NCTS-ITHEMS JOINT WORKSHOP ON

MATTERS TO SPACETIME: SYMMETRIES AND GEOMETRY

AUGUST 26-29, 2024, NATIONAL CENTER FOR THEORETICAL SCIENCES, TAIPEI, TAIWAN

Day 1: Aug. 26		
Time	Speaker	Talk Title
09:00~09:30	Registration	
Chair : Ching-Kai Chiu, Yang-Hao Chan (Workshop Co-Chairs)		
09:30~09:40	Prof. Guang-Yu Guo	Directors' opening remark
Chair : Ching-Kai Chiu		
09:40~10:30	Plenary Talk: Vic Kam Tuen Law	Quantum Metric Length in Flat Band Superconductors
10:30-11:00	Break	
Chair : Pei-Ming Ho		
11:00~11:30	Christy Kelly	Baby Universes and Branching Singularities in Euclidean Quantum Gravity
11:30~12:00	Ken Kikuchi	Proving spontaneous symmetry breaking
12:00-14:00	Lunch (Registered Participant Only)	
Chair : Po-Yao Chang		
14:00~14:30	Chang-Tse Hsieh	Generalized Lieb-Schultz-Mattis theorem for 1d quantum magnets
14:30~15:00	Steffen Backes	Symmetry properties of the Coulomb interaction tensor and their implications in correlated electron systems
15:00~15:30	Yung-Yeh Chang	A mechanism for the strange metal phase in rare-earth intermetallic compounds
15:30~16:00	Break	
Chair : Che-Yu Chen		
16:00~16:30	Yuki Yokokura	Black Hole from Entropy Maximization
16:30~17:00	Amaury Micheli	Simulating a preheating scenario in the lab?
17:00~18:00	Free Discussion	
18:00~	Dinner (Invited Only)	

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Day 2: Aug. 27		
Time	Speaker	Talk Title
Chair : Satoshi Iso		
09:30~10:00	Chong-Sun Chu	A proposal for quantum gravity and quantum mechanics of black hole
10:00~10:30	Puttarak Jai-akson	Corner Symmetries and Quasi-Local Holography
10:30-11:00	Break	
Chair : Chang-Tse Hsieh		
11:00~11:30	Yu-tin Huang	Quantum Gravity constraints on global symmetries
11:30~12:00	Po-Hao Chou	Curvature induced effects in the surface states of topological insulators
12:00-14:00	Lunch (Registered Participant Only)	
Chair : Chen-Hsuan Hsu		
14:00~14:30	Guang-Yu Guo	Quantum geometry and nonlinear electromagnetic responses of solids
14:30~15:00	Tomoki Ozawa	Quantum metric and topology
15:00~15:30	Ching-Kai Chiu	Exploring Topological States with superconductivity or with twists
15:30~18:00	Free Discussion	
18:00~	Banquet (Registered Participant Only)	

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Day 3: Aug. 28		
Time	Speaker	Talk Title
Chair : Guang-Yu Guo		
09:30~10:00	Seishiro Ono	Fermi-surface diagnosis for topological superconductivity
10:00~10:30	Tay-Rong Chang	Feature-energy duality of topological boundary states in multilayer quantum spin Hall insulator
10:30-11:00	Break	
Chair : Yuki Yokokura		
11:00~11:30	Osamu Fukushima	Higher-form symmetry and eigenstate thermalization hypothesis
11:30~12:00	Himanshu Parihar	Massless Lifshitz Field Theory for Arbitrary z
12:30-15:00	Lunch (Registered Participant Only) and Free Discussion	

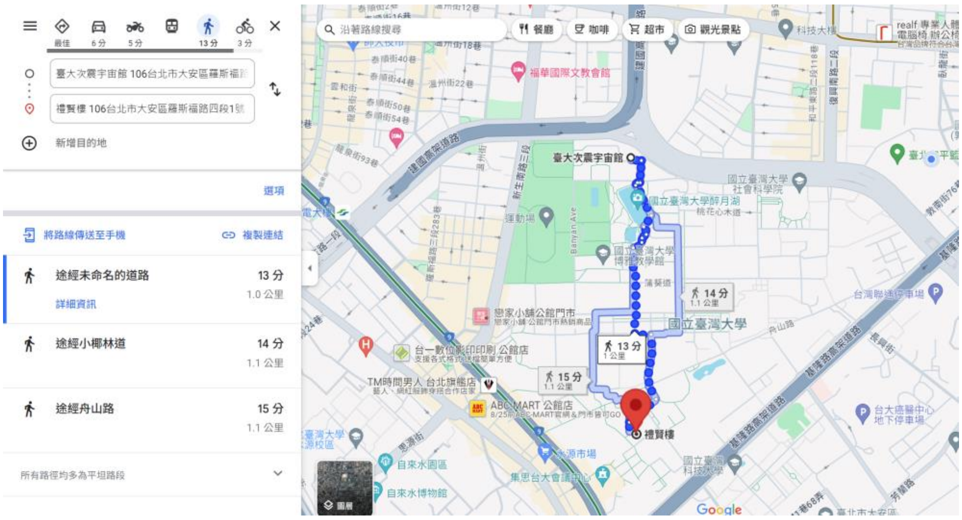
Day 4: Aug. 29		
Time	Speaker	Talk Title
Chair : Yu-tin Huang		
09:30~10:00	Okuto Morikawa	Lattice implementation of generalized symmetry and ’t Hooft anomaly
10:00~10:30	Yuto Moriwaki	Algebraic structure of space-time geometry and operator product expansion
10:30~11:00	Break	
Chair : Yang-Hao Chan		
11:00 ~ 11:30	Yuta Sekino	Tunneling spin and heat transport in ultracold atomic systems
11:30~12:00	Chen-Hsuan Hsu	Topological superconductivity in proximitized double helical liquids
12:00~12:10	Dr. Satoshi Iso	Closing remark
12:10-15:00	Lunch (Registered Participant Only) and Free Discussion	

8/26 Dinner (Invited Only)

[品軒樓](#)

位於台大校園禮賢樓二樓 2F, Lixian Hall, NTU

地圖：https://maps.app.goo.gl/n9j9tq5YFzJf5JU76



8/27 Banquet (Registered Participant Only)

水源福利會館 La Marée https://www.lamaree.com.tw/gongguan/

台北市中正區思源街 16 號 2 樓

2F, No.16, Siyuan St., Zhongzheng Dist., Taipei City 100, Taiwan.

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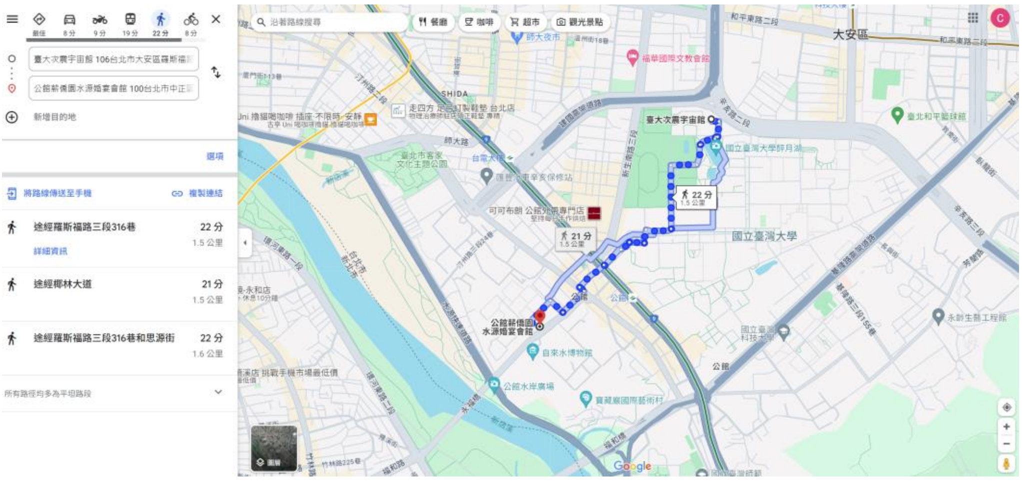

Quantum Metric Length in Flat Band Superconductors

Vic Kam Tuen LAW 羅錦團 (Hong Kong University of Science and Technology)

Recently, it has been observed that superconducting and interaction-driven quantum anomalous Hall states can appear simultaneously in gate-defined Josephson junctions in twisted bilayer graphene [1]. The interaction-driven state serves as the weak link in the superconductor/correlated state/superconductor Josephson junction. In this talk, we will discuss how the interaction-driven valley polarization is essential for the Josephson diode effect observed in experiments [2]. Moreover, many of the superconducting properties of moiré superconductors with ultra-flat bands deviate greatly from conventional BCS theory predictions [3]. In the second half of the talk, I would like to present a Ginzburg-Landau theory derived from a microscopic flat band Hamiltonian, which incorporates the quantum metric effects of moiré flat band superconductors [4,5,6]. The theory explains how the length scale defined by quantum metric, which we call the quantum metric length, is critically important in determining the properties of moiré flat band superconductors and topological superconductors with flat bands [7].

[1] J Díez-Mérida, A Díez-Carlón, SY Yang, Y-M Xie, X-J Gao, J Senior, K Watanabe, T Taniguchi, X Lu, AP Higginbotham, KT Law, Dmitri K Efetov, Nature Communications 14: 2396 (2023).

[2] Jin-Xin Hu, Zi-Ting Sun, Ying-Ming Xie, K. T. Law, Physical Review Letters 130 , 266003 (2023).

[3] Haidong Tian, et al. Nature 614, 440 (2023).

[4] Shuai A Chen, KT Law, Phys. Rev. Lett. 132, 026002 (2024).

[5] Jin-Xin Hu, Shuai A Chen, KT Law, arXiv:2308.05686.

[6] Zhong CF Li, Yuxuan Deng, Shuai A Chen, Dmitri K Efetov, KT Law, arXiv:2404.09211.

[7] Xingyao Guo, Xinglei Ma, Xuzhe Ying, KT Law, arXiv:2406.05789.

Baby Universes and Branching Singularities in Euclidean Quantum Gravity

Christy Kelly (RIKEN iTHEMS)

Accepting that quantum fluctuations may lead to changes in the topology of space(time), it is natural to imagine that so-called baby universes will `branch off' from the main `trunk' of spacetime. In a Euclidean framework, such baby universes represent the tunnelling of a small universe to nothing. When Euclidean quantum gravity is described as the scaling limit of a statistical theory of random (dynamical) triangulations, the nucleation of baby universes totally dominates in dimensions $D>2$ for entropic reasons and the theory is described by a so-called branched polymer phase. This is a pathological model of the effective geometry of high dimensional quantum spacetime. We argue that this type of branching singularity can be cured through the consideration of a scaling limit in which branching (baby universe nucleation) is suppressed for dynamical reasons. We also show that this can be achieved using a suitable regularisation of the Einstein-Hilbert action. The choice of regularisation can be related in a systematic manner to a choice of topology on the space of triangulations. In general a choice of topology on the space of discretised field configurations encodes subtle properties of the quantum field in question, from the degree of localisability, to mesoscopic and long range (infrared) properties such as the nature of the symmetries of the field. Concretely, these properties become manifest through the way the topology on the space of discrete configurations determines the support of the limiting path-integral measure.

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Proving spontaneous symmetry breaking

Ken Kikuchi (NTU)

The problem in quantum field theory (QFT) has the following structure; problems are theories defined at short distances (or ultraviolet, UV), and answers are their long distance (or infrared, IR) behaviors. An example is the quantum chromodynamics (QCD); it is defined in UV as an SU(3) gauge theory with matter fields (problem). Its IR theory is believed (conjectural answer) to be gapped, confined (e.g. for adjoint quarks), and have spontaneously broken chiral symmetry (for massless quarks). However, since the theory becomes strongly-coupled in IR, we have not succeeded to show these IR behaviors. In this talk, we assume IR theories are gapped just like QCD, and mathematically prove certain spontaneous symmetry breaking. More detailed study constrains allowed ground state degeneracies to only a few numbers. The constraints refine the Lieb-Schultz-Mattis theorem.

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Symmetry properties of the Coulomb interaction tensor and their implications in correlated electron systems

Steffen Backes (RIKEN Quantum)

To study the properties of strongly correlated electron materials, effective low-energy models for the electron part of the full Hamiltonian are highly popular and successful. In these models, the interaction term is given by the electron-electron Coulomb interaction, which is a four-index tensor with a highly non-trivial structure. For realistic multi-orbital models, the determination of suitable Coulomb tensor elements as well as a systematic study of their effect on the electronic properties thus becomes difficult.

In this talk I will discuss the constraints imposed by the atomic symmetry groups induced by the crystal symmetry on the form of the Coulomb interaction, and how the resulting non-zero elements can be obtained from a minimal set of physically meaningful parameters for specific systems.

I will present examples for the Coulomb terms for real materials obtained from material-specific approximate methods and discuss cases where the symmetry properties show a non-trivial effect on the electronic structure. Using exact diagonalization of finite systems and the dynamical mean-field theory for lattice models and real materials, I will present the impact of these terms on electronic properties such as the spectral function.

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A mechanism for the strange metal phase in rare-earth intermetallic compounds

Yung-Yeh Chang (AS)

A major mystery in strongly interacting quantum systems is the microscopic origin of the “strange metal” phenomenology, with unconventionalmetallic behavior that defies Landau’s Fermi liquid framework for ordinary metals. This state is found across a wide range of quantum materials, notably in rare-earth intermetallic compounds at finite temperatures (T) near a magnetic quantum phase transition, and shows a quasilinear-in-temperature resis- tivity and a logarithmic-in-temperature specific heat coefficient. Recently, an even more enigmatic behavior pointing toward a stable strange metal ground state was observed in CePd1−xNixAl, a geometrically frustrated Kondo lattice compound. Here, we propose a mechanism for such phenomena driven by the in- terplay of the gapless fermionic short-ranged antiferromagnetic spin correlations (spinons) and critical bosonic charge (holons) fluctuations near a Kondo breakdown quantum phase transition. Within a dynamical large-N approach to the Kondo–Heisenberg lattice model, the strange metal phase is realized in transport and thermodynamical quantities. It is manifested as a fluctuating Kondo-scattering–stabilized critical (gapless) fermionic spin-liquid metal. It shows ω/T scaling in dynamical electron scattering rate, a signature of quantum criticality. Our results offer a qualitative understanding of the CePd1−xNixAl compound and suggest a possibility of realizing the quantum critical strange metal phase in correlated electron systems in general.

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Black Hole from Entropy Maximization

Yuki Yokokura (RIKEN iTHEMS)

One quantum characterization of a black hole is that it maximizes thermodynamic entropy for a given surface area. In the context of quantum gravity, this could be more fundamental than the classical characterization by a horizon. As a first step, we explore this possibility by solving the 4D semi-classical Einstein equation with many matter fields for spherical static configurations, and find the unique picture of a black hole, i.e. a condensed configuration of self-gravitating quanta without horizon or singularity. The interior metric is a self-consistent and non-perturbative solution for Planck's constant. The maximum entropy, given by the volume integral of the entropy density, agrees exactly with the Bekenstein-Hawking formula through self-gravity, deriving the Bousso bound for thermodynamic entropy. We finally see the speculative view that the configuration represents semi-classically a quantum-gravitational condensate. [arXiv:2309.00602]

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Simulating a preheating scenario in the lab?

Amaury Micheli (RIKEN iTHEMS)

First, I will briefly present the motivations and formalism originally underpinning the analogue gravity programme.

I will then describe an experiment that aims at simulating several features of the preheating scenario.

The talk will be mainly dedicated to the early-time parametric creation of particle pairs out of the quantum vacuum and the evolution of entanglement that is a signature of it.

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A proposal for quantum gravity and quantum mechanics of black hole

Chong-Sun Chu (NTHU/NCTS)

We propose a quantum mechanical theory of quantum spaces described by large N noncommutative geometry as a model for quantum gravity. The theory admits fuzzy sphere and fuzzy ellipsoid as solution. We show that these solutions reproduces precisely the horizon radius of a Schwarzschild black hole and a Kerr black hole.
Moreover our quantum mechanical description gives rise to a set of microstates over these geometries, which reproduces precisely the Bekenstein-Hawking entropy of black hole. These results provide strong support that our proposed theory of quantum spaces is a plausible candidate for the theory of quantum gravity.

The seminar is based on the following papers: 2406.01466, 2406.12704.

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Corner symmetries, Quasi-local holography, and Carrollian geometro-hydrodynamics

Puttarak Jai-akson (RIKEN iTHEMS)

Boundaries, whether at asymptotic infinities or finite distances (such as black hole horizons or entangling cuts), hold a special status in the context of gauge theories and gravity. Through the Noether theorems, these boundaries transform the gauge redundancy of the theory into physical symmetries, encoded in corner (codimension-2) charges and their algebras. The presence of non-trivial corner symmetries at any boundary imposes stringent constraints on the mathematical structure of the theory and serves as a guide for quantization. In this talk, I will review the key ideas and developments of the quasi-local holography program based on the corner symmetries of gravity. Finally, I will discuss the recent understanding of gravitational dynamics along null surfaces as the conservation of symmetry charges associated with a Carrollian fluid.

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Quantum metric and topology

Tomoki Ozawa (Tohoku University)

In this talk, I will introduce the concept of quantum metric relevant in physics of topological insulators and discuss its relations to topology, especially the Chern number in two dimensional settings. Quantum metric is the metric defined in a parameter space (often quasi-momentum space) induced from the quantum states defined on the parameter space. It is a geometric quantity similar to the Berry curvature, and has some relations to topological structures of quantum states on the parameter space. I will discuss, in particular, the inequality between the Chern number, which is a topological invariant of quantum states defined in a two-dimensional parameter space, and the quantum volume, which is the area of the two-dimensional parameter space measured using the quantum metric. The condition that this inequality saturates leads to interesting classes of energy bands called the Kähler bands or ideal Chern bands, which are similar to lowest Landau levels and relevant in certain limits of twisted bilayer graphene.

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Exploring Topological States with superconductivity or with twists

Ching-Kai Chiu (RIKEN iTHEMS)

Holomorphic functions are a crucial mathematical concept with significant applications across various sub-fields of physics, including conformal field theory and condensed matter physics. In this talk, I will demonstrate the use of holomorphic functions to establish the presence of energy flat bands in twisted bilayer graphene and other bilayer systems. Prior to delving into the mathematical application, I will provide an introduction to twisted bilayer graphene and our classification work on twisted bilayers based on topological nodes.

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Fermi-surface diagnosis for topological superconductivity

Seishiro Ono (RIKEN iTHEMS)

Theoretical prediction of topological superconductivity is key to their discovery. Recently, it has been proved that in 199 out of 230 space groups, topological superconductivity coexists with an s-wave-like pairing symmetry, raising the hope of finding more candidates for this exotic phase. However, a comprehensive and efficient method for diagnosing topological superconductivity in realistic materials remains elusive. Here, we derive Fermi-surface formulas for gapped and gapless topological phases of time-reversal symmetric superconductors with s-wave-like pairing symmetries in all layer and space groups, applicable to thin-film and bulk materials. Our diagnosis uses only the sign of the pairing and the Fermi velocity at several Fermi points, and yields complete (partial) diagnosis for gapped topological superconductivity in 159 (40) out of the 199 space groups. This provides a fundamental basis for the first-principles prediction of new topological superconductors.

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Higher-form symmetry and eigenstate thermalization hypothesis

Osamu Fukushima (RIKEN iTHEMS)

The eigenstate thermalization hypothesis (ETH) is a successful framework that provides criteria for thermalization in isolated quantum systems. We elucidate how the presence of higher-form symmetries affects the ETH. Under reasonable assumptions, we analytically show that a p-form symmetry in a (d+1)-dimensional quantum field theory leads to the breakdown of the ETH for many nontrivial (d−p)-dimensional observables. For higher-form (i.e., p≥1) symmetry, this implies the absence of thermalization for observables that are non-local but much smaller than the whole system size. We numerically demonstrate this argument for the (2+1)-dimensional $\mathbb{Z}2$ lattice gauge theory. While local observables such as the plaquette operator thermalize even for mixed symmetry sectors, the non-local observable exciting a magnetic dipole instead relaxes to the generalized Gibbs ensemble that takes account of the $\mathbb{Z}2$ 1-form symmetry.

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Massless Lifshitz Field Theory for Arbitrary z

Himanshu Parihar (NCTS)

In this talk, I will present our recent work on the construction of the Lifshitz scale invariant ground state and its entanglement properties for an arbitrary dynamical exponent z using the path integral representation. In this context, we introduce a class of massless Lifshitz scalar field theory in (1+1)-dimension with an arbitrary z using the concept of fractional derivatives and find that the ground state of the theory takes the form of Rokhsar-Kivelson (RK) vacuum. We show that there is a continuous family of ground states with degeneracy parameterized by the choice of solution to the equation of motion of an auxiliary classical system. Subsequently, the computation of various entanglement measures like entanglement entropy, mutual information, reflected entropy and Markov gap in this theory will be presented. Finally, we consider the holographic description of the Lifshitz field theory. In order to match with the field theory result for the entanglement entropy, we propose a z-dependent radius scale for the Lifshitz background.

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Lattice implementation of generalized symmetry and ’t Hooft anomaly

Okuto Morikawa (RIKEN iTHEMS)

Recently, the notion of symmetry is generalized in terms of topological operators so that we can get further information on dynamics in strongly coupled field theories. It would be crucial that topology of gauge fields is nontrivial in a fully regularized framework; e.g., continuity appears to be lost under lattice regularization. We apply lattice construction to generalized symmetries and observe topological phenomena even on the lattice. Lattice SU(N) gauge theories can be coupled with Z_N 2-form gauge fields, and then the topological charge possesses fractionality on an appropriate principal bundle; the mixed 't Hooft anomaly is realized. We become interested in monopole physics, numerical simulation, and so on.

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Algebraic structure of space-time geometry and operator product expansion

Yuto Moriwaki (RIKEN iTHEMS)

Conformal field theories are characterized by structure constants (3-point correlation functions). In order for the theory to be consistent, the structure constants must satisfy the “bootstrap equation", which is useful to numerically solve, for example, for the critical exponent of the 3d Ising model.

From a mathematical point of view, the bootstrap equation arises from the operad structure of spacetime, and such mathematics may be useful to find (as yet undiscovered) constraints on quantum field theory. In this talk, we will introduce the notion of operad and discuss the relation between operads and operator product expansions based on mathematical studies of conformal field theories in two dimensions.

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Tunneling spin and heat transport in ultracold atomic systems

Yuta Sekino (RIKEN Quantum)

In this presentation, we explore quantum simulations of spin and heat transport in ultracold atomic systems, addressing challenges in condensed matter physics where heat transport mediated by spin is a key focus. Advances in microfabrication of solid-state materials have spurred research into spin-heat interconversion at the nanoscale, with implications for both fundamental science and thermoelectric devices. However, correlating experimental data with microscopic theories is difficult due to factors intrinsic to solids such as impurities, lattice defects, and lattice vibrations.

Our theoretical framework for quantum simulation with ultracold atoms aims to bypass these complexities. We investigate spin and heat transport between two Heisenberg ferromagnets connected by a quantum point contact. Findings include divergent spin conductance and slowed spin relaxation, linked to magnon critical points and spontaneous magnetization.

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Topological superconductivity in proximitized double helical liquids

Chen-Hsuan Hsu *(Institute of Physics, Academia Sinica, Taiwan)*

Time-reversal-invariant topological insulators support helical liquids at their edges. Introducing local and nonlocal pairings from an adjacent superconductor, two parallel channels of these helical liquids can induce topological superconductivity. This setup facilitates the stabilization of zero modes at the system corners without the need for magnetic fields [1,2].

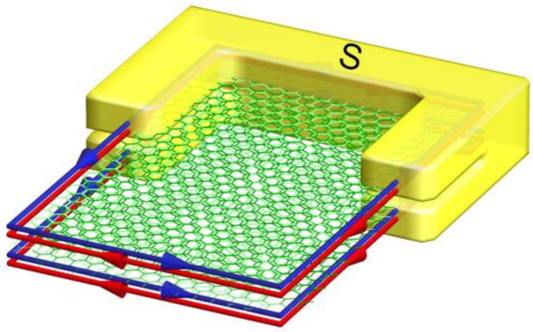

Fig.1 Double helical liquids in twisted bilayer structure (green) in contact with an *s*-wave superconductor (yellow). Upon tuning the charge density, the bulk is at one of the (fractional) quantum spin Hall insulating states, with the edges hosting counterpropagating spin-up (red) and spin-down (blue) electron states.

In this talk, we discuss the effects of electron-electron interactions and electron-phonon coupling on the topological superconducting phase in proximitized double helical liquids [3]. We find that both interchannel interactions and electron-phonon coupling generally suppress nonlocal pairing. Contrary to earlier perturbative analyses, our nonperturbative approach shows that phonons can induce transitions between topological and trivial phases, thus suppressing topological superconductivity and associated zero modes. Our findings indicate that electrically tunable topological phase transitions can occur in proximitized double helical liquids by adjusting the strengths of intrachannel and interchannel interactions. Importantly, given the ubiquitous presence of electron-electron interactions and phonons, our results highlight significant practical challenges in achieving topological zero modes in systems with helical channels. This includes quantum spin Hall insulators, higher-order topological insulators, and their fractional analogs recently identified in twisted bilayer systems.

*This work was financially supported by National Science and Technology Council (NSTC), Taiwan through Grant No. NSTC-112-2112-M-001-025-MY3.

References:

[1] Chen-Hsuan Hsu et al., **Semicond. Sci. Technol.** 36, 123003 (2021).

[2] Chen-Hsuan Hsu et al., **Phys. Rev. Lett.** 121, 196801 (2018).

[3] Chen-Hsuan Hsu, **Nanoscale Horiz.** (2024), in press. DOI: 10.1039/D4NH00254G.