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**Search for Majorana Fermions in S-Wave Fermionic Superfluids**

**Chuanwei Zhang**  
**UNIVERSITY OF TEXAS AT DALLAS**

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**04/01/2016**  
**Final Report**

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14. ABSTRACT Majorana fermions (MFs) are quantum particles that are their own anti-particles, and satisfy non-Abelian exchange statistics. The latter is the key for their potential use in fault-tolerant topological quantum computation. In this project, we proposed to investigate the possibility of realizing MFs in much more physically robust s-wave superfluids by utilizing two additional components: spin-orbit coupling and Zeeman fields. In the last year grant period, we have made the following important achievements: 1) We found a large BKT transition temperature due to large effective superfluid densities in a spin-orbit coupled Fulde-Ferrell superfluid, making it possible to observe 2D Fulde-Ferrell superfluids at finite temperature; 2) Collaborated with Ian Spielman's group, we demonstrated the tunable spin-orbit coupling through the modulation of the Raman coupling strength in experiments; 3) We found that the spin-orbit coupled Fulde-Ferrell superfluids can support Weyl points or rings with nontrivial topological structures; 4) We proposed and experimentally realized a new type of tunable spin-orbit coupling using optical lattice band pseudospins. The research leads to 23 peer-reviewed publications, including 4 in Physical Review Letters and 1 in Nature Communications.					
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## **Final Progress Report for Award # FA9550-13-1-0045**

**Period:** 02/01/2013-01/31/2016

### **Title: Search for Majorana Fermions in S-Wave Fermionic Superfluids**

PI: Chuanwei Zhang, University of Texas at Dallas

Co-PI: Sumanta Tewari, Clemson University

Program manager: Dr. Tatjana Curcic, Atomic and molecular physics

### **Objectives and research goals**

Majorana fermions were envisioned by E. Majorana in 1935 to describe neutrinos. The Majorana fermions are intriguing because they can be construed as their own anti-particles, unlike Dirac fermions where electrons and positrons (holes) are distinct. Although the emergence of Majorana excitations in physical systems is by itself a truly extraordinary phenomenon, a great deal of recent attention has also been focused on them due to their potential use in fault tolerant topological quantum computation (TQC). However, despite the tremendous technological potential, Majorana fermions have proven to be hard to observe in natural physical systems such as quantum Hall systems and chiral  $p$ -wave superconductors/superfluids.

In this project, we proposed to investigate the possibility of realizing Majorana fermions in much more physically robust  $s$ -wave superfluids by utilizing two additional components: spin-orbit coupling and Zeeman fields. Cold atomic superfluids are excellent platforms for implementing this technique because of the tunability of various parameters as well as the absence of disorder. We proposed to develop concrete experimental procedures and theoretical foundation necessary for observing Majorana fermions and the associated topological phase transitions using experimental techniques which have already been realized for ultra-cold atomic gases.

In the three year grant period, we have made great achievements for realizing the ideas and schemes proposed in the original proposal. In total, we have published over 40 peer-reviewed publications, including 1 in Nature Physics, 3 in Nature Communications, and 7 in Physical Review Letters. Research accomplishments in previous two year grant periods have been reported in details in previous annual reports, therefore here we focus on the last year grant period. In the last year grant period, we have made the following important achievements.

### **Important achievements:**

#### **1. Berezinskii-Kosterlitz-Thouless Phase Transition in 2D Spin-Orbit Coupled Fulde-Ferrell Superfluids**

Yong Xu and Chuanwei Zhang  
**Phys. Rev. Lett. 114, 110401 (2015).**

The experimental observation of traditional Zeeman-field induced Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superfluids has been hindered by various challenges, in particular, the requirement of low dimension systems. In 2D, it is well known that finite temperature phase fluctuations lead to extremely small Berezinskii-Kosterlitz-Thouless (BKT) transition temperature, raising serious concern regarding the observability of 2D FFLO superfluids.

Recently, it was shown that FFLO superfluids can be realized using a Rashba spin-orbit coupled Fermi gas subject to Zeeman fields, which may also support topological excitations such as Majorana fermions in 2D. Here we address the finite temperature BKT transition issue in this system, which may exhibit gapped, gapless, topological, and gapless topological FF phases. We find a large BKT transition temperature due to large effective superfluid densities, making it possible to observe 2D FF superfluids at finite temperature. In addition, we show that gapless FF superfluids can be stable due to their positive superfluid densities. These findings pave the way for the experimental observation of 2D gapped and gapless FF superfluids and their associated topological excitations at finite temperature.

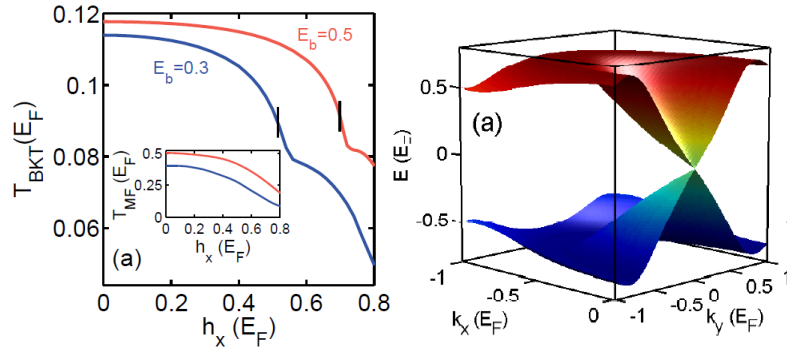


Figure 1: (Left) The change of the BKT transition temperature with respect to the in-plane Zeeman field. (Right) The quasiparticle excitation at the critical point from normal superfluids to topological superfluids.

**2. Structured Weyl Points in Fulde-Ferrell Superfluids,**  
Yong Xu, Fan Zhang, Chuanwei Zhang,  
**Phys. Rev. Lett. 115, 265304 (2015)**

Weyl fermions were initially conceived to describe neutrinos in particle physics. Recently, Weyl fermions have been widely examined in a class of solid-state materials dubbed as Weyl semimetals. Remarkably, these semimetals can be described by Weyl Hamiltonian near their unusual Weyl points, where two linearly dispersed bands cross. In this paper, We demonstrate, for the first time, that a Weyl point can develop a pair of non-degenerate gapless spheres. Such a bouquet of two spheres is characterized by three distinct topological invariants of manifolds with full energy gaps, i.e., the Chern number of a 0D point inside one developed sphere, the winding number of a 1D loop around the original Weyl point, and the Chern number of a 2D surface enclosing the whole bouquet. We show that such structured Weyl points can be realized in the Fulde-Ferrell superfluid quasiparticle spectrum of a 3D degenerate Fermi gas subject to spin-orbit couplings and Zeeman fields.

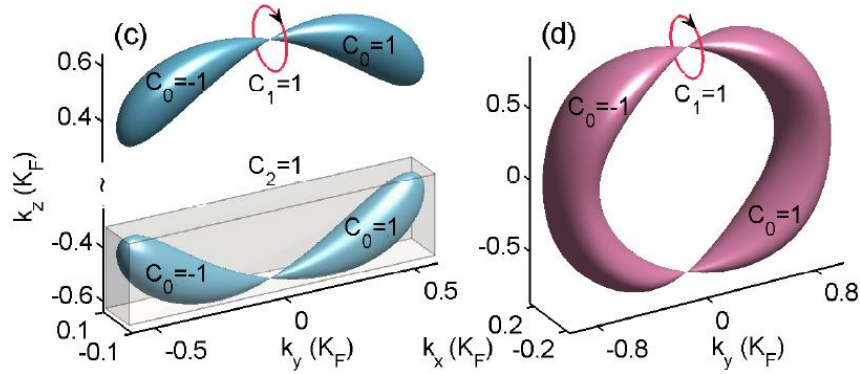


Figure 2: (Left) Structured Weyl points in a FF superfluid.  $C_0$ ,  $C_1$ , and  $C_2$  are three different types of topological Chern numbers. (Right) Connected structured Weyl points.

### 3. Tunable Spin-Orbit Coupling via Strong Driving in Ultracold Atom Systems,

K. Jiménez-García, L. J. LeBlanc, R. A. Williams, M. C. Beeler, C. Qu, M. Gong, C. Zhang, I. B. Spielman,

**Phys. Rev. Lett.** 114, 125301 (2015),

**PRL Editors' Suggestions**

See **Physics News and Commentary**: [On demand spin-orbit coupling](#) by Michael Schirber

The properties of electronic materials are deeply entwined with their bandstructure or more generally, their single-particle spectrum, which gives rise to: conductors, semiconductors, conventional insulators and now topological insulators. Understanding and controlling bandstructure in new ways therefore allows access to new phenomena. Spin-orbit coupling (SOC) plays a fundamental role in most topological materials, linking the spin and the momentum of quantum particles. In ultracold atom systems we precisely design, introduce and manipulate SOC by coupling the internal atomic degrees of freedom with laser. Here, we illuminated an ultracold atom system with a pair of Raman lasers, inducing SOC in an effective two-level system with SOC strength defined by the laser geometry alone. In this letter, we experimentally show that strongly modulating the Raman coupling tunes the SOC strength, independently of geometry and in agreement with theory.

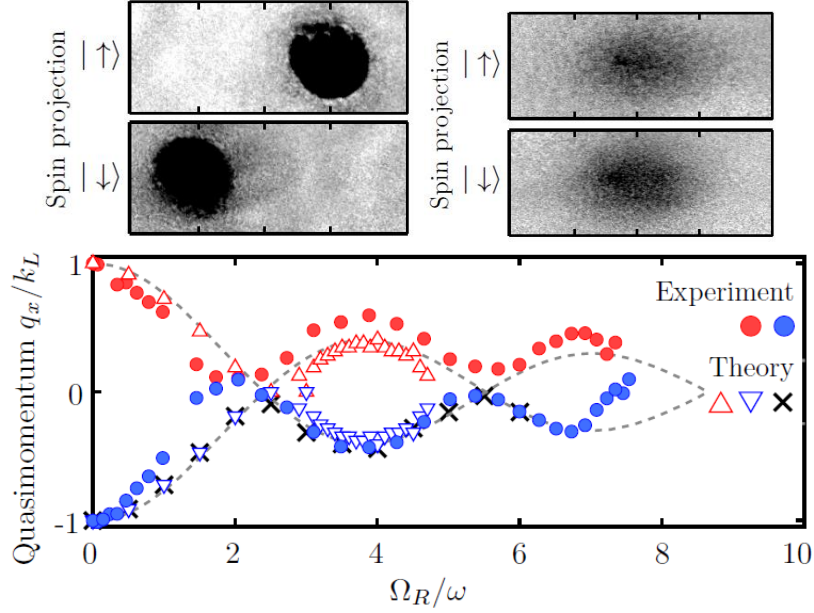


Figure 3: Top: Atom distributions without (left) and with (right) tuning the SOC strength. Bottom: change of the quasimomentum due to tunable SOC.

#### 4. Fulde-Ferrell superfluids without spin imbalance in driven optical lattices

Zhen Zheng, Chunlei Qu, Xubo Zou, and Chuanwei Zhang  
arXiv:1501.00448, **Phys. Rev. Lett.** (in press 2016)

Spin-imbalanced ultra-cold Fermi gases have been widely studied recently as a platform for exploring the long-sought Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superfluid phases, but so far conclusive evidence has not been found. Here we propose to realize an FF superfluid without spin imbalance in a three-dimensional (3D) fermionic cold atom optical lattice, where s- and p-orbital bands of the lattice are coupled by another weak moving optical lattice. Such coupling leads to a spin-independent asymmetric Fermi surface, which, together with the s-wave scattering interaction between two spins, yields an FF type of superfluid pairing. Unlike traditional schemes, our proposal does not rely on the spin imbalance (or an equivalent Zeeman field) to induce the Fermi surface mismatch and provides a completely new route for realizing FF superfluids. The proposed experimental scheme for generating asymmetric band structure has been realized in experiments for a BEC (see the achievement 5 below).

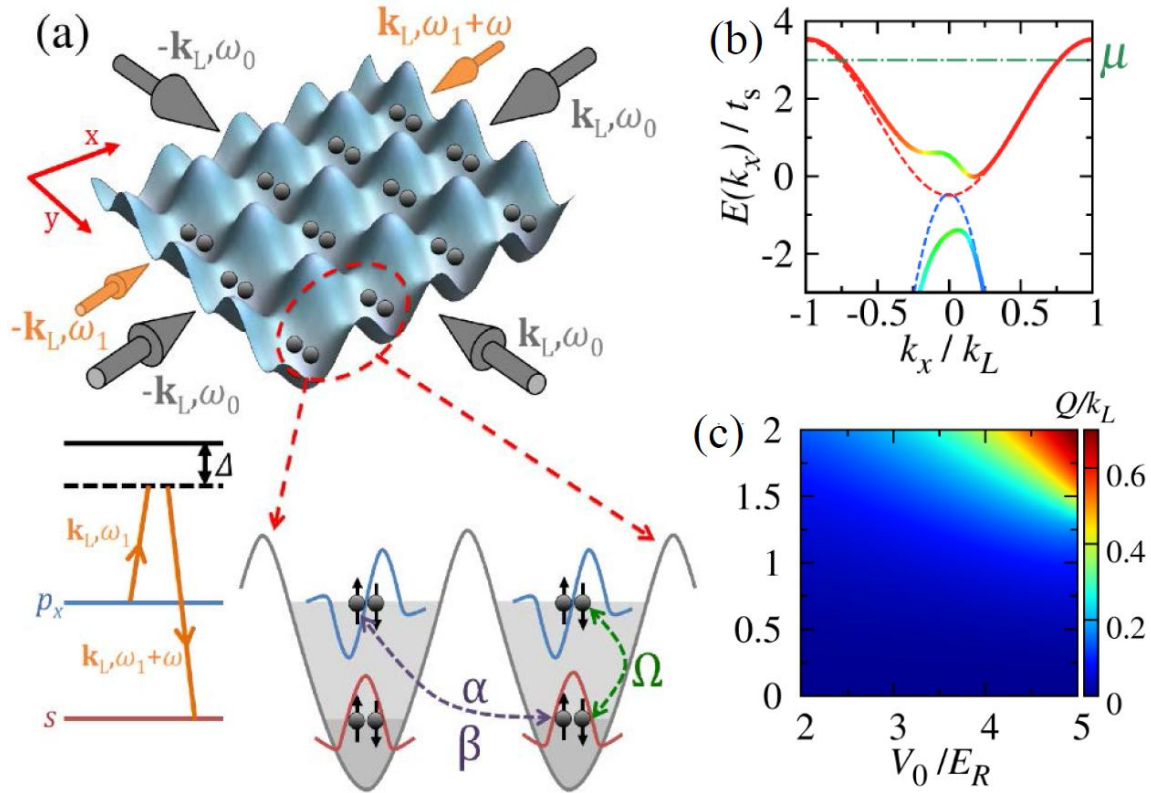


Figure 4: (a) Proposed experimental setup and level diagram for realizing FF superfluids in driven optical lattices. (b) The resulting asymmetric band structure due to the coupling between s- and p-bands. (c) The dependence of the Cooper pair momentum  $Q$  on lattice parameters.

### 5. Spin-momentum coupled Bose-Einstein condensates with lattice band pseudospins

M. A. Kamehchi, Chunlei Qu, M. E. Mossman, Chuanwei Zhang, P. Engels,  
**Nature Communications** 7, 10867 (2016)

The quantum emulation of spin-momentum coupling, a crucial ingredient for the emergence of topological phases, is currently drawing considerable interest. In previous quantum gas experiments, typically two atomic hyperfine states were chosen as pseudospins. Here, we report the observation of a spin-momentum coupling achieved by loading a Bose-Einstein condensate into periodically driven optical lattices. The s and p bands of a static lattice, which act as pseudospins, are coupled through an additional moving lattice that induces a momentum-dependent coupling between the two pseudospins, resulting in s-p hybrid Floquet-Bloch bands. We investigate the band structures by measuring the quasimomentum of the Bose-Einstein condensate for different velocities and strengths of the moving lattice, and compare our measurements to theoretical predictions. The realization of spin-momentum coupling with lattice bands as pseudospins paves the way for engineering novel quantum matter using hybrid orbital bands.

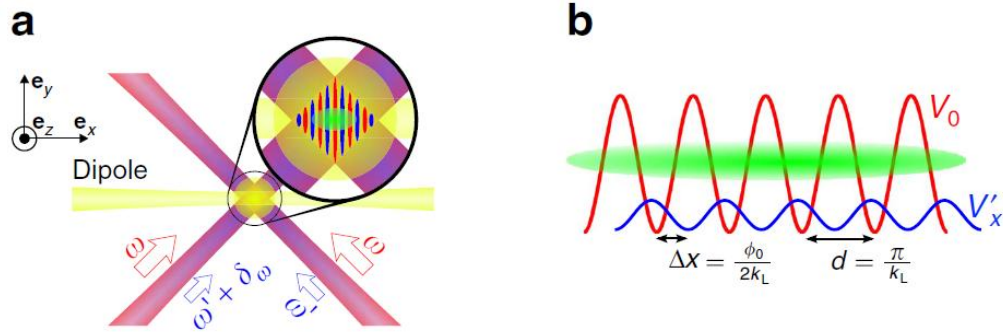


Figure 5: Experimental setup for realizing the spin-momentum coupling with lattice band pseudospins.

**6. Spin-orbital-angular-momentum coupling in Bose-Einstein condensates,**  
Kuei Sun, Chunlei Qu, Chuanwei Zhang  
[Phys. Rev. A 91, 063627 \(2015\)](#)

**& Quantum phases of Bose-Einstein condensates with synthetic spin-orbital-angular-momentum coupling**  
Chunlei Qu, Kuei Sun, Chuanwei Zhang,  
[Phys. Rev. A 91, 053630 \(2015\)](#)

Spin-orbit coupling (SOC) plays a crucial role in many branches of physics. In this context, the recent experimental realization of the coupling between spin and linear momentum of ultracold atoms opens a completely new avenue for exploring new spin-related superfluid physics. We proposed that another important and fundamental SOC, the coupling between spin and orbital angular momentum (SOAM), can be implemented for ultracold atoms using higher-order Laguerre-Gaussian laser beams to induce Raman coupling between two hyperfine spin states of atoms. We studied the ground-state phase diagrams of SOAM-coupled Bose-Einstein condensates on a ring trap and explored their applications in gravitational force detection.

In addition, we studied quantum phases of a realistic Bose-Einstein condensate (BEC) with this synthetic SOAM coupling in a disk-shaped geometry, respecting radial inhomogeneity of the Raman coupling. We found that the experimental system naturally resides in a strongly interacting regime in which the phase diagram significantly deviates from the single-particle picture. The interplay between SOAM coupling and interaction leads to rich structures in spin-resolved position and momentum distributions, including a stripe phase and various types of immiscible states. Our results may provide the basis for further investigation of intriguing superfluid physics induced by SOAM coupling as well as guide the experimental investigation of SOAM-coupled BECs. Experimental investigation of such SOAM coupling is ongoing in several groups.

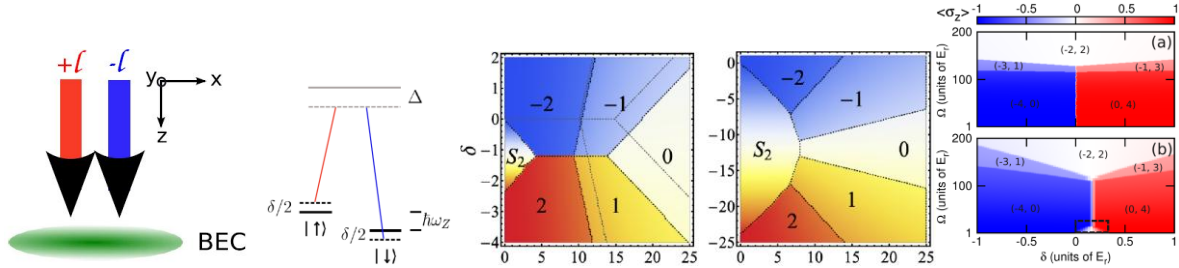


Figure 3: (1,2) Laser setup and level diagram for realizing SOAM coupling. (3-4) Phase diagram for a SOAM coupled BEC on a ring. (5) Phase diagram for a SOAM coupled BEC in a disk shape.

## 7: Tunneling conductance for Majorana fermions in spin-orbit coupled semiconductor-superconductor heterostructures using superconducting leads

G. Sharma, S. Tewari  
arXiv: 1510.07737

It has been recently pointed out that the use of a superconducting (SC) lead instead of a normal metal lead can suppress the thermal broadening effects in tunneling conductance from Majorana fermions, helping reveal the quantized conductance of  $2e^2/h$  which is taken as a smoking gun signature of Majorana quasiparticles. In this work we discuss the specific case of tunneling conductance with SC leads of spin-orbit coupled semiconductor-superconductor (SM-SC) heterostructures in the presence of a Zeeman field, a system which has been extensively studied both theoretically and experimentally using a metallic lead. We examine the  $dI/dV$  spectra using a SC lead for different sets of physical parameters including temperature, tunneling strength, wire length, magnetic field, and induced SC pairing potential in the SM nanowire. We conclude that in a finite wire the Majorana splitting energy  $\Delta E$ , which has non-trivial dependence on these physical parameters, remains responsible for the  $dI/dV$  peak broadening, even when the temperature broadening is suppressed by the SC gap in the lead. In a finite wire the signatures of Majorana fermions with a SC lead are oscillations of quasi-Majorana peaks about bias  $V = \pm\Delta_{\text{lead}}$ , in contrast to the case of metallic leads where such oscillations are about zero bias. Our results will be useful for analysis of future experiments on SM-SC heterostructures using SC leads.

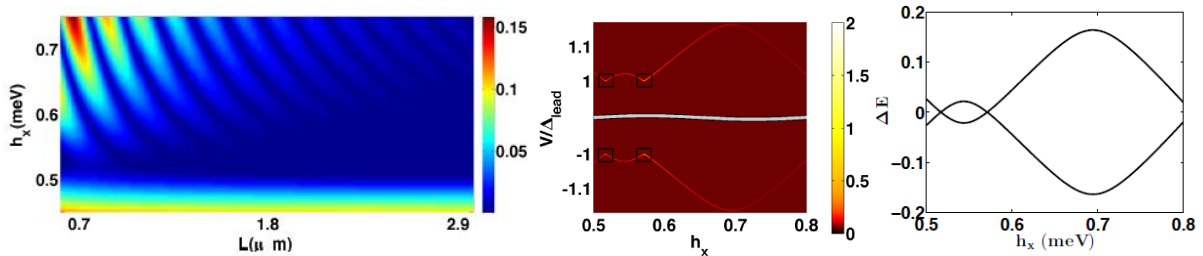


Fig.7. Left: Majorana splitting energy  $\Delta E$  as a function of length of the wire  $L$  and applied magnetic field  $h_x$ , showing oscillations for small  $L$  values, for a wide range of  $h_x$  above the topological phase transition at  $h_x = 0.5$  meV. The amplitude of oscillations in  $\Delta E$  subsequently suppressed for wires with longer length. The value of SC gap chosen for these plots was  $\Delta = 0.5$  eV, and the color bar on the right is in the units of meV. Middle: Majorana  $dI/dV$  profile with a superconducting lead for a short wire of length  $L = 0.5 \mu\text{m}$ , showing oscillations about  $V =$

$\pm\Delta_{lead}$  as a function of magnetic field  $h_x$  (in meV). The color bar on the right is in the unit of  $e^2/h$  and the value of SC gap chosen was  $\Delta= 0.5\text{meV}$ . The four square boxes highlight the regions where the quantized peak height of magnitude  $G_M = (4 - \pi) e^2/h$  should be observed. Right: The energy splitting  $\Delta E$  (in meV) as a function of  $h_x$  for the same system, showing oscillations about zero energy. In an experiment done with a normal metallic lead instead of a superconducting lead, the oscillations will be about zero bias voltage in a similar fashion as displayed here.

## 8: Spin polarization of Majorana zero modes and topological quantum phase transition in semiconductor Majorana nanowires

T. D. Stanescu, S. Tewari  
arXiv: 1603.02255

A number of recent works have discussed the issue of spin polarization of a Majorana zero mode in low temperature systems. In this work we show that the spin polarization density of a Majorana zero mode, computed as an average of the spin operator over its wave function, is identically zero. A single non-degenerate Majorana zero mode, therefore, does not couple to an applied magnetic field, except via hybridization with higher energy excited states (if present), which may perturb its wave function. If spin is defined by considering only the particle components of the wave function, as has been done in some recent works, Majorana zero modes do have a non-zero spatial profile of this quantity, which is measurable in scanning tunneling microscopy (STM) experiments. However, if such a quantity is measured in spin-resolved tunneling experiments (without spatial resolution), we show that it cannot be used as a unique signature of Majorana zero modes in the topologically non-trivial phase. As a byproduct, we show in this work that in spatially inhomogeneous systems (specifically, in systems with a soft boundary), accidental zero energy modes (which for all practical purposes behave as Majorana zero modes) can appear with increasing magnetic field even in the absence of a topological quantum phase transition (TQPT). But only after gap closing and the associated TQPT, the modes are localized near the system edges, resulting in the maximum topological protection. In light of these considerations, demonstrating the nonlocal character of the topologically-protected Majorana pair and its emergence after the systems undergo a TQPT, become critical tasks for the ongoing experimental search for Majorana bound states in low temperature systems.

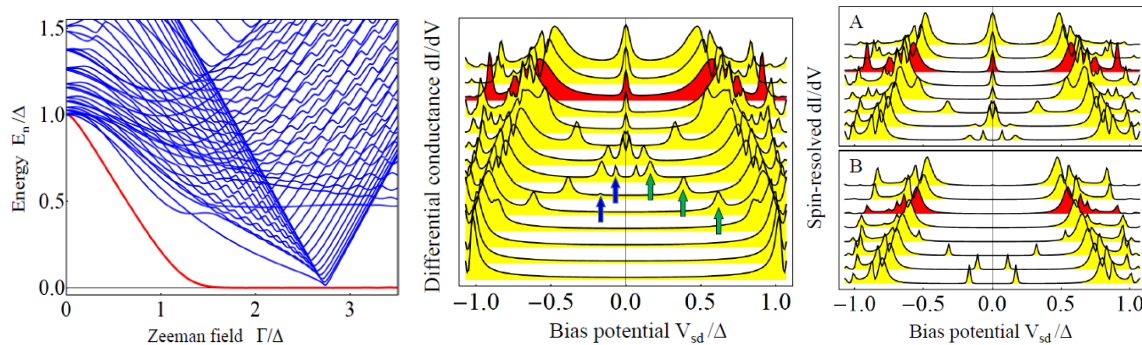


Fig. 8. Left: Dependence of the low-energy BdG spectrum on the applied Zeeman field for a system of superconducting chains with smooth confinement. Only the positive energies are shown. Note the vanishing of the bulk gap (blue lines) at the critical field  $\Gamma = \Gamma_c \sim 2.7 \Delta$ , which signals a topological quantum phase transition. Note that remarkable result that the zero-energy

mode extends into the topologically trivial phase for  $\Gamma < \Gamma_c$ . Middle: Differential conductance as a function of the bias potential for different values of the Zeeman field ranging from  $\Gamma = 0$  (lowest curve) to  $\Gamma = 3.5 \Delta$  (top curve) in steps of  $0.25 \Delta$ . The curves have been shifted for clarity. The red-filled curve corresponds to  $\Gamma = \Gamma_c \sim 2.75 \Delta$ ; note the absence of any signature associated with the closing of the bulk gap and the emergence of a zero-bias peak for  $\Gamma < \Gamma_c$  (i.e. in the topologically-trivial regime). The peaks marked by blue arrows, which merge into the zero-bias peak, correspond to the lowest energy mode (red line) in top left, while the peaks marked by green arrows are associated with Andreev bound states localized inside the potential barrier region. Right: Differential conductance for spin-resolved tunneling into the end of the wire. The Zeeman field ranges from  $\Gamma = 1.5 \Delta$  (lowest curves) to  $\Gamma = 3.25 \Delta$  (top curves) in steps of  $0.25 \Delta$ . Panel A corresponds to the tunneling of electrons with spin parallel to the applied Zeeman field, while panel B shows the differential conductance corresponding to the opposite spin orientation. Note that that the zero bias peak is absent when tunneling electrons with a spin-orientation opposite to the spin polarization of the leftmost Majorana bound state.

**Publications supported by the grant in this period (include 4 Phys. Rev. Lett., 1 Nature Communications, 10 Phys. Rev. A and B, 1 Scientific Reports, 1 selected as PRL Editors' Suggestions and reported by Physics News and Commentary)**

Underlined authors: graduate students and postdoctors supervised by the PIs.

1. Yong Xu, **Chuanwei Zhang**, *Dirac and Weyl Rings in Three Dimensional Cold Atom Optical Lattices*,  
[arXiv:1510.03355](https://arxiv.org/abs/1510.03355)
2. Zengming Meng, Lianghai Huang, Peng Peng, Donghao Li, Liangchao Chen, Yong Xu, **Chuanwei Zhang**, Pengjun Wang, Jing Zhang, *Experimental observation of topological band gap opening in ultracold Fermi gases with two-dimensional spin-orbit coupling*,  
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3. Beibing Huang, Pak Hong Chui, Jia Liu, **Chuanwei Zhang**, Ming Gong, *Topological superfluids with time-reversal symmetry from  $s$ -wave interaction in a bilayer system*,  
[arXiv:1511.01713](https://arxiv.org/abs/1511.01713)
4. Lei Jiang, Chunlei Qu, **Chuanwei Zhang**, *1D topological chains with Majorana fermions in 2D non-topological optical lattices*,  
[arXiv:1503.01810](https://arxiv.org/abs/1503.01810)
5. Zhen Zheng, Chunlei Qu, Xubo Zou, **Chuanwei Zhang**, *Fulde-Ferrell superfluids without spin-imbalance in three-dimensional driven spinful fermionic optical lattices*,  
[arXiv:1501.00448](https://arxiv.org/abs/1501.00448), to appear in Phys. Rev. Lett.
6. Kuei Sun, Chunlei Qu, Yong Xu, Yongping Zhang, **Chuanwei Zhang\***, *Interacting spin-orbit-coupled spin-1 Bose-Einstein condensates*,  
[Phys. Rev. A 93, 023615 \(2016\)](https://doi.org/10.1103/PhysRevA.93.023615).
7. M. A. Khomehchi, Chunlei Qu, M. E. Mossman, **Chuanwei Zhang\***, P. Engels\*, *Spin-momentum coupled Bose-Einstein condensates with lattice band pseudospins*,  
[Nature Communications 7, 10867 \(2016\)](https://doi.org/10.1038/ncomms10867)
8. Yong Xu, Fan Zhang, **Chuanwei Zhang\***, *Structured Weyl Points in Spin-Orbit Coupled Fermionic Superfluids*,  
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9. Yuri Gartstein\*, Xiao Li, and **Chuanwei Zhang\***, *Exciton-polaritons in transition-metal dichalcogenides and their direct excitation via energy transfer*,  
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[Phys. Rev. A 92, 013633 \(2015\)](#)
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13. Kuei Sun, Chunlei Qu, **Chuanwei Zhang\***, *Spin-orbital-angular-momentum coupling in Bose-Einstein condensates*  
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[Phys. Rev. A 91, 053630 \(2015\)](#)
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[Phys. Rev. Lett. 114, 125301 \(2015\)](#), **Editors' Suggestions, Featured in Physics**  
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18. Yong Xu, **Chuanwei Zhang\***, *Berezinskii-Kosterlitz-Thouless Phase Transition in 2D Spin-Orbit Coupled FF Superfluids*,  
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19. G. Sharma, **S. Tewari**, P. Goswami, Victor M. Yakovenko, S. Chakravarty, *A Calculation of polar Kerr effect in high temperature cuprate superconductors*,  
[Phys. Rev. B 93, 075156 \(2016\)](#).
20. G. Sharma, P. Goswami, **S. Tewari**, *Nernst and magneto-thermal conductivity in a lattice model of Weyl fermions*,  
[Phys. Rev. B 93, 035116 \(2016\)](#).
21. G. Sharma, **S. Tewari**, *Tunneling conductance for Majorana fermions in spin-orbit coupled semiconductor-superconductor heterostructures using superconducting leads*,  
[arXiv: 1510.07737](#)
22. K. Seo, J. D. Sau, **S. Tewari**, *Robust Zero Energy Bound States Localized at Magnetic Impurities in Iron-based Superconductors*,  
[arXiv: 1512.03450](#)

23. T. D. Stanescu, and S. Tewari, *Spin polarization of Majorana zero modes and topological quantum phase transition in semiconductor Majorana nanowires*,

[arXiv:1603.02255](https://arxiv.org/abs/1603.02255)

### Invited talks

- **PI Chuanwei Zhang**

1. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, Condensed Matter Seminar, The University of California at San Diego, Oct 2015, San Diego, California
2. *Majorana fermions and topological quantum computation*, Physics Colloquium, The University of Texas at San Antonio, Sep 2015, San Antonio, Texas
3. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, AMO seminar, Eastern China Normal University, June 2015, Shanghai, China
4. *Majorana fermions and topological quantum computation*, Physics Colloquium, Eastern China Normal University, June 2015, Shanghai, China
5. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, Seminar in Wilczek Quantum Center, Zhejiang University of Technology, May 2015, Hangzhou, China
6. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, AMO seminar, University of Science and Technology of China, May 2015, Hefei, China
7. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, Condensed Matter Seminar, Beijing University, May 2015, Beijing, China
8. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, AMO seminar, Shanxi University, May 2015, Taiyuan, China
9. *Majorana fermions and topological quantum computation*, Physics Colloquium, Physics Colloquium, Shanxi University, May 2015, Taiyuan, China
10. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, American Physical Society March Meeting invited talk, March 2015, San Antonio, Texas

- **PI Sumanta Tewari**

1. *Lectures/short course (3 lectures) on Majorana fermions in topological superconductors/superfluids*, Indian Institute of Science Education and Research (IISER), Pune, India, August, 2015
2. *“Quest for the quirky quantum particle comes good: Search for Majorana fermions in topological superconductors”*, Indian Institute of Science Education and Research (IISER), Pune, India, August, 2015

1.

**1. Report Type**

Final Report

**Primary Contact E-mail****Contact email if there is a problem with the report.**

chuanwei.zhang@utdallas.edu

**Primary Contact Phone Number****Contact phone number if there is a problem with the report**

972-883-4520

**Organization / Institution name**

University of Texas at Dallas

**Grant/Contract Title****The full title of the funded effort.**

Search for Majorana Fermions in S-Wave Fermionic Superfluids

**Grant/Contract Number****AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".**

FA9550-13-1-0045

**Principal Investigator Name****The full name of the principal investigator on the grant or contract.**

Chuanwei Zhang

**Program Manager****The AFOSR Program Manager currently assigned to the award**

Tatjana Curcic

**Reporting Period Start Date**

02/01/2013

**Reporting Period End Date**

01/31/2016

**Abstract**

Majorana fermions (MFs) are quantum particles that are their own anti-particles, and satisfy non-Abelian exchange statistics. The latter is the key for their potential use in fault-tolerant topological quantum computation. In this project, we proposed to investigate the possibility of realizing MFs in much more physically robust s-wave superfluids by utilizing two additional components: spin-orbit coupling and Zeeman fields. In the last year grant period, we have made the following important achievements: 1) We found a large BKT transition temperature due to large effective superfluid densities in a spin-orbit coupled Fulde-Ferrell superfluid, making it possible to observe 2D Fulde-Ferrell superfluids at finite temperature; 2) Collaborated with Ian Spielman's group, we demonstrated the tunable spin-orbit coupling through the modulation of the Raman coupling strength in experiments; 3) We found that the spin-orbit coupled Fulde-Ferrell superfluids can support Weyl points or rings with nontrivial topological structures; 4) We proposed and experimentally realized a new type of tunable spin-orbit coupling using optical lattice band pseudospins. The research leads to 23 peer-reviewed publications, including 4 in Physical Review Letters and 1 in Nature Communications.

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**Change in AFOSR Program Manager, if any:**

**Extensions granted or milestones slipped, if any:**

**AFOSR LRIR Number**

**LRIR Title**

**Reporting Period**

**Laboratory Task Manager**

**Program Officer**

**Research Objectives**

**Technical Summary**

**Funding Summary by Cost Category (by FY, \$K)**

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

**Report Document**

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**Appendix Documents**

**2. Thank You**

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