interest because they can encode topological qubits and ultimately provide a new direction in topological quantum computation [1,2].

First, it will be demonstrated how well defined 1D atomic chains of magnetic adatoms on superconducting substrates with high spin-orbit coupling can be artificially fabricated using STM-based atom-manipulation techniques. Spin-polarized STM measurements [3] allow revealing the presence of non-collinear spin textures, i.e. spin spiral ground states, stabilized by interfacial Dzyaloshinskii-Moriya interactions [4-6]. Simultaneously performed scanning tunneling spectroscopy on the magnetic atom chains on the superconductor substrate reveal the evolution of the spatially and energetically resolved local density of states as well as the emergence of zero-energy bound states at the chain ends above a critical chain length. Based on the exact knowledge of the geometrical, electronic, and spin structure of the magnetic chain – superconductor hybrid system, the experimental results can be compared rigorously with ab-initio and model-type tight-binding calculations supporting the interpretation of the spectroscopic signatures at the ends of the chains as Majorana bound states [7]. More recently, the atomic-scale design of more complex network structures for Majorana state manipulation, including braiding operations has been in the focus of our research.

Second, we will address experimental and theoretical studies of monolayer topological superconductivity and chiral Majorana edge modes in model-type 2D magnetic islands on elemental superconductors [8]. In particular, we demonstrate that interface engineering by an atomically thin oxide layer is crucial for driving the studied hybrid system into a topologically non-trivial state as confirmed by theoretical calculations of the topological invariant, the Chern number.

Finally, the prospects for studies of Majorana states in skyrmion – superconductor hybrid systems [9] will be highlighted.

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References

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[2] S. Nadj-Perge et al., PRB 88, 20407 (2013); H.-Y. Hui et al., Sci. Rep.. 5, 8880 (2015).
[3] R. Wiesendanger, Rev. Mod. Phys. 81, 1495 (2009).
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[7] H. Kim et al., Science Advances 4, eaar5251 (2018).
[8] A. Palacio-Morales et al. (2018), arXiv:1809.04503.
[9] N. Romming et al., Science 341, 6146 (2013).

Clean and robust Majorana zero modes in an iron selenide

Donglai Feng

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The Majorana zero modes (MZM) in many topological superconductors are often not clean or robust, due to the necessity of impurities or large Fermi energy, which hampers further manipulations of Majorana fermions. Using scanning tunneling spectroscopy, we found that a zero-bias conductance peak (ZBCP) well separated from the other discrete Caroli-de Gennes-Matricon states exists ubiquitously in all cores of free vortices in the defect free regions of (Li0.84Fe0.16)OHFeSe, which has a superconducting transition temperature of 42 K. Moreover, a Dirac-cone-type surface state is observed by angle-resolved photoemission spectroscopy, and its topological nature is confirmed by band calculations. The observed ZBCP can be naturally attributed to an MZM arising from this chiral topological surface states of a bulk superconductor. (Li0.84Fe0.16)OHFeSe thus provides an ideal platform for studying MZMs and topological quantum computing. [1]

On FeSe/STO, we show that neither MZMs exist in the vortex cores nor do they show up on the iron impurities, which suggests the band inversion along kz is critical for the realization of topological superconductivity in FeSe based systems. [2]

References

[1] Q. Liu et al. arXiv: 1807.01278, PRX (in press)
[2] C. Chen et al. (in preparation)

Majorana nanowires: progress and challenges

Hao Zhang

Tsinghua University, China

A semiconductor nanowire coupled to a superconductor can be tuned into a topological superconductor with two Majorana zero-modes localized at the wire ends. Tunneling spectroscopy in electrical transport is the primary tool to identify the presence of Majorana zero-modes, which manifests itself as a zero-bias peak (ZBP) in the differential-conductance. The Majorana ZBP-height is predicted to be quantized at the universal conductance value of 2e2/h at zero temperature. Previous experiments, however, have shown ZBPs much smaller than 2e2/h. In this talk, I will show how the experimental progress gradually leads to the quantization of the Majorana conductance. Finally I will discuss the progress and challenge towards the first topological qubit based on these Majorana zero modes.

Quest for Majorana Bound States in Topological Superconductors

Xiao Hu

*International Center for Materials Nanoarchitectonics (WPI-MANA)

National Institute for Materials Science (NIMS), Tsukuba, Japan

**Kavli Institute of Theoretical Science, Beijing, China

We propose a method to manipulate Majorana bound states (MBS) in two nanowire topological superconductors coupled by a quantum tunneling junction [1]. We show theoretically that a bias voltage across the junction induces a Landau-Zener-Stuckelberg (LZS) interference between parity states composed by MBS. Adjusting the time lengths of bias voltage and gate voltage at junction, one can build a LZS interferometry as a universal gate for the Majorana qubit. The quantum mechanical dynamics of Majorana qubit can be monitored by analyzing spectra of microwaves radiated from the system, which includes a novel spectrum peak induced by the fractional Josephson effect associated with MBS, in addition to the spectrum peak due to the conventional Josephson effect of Cooper pairs. I will also discuss unique spin textures associated with MBS at vortex cores of a typical 2D topological superconductor formed by the heterostructure between a 3D topological insulator and an s-wave superconductor [2].

References

[1] Z. Wang, W.-C. Huang, Q.-F. Liang and X. Hu, Sci. Rep. **8**, 7920 (2018).

[2] T. Kawakami and X. Hu, Phys. Rev. Lett. **115**, 117001 (2015).

Search for topological nature of Majorana bound states in Fe(Te,Se)

Ling-Yuan Kong

Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

Majorana bound states (MBS) can emerge as zero-energy quasi-particle excitations in a vortex core of superconducting topological surface states [1]. Inspired by Fu-Kane model, we raised a new and promising platform ($FeTe_{0.55}Se_{0.45}$) supporting Majorana-type excitations, which does not require complicated hererostructure fabrications.

Previously, our low temperature STM experiments [2] show non-split zero bias peak (ZBP) across a vortex core. Its intensity line-profile was reproduced very well by a theoretical model of topological surface states. Temperature evolution of ZBP shows enhanced suppression at lifting temperatures, which indicates the bulk component may poison ZBP by thermal quasi-particles over the mini-gap inside bulk vortex line. Although those observations provide strong evidence towards MBS, the behavior of ZBP alone is not enough to prove it. Recently, we performed thorough studies on vortices of $FeTe_{0.55}Se_{0.45}$, the topological nature of MBS was distinguished under a global view.

References

[1]. L. Fu & C. L. Kane, Phys. Rev. Lett. 100, 096407 (2008).
[2]. D. Wang, L. Kong, P. Fan et al., Science 362, 333 (2018).

Vortex bound states and Majorana mode in FeTe0.55Se0.45 and Bi2Te3/FeTe0.55Se0.45

Mingyang Chen, Xiaoyu Chen, Huan Yang and Hai-Hu Wen

Physics Department, Nanjing University, China

Topological superconductor is a timely and frontier topic in condensed matter physics. By measuring the spatial evolution of tunnelling spectra on the surface of $FeTe_{0.55}Se_{0.45}$, we observed the long sought discrete Caroli-de Gennes-Matricon bound states[1] within some vortex cores. By analyzing the energies of the lowest level and the interval between the energy levels, we found that the iron based superconductor $FeTe_{0.55}Se_{0.45}$ has the shallow band with the Fermi energy of about 5-20 meV, indicating the possibility of a crossover from BEC-BCS. Furthermore we have measured the vortex core bound states on many other vortices in different areas and/or different samples, and found that, in some vortices there is a strong bound state peak locating at zero energy. With the rather symmetric shape at the gap edge, we would conclude that it may correspond to the Majorana mode[2]. With increase the magnetic field, the zero energy mode of the vortices locating at the same position is systematically suppressed. Meanwhile, we also find that the probability of observing the zero energy mode decreases with increasing the magnetic field. We find no clear connection between the surface concentration of Te/Se ratio. By increasing temperature, the zero energy mode is suppressed quickly and merged into the side peak in the occupied state at about 4K.

We deposit Bi_2Te_3 thin film on the $FeTe_{0.55}Se_{0.45}$ substrate and get the proximity induced superconductivity. By using the quasiparticle interference technique, we demonstrate clear evidence of twofold symmetry of the superconducting gap. The gap minimum is along one of the main crystalline axis following the so-called Δ_{4y} notation. This is also accompanied by the elongated vortex shape. Within the vortex core, along the stretched direction, a zero energy peak appears and stays until going out of the vortex. Our results reveal the direct evidence of superconductivity with two-fold symmetry in Bi_2Te_3 thin film[3] .

References

[1] Mingyang Chen, Xiaoyu Chen, Huan Yang, Hai-Hu Wen et al. ***Nat. Commun.*** 9, 970 (2018).

[2] Xiaoyu Chen, Mingyang Chen, Huan Yang, Hai-Hu Wen et al. to be published.

[3]Mingyang Chen, Xiaoyu Chen, Huan Yang, Zengyi Du, Hai-Hu Wen. ***Science Adv.*** 4, eaat1084 (2018).

Nature of the Zero-Energy Vortex Bound State in Fe(Se,Te)

Tetsuo Hanaguri

RIKEN, Japan

Bulk superconductors with a topological surface state attract much attention because vortex cores at the surface can accommodate Majorana quasiparticles. We performed ultra-low-temperature spectroscopic-imaging STM experiments on Fe(Se,Te) that host superconducting topological surface state. We found various chemical and electronic quenched disorders at the surface and two kinds of vortices with and without zero-energy vortex bound state, which may represent the Majorana quasiparticle. Interestingly, there is no clear correlation between the quenched disorders and the zero-energy vortex bound state. We argue that a disorder in the vortex lattice may play a role for the appearance of the zero-energy vortex bound state.

Majorana lattice with disorder

Ching-Kai Chiu

KITS, UCAS, China

Recent scanning tunnelling spectroscopy measurement observed the zero-bias conductance peaks at the vortex cores of the topological superconductor candidates, consistent with MZM tunnelling interpretation. This year in the experiment based on the iron-based superconductor (FeTexSe1-x), Caroli-de Gennes-Matricon modes with energy higher than zero were observed near the vortex cores; hence, the observation of the zero bias peak might be tentative evidence of an isolated Majorana zero mode trapped in a vortex core. In the current experiment, the most controllable parameter is magnetic field strength adjusting the intervortex distance. The change of the magnetic field strongly affects LDOS near the vortex cores. In this talk, we theoretically study the LDOS of the vortex lattice with and without disorder as a function of the magnetic field in the presence of the Majorana modes and further predict the observable signs of the Majorana physics.

Nanoscale assembly of superconducting vortices with STM tip

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Abstract

Vortices play a crucial role in determining the properties of superconductors as well as their applications. Therefore, characterization and manipulation of vortices, especially at the single vortex level, is of great importance. Among many techniques to study single vortices, scanning tunneling microscopy (STM) stands out as a powerful tool, due to its ability to detect the local electronic states and high spatial resolution. However, local control of superconductivity as well as the manipulation of individual vortices with the STM tip is still lacking. Here we report a new function of the STM, namely to control the local pinning in a superconductor through the heating effect. Such effect allows us to quench the superconducting state at nanoscale, and leads to the growth of vortex-clusters whose size can be controlled by the bias voltage. We also demonstrate the use of an STM tip to assemble single quantum vortices into desired nanoscale configurations.

Keywords: *vortices, STM, superconductor*

References:

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STM study of the nematic superconductivity in CuxBi2Se3 and RbFe2As2

Tong Zhang
Fudan University, China

$Cu_xBi_2Se_3$ hosts both topological surface states and bulk superconductivity. It has been identified recently as a topological superconductor (TSC) with an extraordinary nematic superconducting state and odd-parity pairing. By using scanning tunneling microscopy (STM), we directly examine the response of the superconductivity of $Cu_xBi_2Se_3$ to magnetic field. Under out-of-plane fields, we discover elongated magnetic vortices hosting zero-bias conductance peaks consistent with the Majorana bound states expected in a TSC. Under in-plane fields, the average superconducting gap exhibits two-fold symmetry with field orientation; the long C_2 symmetry axes are pinned to the dihedral mirror planes under $B_{//}$=0.5 T but rotate slightly under $B_{//}$=1.0 T. A nodeless Δ_{4x} gap structure is semi-quantitatively determined for the first time. I will also present our recent results on the discovery of (π, π) nematicity in heavily hole-doped Fe-based superconductor $RbFe_2As_2$.

Multiple Topological Superconductivity in Iron-Based Superconductors

Masatoshi Sato
Yukawa Institute for Theoretical Physics, Kyoto University, Japan

Because of a unique band inversion structure, iron-based superconductors may host both topological insulating and Dirac semimetal phases in the normal state. I will discuss resulting multiple topological superconductivity in iron-based superconductors. In particular, I will argue possible unique superconductivity in the Dirac semimetal phase.

How to identify the factors that govern the zero-energy vortex bound state in Fe(Se,Te)?

Tadashi Machida
RIKEN, Japan

We argue key technical aspects that are important to investigate the zero-energy vortex bound state in the superconducting topological surface state of Fe(Se,Te) by spectroscopic-imaging STM. The most important factor is the high energy resolution (~20 micro-eV) that we achieved by newly-developed dilution-refrigerator scanning tunneling microscope. Another important issue is the relation between the zero-energy vortex bound state and various quenched disorders in Fe(Se,Te), which we argue based on the cross-correlation analyses. We also describe the Voronoi analyses of the vortex-lattice structure that may affect the zero-energy vortex bound state.

Quantum anomalous vortex and Majorana zero mode in iron-based superconductor Fe(Te,Se)

Dai Xi
Hong Kong University of Science and Technology

In topological insulators doped with magnetic ions, spin-orbit coupling and ferromagnetism give rise to the quantum anomalous Hall effect. Here we show that in s-wave superconductors with strong spin-orbit coupling, magnetic impurity ions can generate topological vortices in the absence of external magnetic fields. Such vortices, dubbed quantum anomalous vortices, support robust Majorana zero-energy modes when superconductivity is induced in the topological surface states. We demonstrate that the zero-energy bound states observed in Fe(Te,Se) superconductors are possible realizations of the Majorana zero modes in quantum anomalous vortices produced by the interstitial magnetic Fe. The quantum anomalous vortex matter not only advances fundamental understandings of topological defect excitations of Cooper pairing, but also provides new and advantageous platforms for manipulating Majorana zero modes in quantum computing.

Topologically protected quantum computation based on Majorana zero modes: A theory perspective

Dong Liu
Tsinghua University, China

Majorana zero modes provide a potential platform for the storage and processing of quantum information with intrinsic error rates that decrease exponentially with inverse temperature and with the length scales of the system. In the first part of the talk, I will review the recent progress and challenges in Majorana search and topological quantum computation from a theoretical point of view. In the second part of the talk, I will focus on a near term question: What is the simplest way to reveal the coherent signatures of Majorana devise? Recent experimental progresses are mostly about the Majorana resonance which cannot give their coherent information. We propose a Fu's Majorana teleportation setup with extra energy dissipation in the tunneling processes. We find energy dissipation significantly suppresses the transport for non-Majorana incoherent tunneling, but enhance the coherent Majorana transport. Therefore, this simple setup could serve as near term coherence-detector of Majorana systems.

Symmetry-protected non-Abelian Majorana braiding

Xiong-Jun Liu
International Center for Quantum Materials, Peking University, China

Due to the Kramers theorem, Time-reversal (TR) invariant Topological superconductors (TSCs) host Majorana zero modes in pairs, called Majorana Kramers pairs (MKPs). The recent work proposed that, the MKPs may obey the so-called symmetry-protected non-Abelian braiding statistics. In this talk, we shall introduce how to develop the complete theory for non-Abelian braiding of MKPs and discuss the possible applications. By introducing an effective Hamiltonian approach to describe the process of braiding the MKPs, we show that the non-Abelian braiding is protected when the effective Hamiltonian exhibits a new TR like anti-unitary symmetry, which is satisfied if the system is free of dynamical noise. This result tells that the symmetry-protected non-Abelian braiding indeed requires that both the static Hamiltonian and the braiding process satisfy the TR symmetry. Interestingly, even the dynamical noise may not cause error in braiding, unless the noise correlation function breaks a dynamical TR symmetry, which generalizes the TR symmetry protection of MKPs to dynamical regime. Moreover, the resulted error by noise is shown to be a higher order effect, compared with the decoherence of Majorana qubits without TR symmetry protection. These results show that the non-Abelian braiding of MKPs is observable in real systems and may have versatile applications to future quantum computation technologies.

Lattice symmetry assisted second order topological superconductors and Majorana patterns

Xin Liu
Huazhang University of Science and Technology

The recent studies of the second order topological states are bring new insights of realizing MZMs. In this talk, we propose a realization of the lattice symmetry assisted second order topological superconductors with corner Majorana zero mode (MZMs) based on two-dimensional topological insulators (2DTIs). The lattice symmetry can naturally lead to the anisotropic coupling of edge states along different directions to the uniform magnetic field and conventional s-wave pairings, thus leading to a single MZM locating at the corners for various lattice patterns. In particular, we focus on D3d group symmetry under an in-plane magnetic field and s-wave pairing and find different types of gap opening for the edge states along the armchair and zigzag edges in a broad range of parameters. As a consequence, a single MZM exists at the corner between the zigzag and armchair edges, and is robust against weakly symmetry broken. We propose to realize such corner MZMs in a variety of polygon patterns, such as triangles and quadrilaterals. We further show their potentials in building the Majorana network such as Majorana Y-junction under a uniform in-plane magnetic field.

Coulomb-blockade-assisted Majorana qubit readout scheme for testing non-Abelian statistics

Chunxiao Liu
KITS/Delft University, China/Netherland

The successful test of non-Abelian statistics is not only a milestone in fundamental physics but also provides a quantum gate in topological quantum computation. An accurate and efficient readout scheme of topological qubit is an essential step toward the experimental confirmation of non-Abelian statistics. In the current work, we propose a scheme to read out the quantum state of the Majorana qubit system in a Coulomb blockaded topological superconductor. The protocol consists of four spatially well-separated Majorana zero modes trapped in vortex cores on the two-dimensional surface topological superconductor with charging energy. Projective measurement can be implemented by a pair of weakly coupled Majorana modes in touch with two external metallic leads in the Coulomb blockade valley, while high resolution readout of the measurement outcome can be achieved by conductance measurement at charge degenerate points. Using this protocol, we can further reveal the non-Abelian statistics of Majorana zero modes. Finally, we discuss how our proposal is able to distinguish Majorana zero modes from Caroli-de Gennes-Matricon modes by observing the conductance at different intervortex distance and temperature.

Platform of chiral Majorana edge modes and its quantum transport phenomena

Jun He
RIKEN, Japan

In this talk, I first propose a system of chiral Majorana modes which is currently achievable in research labs. Such a system consists of a heterostructure of a ferromagnetic material, a thin film of topological insulator and a superconductor. A chiral Majorana edge mode exists even for large magnetization and small pairing order parameter. Based on this system, we further propose a way to uniquely determine the existence of such Majorana modes. A Josephson junction is used as part of the measurement setup and the current is tuned from a small value below the Josephson critical current to a value that is much larger. The conductance is changed in a unique way due to the existence of the Majorana modes. Furthermore, we investigate the effect of several unconventional pairing forms such as spin-triplet p-wave and spin-singlet d-wave order parameters. We find Majorana edge states and flat bands in nodal superconductors. Interestingly, we also find that multiple chiral Majorana modes can exist with certain forms of order parameters.