QUANTUM AVALANCHE IN CORRELATED INSULATORS DRIVEN BY DC FIELDS

Jong E. Han[1], **C. Aron**[2,3]

[1]State University of New York at Buffalo
[2]École Polytechnique Fédérale de Lausanne
[3]Laboratoire de Physique de l'École Normale Supérieure / CNRS

There is a considerable discrepancy between the predicted and experimental switching fields in correlated insulators driven by a strong DC bias. This calls for a reevaluation of the current microscopic understanding of this non-equilibrium phenomenon. We unveil an electron avalanche mechanism that occurs in the bulk of such insulators at arbitrarily low electric fields [1]. This quantum avalanche relies notably on the inelastic scattering of electrons on a phononic medium and it results from the generation of in-gap states through multi-phonon emission. The phonon spectrum dictates the occurrence of a two-stage versus a single-stage switching mechanism, which we relate to charge-density-wave and Mott resistive switchings, respectively. Within this unified framework, the behavior of electron and phonon temperatures, along with the temperature dependence of switching fields, illustrates a crossover between a purely quantum mechanical and a thermal scenario.

[1] Han J.E., Aron C., et al., Nat Commun **14**, 2936 (2023)

QUANTUM PHASE TRANSITIONS IN SPIN CHAINS WITH EXACT NON-INVERTIBLE SYMMETRIES

Arkya Chatterjee, Ömer M. Aksoy, Xiao-Gang Wen

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Symmetry stands as one of the most powerful tools employed in physics. The presence of symmetries allows organizing the Hilbert space into irreducible representations and constraining dynamics as well as the ground state properties. Within the last decade the conventional view on symmetry has been generalized in several directions. One such direction is that of non-invertible symmetries – operators that commute with the Hamiltonian but are not unitary or invertible. In this talk, I will introduce the concept of non-invertible symmetries and show how they can be realized in the context of spin chains. I will focus on two examples. First, I will introduce a spin chain Hamiltonian with non-Abelian S_3 symmetry which at special points of its parameters space features an exact non-invertible $\mathbb{Z}_3$ Kramers-Wannier symmetry. Second, I will introduce a spin chain Hamiltonian with an exact non-invertible symmetry – called $\mathrm{Rep}(S_3)$ – in its entire parameter space.

I will show how the latter example is dual to the former. For each example, I will discuss the corresponding phase diagram – gapped phases, related spontaneous symmetry breaking patterns, and phase transitions between them.

SPECTRA AND TOPOLOGICAL NUMBERS IN HYPERBOLIC LATTICES

Tomáš Bzdušek

University of Zürich

Hyperbolic lattices are a new kind of synthetic matter with emergent negative curvature, which have over the past five years been realized with coupled microwave resonators, in electric-circuit networks, and using photonic systems. In the presence of open boundaries, hyperbolic lattices are characterized by a large boundary-to-bulk ratio that remains finite in the thermodynamic limit, making them an attractive platform for realizing and enhancing topological edge modes. However, theoretical characterization of such systems is hindered by elusive non-Abelian Bloch states, which transform in higher-dimensional representations of a non-commutative translation group and that dominate the bulk energy spectrum.

In this talk, I will first review the current understanding of space group symmetry and band theory in the context of hyperbolic lattices [1, 2] before presenting our recent theoretical findings. Specifically, I will focus on the recently formulated "supercell method" [3], which enables an efficient computation of bulk spectra of a broad range of hyperbolic lattices while taking into account the non-Abelian Bloch states. Then, I will showcase applications of the supercell method to several two-dimensional hyperbolic lattice models, including topological insulators characterized by non-vanishing first and second Chern numbers [4, 5].

[1] J. Maciejko and S. Rayan, Proc. Natl. Acad. Sci. U.S.A. **119**, e2116869119 (2022).

[2] I. Boettcher, A. V. Gorshkov, A. J. Kollár, J. Maciejko, S. Rayan, and R. Thomale, Phys. Rev. B **105**, 125118 (2022).

[3] P. M. Lenggenhager, J. Maciejko, and T. Bzdušek, Phys. Rev. Lett. **131**, 226401 (2023).

[4] D. M. Urwyler, P. M. Lenggenhager, I. Boettcher, R. Thomale, T. Neupert, and T. Bzdušek, Phys. Rev. Lett. **129**, 246402 (2022).

[5] T. Tummuru, A. Chen, P. M. Lenggenhager, T. Neupert, J. Maciejko, and T. Bzdušek, arXiv:2307.09876 (2023).

LOW DIMENSIONAL QUANTUM MAGNETS: FROM QUANTUM PHASE TRANSITIONS TO QUANTUM SIMULATIONS

T. Giamarchi[1]

[1]*DQMP, University of Geneva, 24 Quai Ernest Ansermet, 1211 Geneva, Switzerland*

Quantum spin systems offer a host of different physical properties, ranging from ordered spins states to quantum spin liquids. When the system is made of low dimensional units, such as spin chains or ladders, physics is even more exotic with fractional excitations (such as spinons), and a host of exotic quantum phase transitions.

I will discuss how a new generation of quantum magnets with small exchange coupling constant can be used, under magnetic field, as excellent quantum simulators to investigate phenomena as varied as novel topological and quantum phase transitions [1,2], a single hole propagating in a spin environment (so called t-J model) or a host of other phenomena ranging from disorder to controlled quantum phase transitions.

[1] “Topological quantum phase transition in the Ising-like antiferromagnetic spin chain BaCo2V2O8”,
Quentin Faure, Shintaro Takayoshi, Sylvain Petit, Virginie Simonet, Stéphane Raymond, Louis-Pierre Regnault, Martin Boehm, Jonathan S. White, Martin Månsson, Christian Rüegg, Pascal Lejay, Benjamin Canals, Thomas Lorenz, Shunsuke C. Furuya, Thierry Giamarchi and Béatrice Grenier, Nature Physics volume 14, 716–722 (2018).

[2] “Phase transitions and spin dynamics of the quasi-one-dimensional Ising-like antiferromagnet BaCo2V2O8 in a longitudinal magnetic field”, Shintaro Takayoshi, Quentin Faure, Virginie Simonet, Béatrice Grenier, Sylvain Petit, Jacques Ollivier, Pascal Lejay, and Thierry Giamarchi, Phys. Rev. Research 5, 023205 (2023).

DERIVATION OF A GENERALIZED LLG EQUATION USING ELECTRON-PHONON COUPLING

Shintaro Hoshino

Department of Physics, Saitama University, Sakura, Saitama 338-8570, Japan

Materials with both spin and orbital degrees of freedom show various interesting properties. To quantitatively understand the equilibrium and non-equilibrium states of such systems, it is necessary to incorporate information on the electronic states obtained from first-principles calculations and to analyze them.

The behavior of the electronic system at low temperatures is described by a multi-orbital Hubbard model that incorporates low-energy bands, and the effective model of Mott insulators is derived by taking the strong interaction limit. Based on the tight-binding model obtained from first-principles calculations, a realistic localized electron model can be constructed by incorporating electron-electron interactions as non-perturbative states and incorporating inter-atomic hopping as second-order perturbation [1,2].

For non-equilibrium states, analysis is typically conducted using the Landau-Lifshitz-Gilbert (LLG) equation for conventional spin systems. If the corresponding equations of motion can be formulated in the aforementioned realistic model, it becomes possible to analyze non-equilibrium states relevant to materials. In previous studies, classical equations of motion for multi-orbital systems utilizing SU(N) coherent states have been derived, which are expected to be good approximations in ordered states or high-temperature regimes [2,3]. This method of the equations of motion has also been extended to cases with damping [4]. In actual systems, damping of the electronic system is expected to occur through interactions with phonons. In this presentation, we propose a method for deriving classical equations of motion by combining the electronic system's Hamiltonian with electron-phonon coupling using the path integral method.

This work is done in collaboration with R. Pohle and Y. Motome. The author (SH) thanks R. Iwazaki for useful discussions.

[1] R. Iwazaki and S. Hoshino, Phys. Rev. B. **103**, 235145 (2021).
[2] R. Iwazaki, H. Shinaoka and S. Hoshino, Phys. Rev. B **108**, L241108 (2023).
[3] H. Zhang and C.D. Batista, Phys. Rev. B. **104**, 104409 (2021).
[4] D. Dahlbom, C. Miles, H. Zhang, C.D. Batista, and K. Barros, Phys. Rev. B **106**, 235154 (2022).

FRAMEWORK FOR ENGINEERING EXACT QUANTUM MANY-BODY GROUND STATES IN ONE AND TWO DIMENSIONS

<u>Chisa Hotta</u>, Hidehiro Saito

Graduate School of Arts and Sciences, University of Tokyo

We propose a framework to design a large-scale quantum many-body Hamiltonian and its exact ground states in one and two dimensions using an elementary matrix product state (MPS) representation. This framework applies to a class model referred to as frustration-free.

Previously, there had been several important examples discuss in this category where the exact description of the quantum many body states played a crucial role to clarify the related material phases, such as anyons in Kitaev model[1] and toric codes, specific walkers in Fredkin or Moskin chain[2,3], anyon BEC in XXZ[4] zigzag spin ladders, etc. The exact solutions found there mostly rely on the fact that the models have commutative terms or have conserved quantities after taking some proper transformation.

Here, we present the systematic and general way of building a set of frustration-free Hamiltonian and its exact ground states. The overall strategy is to first consider a small unit cluster and classify the quantum state inside that cluster into the lowest energy manifold and the excited state manifold. The local Hamiltonian is expressed as a penalty Hamiltonian on the latter states. By combining these cluster by making a finite overlap with other clusters, we can design a whole lattice model, and the lattice Hamiltonian is the sum of the local Hamiltonian, which is a typical frustration-free construction. After properly entangling the lowest energy manifold of cluster-states, and ensuring that the resultant state really exists in the finite volume of the Hilbert space, we reach the exact ground state of the bulk frustration-free Hamiltonian. The way to generate such state relies on the basic properties of matrix product state (MPS) techniques. The method is feasible to two-dimensional triangular, square, kagome and other lattice models with a comparable numerical cost as those one-dimension.

We first got the insight of finding such solutions from the study on the zigzag spin 1/2 chain with Heisenberg and Γ term, where we find a Lifshitz quantum multicritical point in the ground state phase diagram, at which we actually find a frustration-free exact solution[5]. We may briefly explain the way how such multicritical points are formed, and how it is related also to the experimental observation on the 4f-spin ladder material, showing that such exact solutions are not necessarily limited to toy models.

[1] A. Kitaev, Annals of Physics 321, 2–111 (2006)
[2] S. Bravyi, L. Caha, R. Movassagh, D. Nagaj, and P. W. Shor, Phys. Rev. Lett. 109, 207202 (2012).
[3] O. Salberger and V. Korepin, Rev. in Math. Phys. 29, 1750031 (2017).
[4] C. D. Batista, Phys. Rev. B 80, 180406 (2009).
[5] H. Saito and C. Hotta, Phys. Rev. Lett. in press(2024), arXiv:2401.06551.

PREDICTING LONG-TIME DYNAMICS OF QUANTUM MANY-BODY SYSTEMS BY DYNAMIC MODE DECOMPOSITION

Ryui Kaneko[1,2], Masatoshi Imada[1,2], Yoshiyuki Kabashima[3,4], Tomi Ohtsuki[1]

[1]*Physics Division, Sophia University*
[2]*Research Institute for Science and Engineering, Waseda University*
[3]*The Institute for Physics of Intelligence, The University of Tokyo*
[4]*Trans-Scale Quantum Science Institute, The University of Tokyo*

Predicting the time evolution of physical quantities in quantum many-body systems is challenging. The most straightforward approach involves solving the time-dependent Schrödinger or Heisenberg equation to obtain the wave function at each time step. While exact diagonalization methods allow simulations for small systems, the exponential increase in memory with system size makes computations for large-scale systems intractable. Conventional quantum Monte-Carlo methods suffer from the infamous negative sign problems in real-time path-integral simulations. Tensor-network methods enable efficient dynamics calculations in spatially one-dimensional systems but become challenging for higher-dimensional systems. Time-dependent variational Monte-Carlo methods are becoming feasible for long-time dynamics in large systems, but computational costs are still demanding.

In such backgrounds, in quantum many-body systems, there exist a significant demand and great potential for predicting the time evolution of physical quantities over long time intervals by applying machine-learning methods to short-time series input data. Here, we focus on one of the machine-learning methods, dynamic mode decomposition (DMD), which is widely used in fluid dynamics [1,2]. The DMD applies to evenly-spaced time-series data and has lower computational costs than conventional, straightforward quantum dynamics calculations.

We study the effectiveness of the DMD in predicting the time evolution of quantum many-body systems through case studies [3]. We specifically examine cases with multiple oscillatory components in the time-series data and those containing critical power-law decay as a function of time by taking the time-dependent spin correlation functions in the transverse-field Ising models as examples. We show that the present method enables accurate forecasts for time periods that are nearly an order of magnitude longer than those of the short-time training data, even at challenging quantum critical points. We also examine how the accuracy of the forecast is maintained in the presence of noise in the input data, which is indispensable for applying the present method to durable long-time forecasts of available short-time experimental data.

[1] J. N. Kutz *et al.*, *Dynamic mode decomposition: data-driven modeling of complex systems* (SIAM, Philadelphia, PA, 2016).
[2] S. L. Brunton and J. N. Kutz, *Data-driven science and engineering: Machine learning, dynamical systems, and control* (Cambridge University Press, Cambridge, England, 2019).
[3] R. Kaneko, M. Imada, Y. Kabashima, and T. Ohtsuki, arXiv:2403.19947.

HYPERUNIFORMITY IN THE TWO-DIMENSIONAL PERIODIC AND QUASIPERIODIC LATTICES

Akihisa Koga[1], **Shiro Sakai**[2]

[1]*Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[2]*Center for Emergent Matter Science, RIKEN, Wako, Saitama, Japan*

Quasiperiodic system has been the subject of extensive research since the discovery of the Al-Mn quasicrystal [1]. The structures of the quasicrystals do not have the translational symmetry in the real space and are characterized by the nontrivial rotation symmetry, which is forbidden in the conventional periodic lattices. Despite the aperiodicity, a quasiperiodic structure is completely ordered, leading to electron states distinct from both periodic and random systems. Hyperuniformity is a framework to quantify the order of a point distribution in a space [2], applicable to periodic, quasiperiodic and random distributions. It is known that Poisson point patterns are not hyperuniform. On the other hand, periodic and quasiperiodic point distributions are known to be hyperuniform, and its order is characterized by a quantity called order metric. Recently, electronic properties on a quasiperiodic structure have been discussed in terms of hyperuniformity [3]. In this paper, we examine the hyperuniformity order metric in several two-dimensional periodic and quasiperiodic lattices [2,4,5]. In particular, we focus on the periodic and quasiperiodic lattices composed of the squares and triangles such as Shastry-Sutherland and trellis lattices, and hexagonal and dodecagonal Stampfli tilings. We then discuss how the rotational symmetry affects the hyperuniformity [6]. Furthermore, we consider the square-triangle tiling which is a spatially random lattice constructed by closely packing the plane with squares and triangles. We clarify whether or not the square-triangle tiling is hyperuniform.

[1] D. Shechtman, I. Blech, D. Gratias, J. W. Cahn, Phys. Rev. Lett. 53 (1984) 1951.
[2] S. Torquato and F. H. Stillinger, Phys. Rev. E 68, 041113 (2003).
[3] S. Sakai, R. Arita, and T. Ohtsuki, Phys. Rev. Research 4, 033241 (2022).
[4] C. E. Zachary and S. Torquato, J. Stat. Mech. 2009, P12015 (2009).
[5] C. Lin, P. J. Steinhardt, and S. Torquato, J. Phys.: Condens. Matter 29, 204003 (2017).
[6] A. Koga and S. Sakai, Phys. Rev. E 109, 044103 (2024).

DISORDER-INDUCED TOPOLOGICAL SUPERCONDUCTIVITY IN A QUANTUM-HALL–SUPERCONDUCTOR HYBRID

Koji Kudo

Department of Physics, Kyushu University, Japan

Quantum-Hall–superconductor (QH-SC) hybrid systems have been predicted to generate various types of (non-Abelian) anyons and provide possible platforms for intrinsically fault-tolerant quantum computing. In this talk, we consider the disordered QH system combined with the type-II SC. By calculating the BdG spectrum and the real space entanglement spectrum, we demonstrate that the interplay between disorders and proximity-induced pairing results in a topological superconducting phase carrying the half-integer Chern number (equivalently the odd BdG Chern number). Historically, the spherical geometry has been commonly used for investigating topologically ordered states, especially in fractional QH physics. Motivated by this, we also formulate a scheme to combine the spherical QH system with the type-II SC. Our numerical calculations are all performed on this geometry. [1]

[1] Koji Kudo, Ryota Nakai, Kentaro Nomura, arXiv:2401.04426

SYMMETRY ADAPTED MODELING AND QUANTIFICATION OF CHIRALITY

Hiroaki Kusunose[1,2], Rikuto Oiwa[3], Satoru Hayami[4], Akane Inda[4], Hiroshi M. Yamamoto[2,5]

[1]*Department of Physics, Meiji University*
[2]*Quantum Research Center for Chirality (QuaRC), Institute for Molecular Science*
[3]*Center for Emergent Matter Science (CEMS), RIKEN*
[4]*Graduate School of Sciene, Hokkaido University*
[5]*Institute for Molecular Science*

In recent years, exotic electronic symmetry breaking such as magnetic toroidal [1,2] and ferroaxial [3-5] orders have been extensively studied which bring about new cross correlations reflecting their characteristics. In order to analyze such orders and their physical outcome in a unified and systematic manner, we have developed a symmetry-adapted modeling procedure for molecules and crystals [6-8]. By using the completeness of multipoles to express spatial and time-reversal parity-specific anisotropic distributions, we can generate systematically the complete symmetry-adapted multipole basis set to describe any of electronic degrees of freedom in isolated cluster systems and periodic crystals [9]. By incorporating density-functional-theory computations, we can construct the symmetry-adapted Wannier-based tight-binding models [10].

By utilizing this symmetry-adapted modeling procedure, we have elucidated fundamental aspect of chirality and quantification of it for chiral molecules and crystals. It is well known that chirality ubiquitously appears in nature, however, its quantification has remained obscure so far owing to the lack of microscopic description at the quantum-mechanical level [11]. As prototypical examples, we apply the symmetry-adapted modeling method to elemental Tellurium [12] and a twisted methane [13]. We will discuss that the vector-type spin-orbit coupling and the spin-dependent imaginary hopping are important ingredients to stabilize an electronic chirality.

[1] B.B. Van Aken, J.-P. Rivera, H. Schmid, and M. Fiebig, Nature **449**, 702 (2007).
[2] N.A. Spaldin, M. Fiebig, and M. Mostovoy, J. Phys.: Condens. Matter **20**, 434203 (2008).
[3] Y.V. Kopaev, Physics-Uspekhi **52**, 1111 (2009).
[4] W. Jin, et al., Nat. Phys. **16**, 42 (2020).
[5] T. Hayashida, et al., Nat. Commun. **11**, 4582 (2020).
[6] H. Kusunose, R. Oiwa, and S. Hayami, Phys. Rev. B **107**, 195118 (2023).
[7] S. Hayami and H. Kusunose, arXiv:2403.09019.
[8] H. Kusunose and S. Hayami, arXiv:2403.09492.
[9] MultiPie: https://cmt-mu.github.io/MultiPie/
[10] SymClosestWannier: https://cmt-mu.github.io/SymClosestWannier/
[11] J. Kishine, H. Kusunose, H.M. Yamamoto, Isr. J. Chem. **62**, e202200049 (2022).
[12] R. Oiwa, and H. Kusunose, Phys. Rev. Lett. **129**, 116401 (2022).
[13] A. Inda, R. Oiwa, S. Hayami, H.M. Yamamoto, and H. Kusunose, arXiv:2402.13611.

SPECTRA OF QUANTUM CRITICAL POINTS ON THE TORUS AND THE SPHERE: FINGERPRINTS AND SCALING DIMENSIONS

Andreas Läuchli[1 2]

[1] *Laboratory for Theoretical and Computational Physics, Paul Scherrer Institute, CH 5132 Villigen, Switzerland*
[2] *Institute of Physics, Ecole Polytechnique Federale de Lausanne, CH 1015 Lausanne, Switzerland*

In this talk I will discuss our efforts to characterize the low-energy spectrum of many body systems at quantum critical points on the torus, and more recently on the sphere. The energy spectrum on the torus is a universal fingerprint of the conformal field theory controlling the quantum critical point, and we will discuss several applications where this technology lead to characterization of quantum critical behavior in 2+1D. Recently work by Yin-Chen He and collaborators demonstrated a scheme to regularize quantum field theories on the “fuzzy” sphere. We will show first results focused on the O(2) model, and an understanding of the finite size corrections distorting the spectrum at small volumes.

REALIZING HIGHER ORDER TOPOLOGY

Titus Neupert[1]

[1]*Department of Physics, University of Zurich, Zurich, Switzerland*

Higher-order topology generalizes the bulk-boundary correspondence of topological phases of matter, by allowing topological modes to be localized at corners and hinges instead of edges and surfaces. I will introduce the theory behind this concept, both for noninteracting as well as interacting systems and consecutively discuss two realizations in rather distinct setups. First, as-grown crystals of bismuth, grey arsenic, as well as bismuth bromide are demonstrated to display the essential physics of higher-order topological insulators. Second, it is shown that lattices of so-called Shiba bound states induced by magnetic adatoms in conventional superconductors can be brought into a higher-order superconducting phase. I will report on experimental progress for both system types based on spanning probe as well as transport measurements.

[1] M. O. Soldini, F. Küster, G. Wagner, S. Das, A. Aldarawsheh, R. Thomale, S. Lounis, S. S. P. Parkin, P. Sessi, T. Neupert, Nature Physics 19, 1848–1854 (2023).
[2] F. Schindler, A. M. Cook, M. G. Vergniory, Z. Wang, S. S. P. Parkin, B. A. Bernevig, T. Neupert, Science Advances, 4, eaat0346 (2018).
[3] N. Shumiya et al., Nature Materials 21, 1111-1115 (2022).
[4] M. S. Hossain et al., Nature 628, 527–533 (2024).

Analyzing Strongly Correlated Electron Systems Using Artificial Neural Networks

Yusuke Nomura

Institute for Materials Research (IMR), Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

Solving quantum many-body problems is a great challenge in physics. In this talk, we will show that artificial neural networks used in machine learning can be useful for analyzing quantum many-body systems, in particular, strongly-correlated electron systems.

Since the first proposal [1], we have continuously worked on the development of the neural-network wave function method for zero-temperature [2-6] and finite-temperature [7] simulations (for a review paper, please see [9]). Through various extensions, the neural-network wave functions are beginning to be applied to challenging problems in physics.

We show such a successful application to the frustrated J_1-J_2 Heisenberg model on the square lattice [9]. On top of the accurate representation of quantum states using neural-network-based wave functions, we employ the combined analyses of correlation ratio and level spectroscopy to mitigate finite-size effects. The quantitative one-to-one correspondence between the ground-state correlation function and the excitation spectra enables the reliable identification of the quantum spin liquid and the emergence of fractionalized spinons in the J_1-J_2 Heisenberg model [9].

We also show a recent attempt to build a platform for comparing the performance of variational methods among different quantum many-body Hamiltonians and different computational algorithms (including both classical and quantum). We collect state-of-the-art results obtained by classical computers, providing the criterion to be achieved by novel classical and quantum algorithms [10].

If time allows, we also discuss an extension to finite-temperature simulations [7], that is achieved by a combination of deep learning model and the physical concept of “purification”.

These works were done in collaboration with A. S. Darmawan, Y. Yamaji, M. Imada, G. Carleo, N. Yoshioka, and F. Nori.

[1] G. Carleo and M. Troyer, Science **355**, 602 (2017)
[2] Y. Nomura *et al*., Phys. Rev. B **96**, 205152 (2017)
[3] G. Carleo, Y. Nomura and M. Imada, Nat. Commun. **9**, 5322 (2018)
[4] Y. Nomura, J. Phys. Soc. Jpn. **89**, 054706 (2020) [Editors’ choice]
[5] Y. Nomura, J. Phys.: Condens. Matter **33**, 174003 (2021) [special topic “Emerging Leaders 2020”]
[6] Y. Nomura, J. Phys. Soc. Jpn. **91**, 054709 (2022)
[7] Y. Nomura*, N. Yoshioka*, and F. Nori, Phys. Rev. Lett. **127**, 060601 (2021)
[8] Y. Nomura, J. Phys.: Condens. Matter **36**, 073001 (2024) [Review]
[9] Y. Nomura and M. Imada, Phys. Rev. X **11**, 031034 (2021)
[10] D. Wu *et al*., arXiv:2302.04919

NONEQUILIBRIUM QUANTUM MAGNETISM BY PULSED MAGNETOPHONONICS

B. Normand[1,2], **B. Demazure**[1,2] **and G. S. Uhrig**[3]

[1] *Paul Scherrer Institute, CH-5232 Villigen-PSI, Switzerland*
[2] *Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*
[3] *TU Dortmund University, Otto-Hahn-Straße 4, D-44221 Dortmund, Germany*

Although ultrafast laser driving has opened a new chapter in the study of nonequilibrium states in quantum matter, the energy scales involved have to date precluded detailed studies of ultrafast quantum magnetism. Magnetophononics, the modulation of magnetic interactions by driven infrared-active lattice excitations, is emerging as a key mechanism for the ultrafast dynamical control of quantum spin systems by coherent light. We consider the properties of a minimal magnetophononic model consisting of a driven, dissipative, dimerized quantum ($S = ½$) spin system coupled strongly to one optical phonon [1]. Continuous, single-frequency driving establishes a nonequilibrium steady state (NESS) of the system that exhibits composite phonon-bitriplon hybrid excitations, phonon self-blocking (a departure from resonance that obstructs its absorption of the driving energy) and global renormalisation of the triplon spectrum.

Ultrafast experiments use ultrashort pulses, which contain driving components over a broad range of frequencies, and Fourier transformation of the transient response reveals an emergent low-frequency energetic oscillation between the lattice and spin sectors which is an intrinsically nonequilibrium collective excitation. We use the method of coherent two-dimensional spectroscopy to separate the nonlinear contributions of hybrid phononic and magnetic nature, which also appear at the sum and difference frequencies of the composite phonon-bitriplon modes. The difference-frequency excitation is the energetic oscillation, explaining its origin as a beat between the two mutually repelling states formed by phonon-bitriplon hybridisation.

We discuss the possible observation of these linear magnetophononic phenomena in the strongly coupled spin-chain material $CuGeO_3$ [3]. In the "Shastry-Sutherland material" $SrCu_2(BO_3)_2$, nonlinear magnetophononic driving is required to explain the nonequilibrium population of the $S = 0$ two-triplon bound state at 0.89 THz by the difference frequency of two driven phonons with characteristic frequencies around 4 THz [4].

[1] M. Yarmohammadi, M. Krebs, G. S. Uhrig and B. Normand, Strong-coupling magnetophononics: Self-blocking, phonon-bitriplons, and spin-band engineering, Phys. Rev. B **107**, 174415 (2023).
[2] B. Demazure, M. Krebs, G. S. Uhrig and B. Normand, Pulsed magnetophononics in a gapped quantum spin chain, unpublished (2024).
[3] L. Spitz, private communication.
[4] F. Giorgianni, B. Wehinger, S. Allenspach, N. Colonna, C. Vicario, P. Puphal, E. Pomjakushina, B. Normand and Ch. Rüegg, Ultrafast frustration breaking and magnetophononic driving of singlet excitations in a quantum magnet, Phys. Rev. B **107**, 184440 (2023).

MOIRÉ IS DIFFERENT: METAL-INSULATOR TRANSITIONS, KONDO LATTICE PHYSICS AND CHIRAL SPIN LIQUIDS IN TRANSITION-METAL DICHALCOGENIDE BILAYERS

Louk Rademaker[1]

[1]*Department of Quantum Matter Physics, University of Geneva, Quai Ernest-Ansermet 24, 1205 Geneva, Switzerland*

The greatest open questions in quantum matter physics revolve around strongly correlated electronic phases, traditionally observed in heavy fermions, cuprates and organics. In recent years, a new class of materials emerged where the strength of correlations can be engineered: “moiré materials”. I will briefly introduce moiré materials such as twisted bilayer graphene and transition-metal dichalcogenide (TMD) bilayers. I will then focus on three recent results: a universal theory for continuous metal-insulator transitions [1], valley-charge-transfer and Kondo lattice physics under pressure in TMD homobilayers [2] and our prediction of a chiral spin liquid phase in TMD heterobilayers [3,4]. These results show that the wealth of phenomena observed in moiré materials allow for new insights in old correlated problems.

[1] Simone Fratini, Sergio Ciuchi, Vladimir Dobrosavljevic, Louk Rademaker, *Universal scaling near band-tuned metal-insulator phase transitions*, Phys. Rev. Lett 131, 196303 (2023); arXiv:2307.09292.
[2] Marta Brzezinska, Marco Gibertini, Sergii Grytsiuk, Malte Rösner, and Louk Rademaker, *Pressure-tuned many-body phases through Γ-K valleytronics in moiré bilayer WSe_2*, arXiv:2404.07165 (2024).
[3] Dario Rossi, Johannes Motruk, Louk Rademaker, Dmitry A. Abanin, *Schwinger boson study of the J_1-J_2-J_3 kagome Heisenberg antiferromagnet with Dzyaloshinskii-Moriya interactions*, Phys. Rev. B 108, 144406 (2023); arXiv:2305.15824.
[4] Johannes Motruk, Dario Rossi, Dmitry A. Abanin, Louk Rademaker, *Kagome Chiral Spin Liquid in Transition Metal Dichalcogenide Moiré Bilayers*, Phys. Rev. Research 5, L022049 (2023); arXiv:2211.15696.

IMPROPER ORDERS IN NONSYMMORPHIC SYSTEMS

Aline Ramires[1], **Andras Szabo**[2]

[1]*Paul Scherrer Institute, 5232 Villigen PSI, Switzerland*
[2]*Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*

The study of improper phases in the context of multiferroic materials has a long history. In this talk, we highlight an overlooked mechanism that couples modulated order parameter bilinears to potentially homogeneous odd-parity order parameters such that the latter emerge as improper orders. For that, we explore a novel perspective of nonsymmorphic symmetries based on extended symmetry groups in real space. We are inspired by the phenomenology of the recently discovered superconductor $CeRh_2As_2$, but our results also have implications for other types of primary orders. In particular, we find that a bilinear in the superconducting order parameter can couple linearly to odd-parity magnetic order in a centrosymmetric system. Our findings open the door for exploring nonsymmorphic symmetries in the broader context of improper orders with potential applications to topological functional materials.

[1] A. Szabo and A. Ramires, arXiv.2309.05664 (2023)

PHOTO-INDUCED HIDDEN PHASES IN MULTI-ORBITAL HUBBARD MODEL: A STEADY STATE APPROACH

Sujay Ray[1], Yuta Murakami[2], Philipp Werner[1]

[1]*Department of Physics, University of Fribourg, Fribourg-1700, Switzerland,*
[2]*Center for Emergent Matter Science, RIKEN, Wako, Saitama 351-0198, Japan*

The search for hidden orders in photo-excited lattice systems is an active research field driven by experimental reports of light-induced or light-stabilized phases. Motivated by recent developments in laser technology and advances in non-equilibrium quantum materials, we investigate hidden electronic orders in strongly correlated two-orbital Hubbard systems. Using non-equilibrium dynamical mean field (DMFT) theory, we uncover a number of hidden phases, many of which arise due to the interplay of different degrees of freedom in multi-orbital systems. First, we explore the possibility of non-thermal supercon- ducting order in two-orbital Hubbard systems, using non-equilibrium steady state DMFT theory. We find that a staggered η-type superconducting phase can be realized on a bipartite lattice in the high photo-doping regime, if the effective temperature of the photo-carriers is sufficiently low. The η superconducting state is stabilized by Hund coupling – a positive Hund coupling favors orbital-singlet spin-triplet η pairing, whereas a negative Hund coupling stabilizes spin-singlet orbital-triplet η pairing. We also demonstrate the appearance of nonthermal ferromagnetic order in photo-doped systems with Hund coupling, when the widths of the two bands differ sufficiently. Moreover, a spin-singlet η-superconducting order appears in such systems in the strong photo-doping regime, and there is a co-existence region with both orders. Next, we investigate the extended Hubbard model with a mean-field approach and find charge ordered photo-doped states. In this photo-doped charge ordered states for the two-orbital systems, the charge excitations also develop spin-orbital Kugel-Khomskii order, giving rise to the exciting possibility of tuning these orders with laser-excitations. The rich nonequilibrium phases uncovered in these works show that Mott insulating multi-orbital systems provide an interesting platform for the realization of nonthermal electronic orders.

[1] Sujay Ray, Yuta Murakami, and Philipp Werner, Phys. Rev. B **108**, 174515 (2023).
[2] Sujay Ray, and Philipp Werner, arXiv:2403.07737.

QUANTIZED KASTELEYN TRANSITION IN A FRUSTRATED ISING MODEL ON THE KAGOME LATTICE

Afonso Rufino[1], Samuel Nyckees[1], Jeanne Colbois[2], Frédéric Mila[1]

[1] Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland
[2] Laboratoire de Physique Théorique, Université de Toulouse, CNRS, UPS, 31400 Toulouse, France

We show that the Kasteleyn transition, the condensation of linear defects in a fluctuation-free low temperature phase, takes an exotic form for the constrained Kagome Ising antiferromagnet obtained in the limit of infinite first and third neighbor couplings. In this model, coexistence between two kinds of linear defects leads to the quantization of the ratio between their densities to integer values. Numerical investigation of the model using the Corner Transfer Matrix Renormalization Group algorithm shows that, as temperature is raised, the system undergoes an infinite sequence of first-order transitions across which the ratio of densities jumps, taking all non-negative integer values. This behavior is in stark contrast with the standard Kasteleyn transition where the density of a single extended defect increases continuously as $(T - T_c)^{1/2}$. The consequences of the quantized Kasteleyn transition for the phase diagram of the model with finite couplings are explored.

APPLICATIONS OF QUANTICS TENSOR CROSS INTERPOLATION TO QUANTUM MANY-BODY PHYSICS

Hiroshi Shinaoka[1]

[1]*Department of Physics, Saitama University*

Tensor networks are a powerful tool for compressing wave functions and density matrices of quantum systems in physics. Recent developments have shown that tensor network techniques can efficiently compress many functions beyond these traditional objects. Notable examples include the solutions to turbulence in Navier–Stokes equations [1] and the computation of Feynman diagrams [2,3]. These advancements have heralded a new era in the use of tensor networks for expediting the resolution of various complex equations in physics.

In this talk, we will overview our recent research in this domain. First, we briefly introduce quantics/quantized tensor train (QTT) representation [3,4] for compressing the space-time dependence of the correlation function in quantum system [5, Talk in TTQM2023]. This method leverages the inherent length-scale separation in the system to efficiently represent a function.

Then, we will introduce a novel and robust tool named “Quantics Tensor Cross Interpolation” [6]. This method allows us to learn a quantics low-rank representation of a given function, showcasing the versatility and potential of tensor network techniques in handling complex functions in physics. As applications, we demonstrate the computation of Brillouin zone integrals [6] as well as the integration of complex self-energy Feynman diagrams of a multiorbital electron-phonon model [7]. If time permits, we will introduce our open-source C++ and Julia implementations of quantics and tensor cross interpolation [8].

[1] N. Gourianov *et al*., Nat. Comput. Sci. **2**, 30 (2022).
[2] Y. N. Fernandez *et al*., PRX **12**, 041018 (2022).
[3] I. V. Oseledets, Dokl. Math. **80**, 653 (2009).
[4] B. N. Khoromskij, Constr. Approx. **34**, 257 (2011).
[5] H. Shinaoka *et al*., PRX **13**, 021015 (2023).
[6] M. K. Ritter, Y. N. Fernández, M. Wallerberger, J. von Delft, H. Shinaoka and X. Waintal, PRL **132**, 056501 (2024).
[7] H. Ishida, N. Okada, S. Hoshino, H. Shinaoka, in preparation.
[8] Y. N. Fernández, M. K. Ritter, M. Jeannin, J.-W. Li, T. Kloss, O. Parcollet, J. von Delft, H. Shinaoka and X. Waintal, in preparation.

ON THE UNIQUNESS OF SYMMETRIC WANNIER FUNCTION

Ken Shiozaki

Yukawa Institute of Theoretical Physics, Kyoto University

The Wannier function is a basic tool in modeling band structures through the tight-binding model. An exponentially localized Wannier function for a specific band is known to exist if the Chern numbers are zero. Furthermore, with (magnetic) space group symmetry, we can ask given Bloch wave functions, can we have exponentially localized Wannier functions whose space group representation is same as the induced representation from a set of atomic orbitals (defined by a set of pairs of Wyckoff positions and irreducible representations of their site symmetry)? Such Wannier functions, which mimic atomic orbitals, are referred to as symmetry-adapted Wannier functions. (see, for example, [1] and references therein.)
In this talk, we want to address the uniqueness of exponentially localized symmetry-adapted Wannier functions. Even if a symmetry-adapted Wannier function exists, their atomic orbitals may not be unique. We present our analysis from perspectives of the Atiyah-Hirzebruch spectral sequence in K-theory [2] and a constraint on topological invariant.

[1] R. Sakuma, Phys. Rev. B **87**, 235109 (2013).
[2] Ken Shiozaki, Charles Zhaoxi Xiong, Kiyonori Gomi, Progress of Theoretical and Experimental Physics, **2023**, 083I01 (2023).

NONLINEARITY-INDUCED TOPOLOGICAL PHASE TRANSITION CHARACTERIZED BY THE NONLINEAR CHERN NUMBER

Kazuki Sone[1,2], Motohiko Ezawa[2], Yuto Ashida[3,4], Nobuyuki Yoshioka[2,5,6], Takahiro Sagawa[2,7]

[1]*Department of Physics, University of Tsukuba*
[2]*Department of Applied Physics, The University of Tokyo*
[3]*Department of Physics, The University of Tokyo*
[4]*Institute for Physics of Intelligence, The University of Tokyo*
[5]*Theoretical Quantum Physics Laboratory, RIKEN Cluster for Pioneering Research (CPR)*
[6]*Japan Science and Technology Agency (JST), PRESTO*
[7]*Quantum-Phase Electronics Center (QPEC), The University of Tokyo*

Since the discovery of the quantum Hall effect, topology of band structures has been one of the important issues in condensed matter physics. The band topology is characterized by the bulk topological invariants such as the Chern number, and nontrivial band topology induces unique phenomena that cannot be seen topologically trivial systems. In particular, gapless modes appear along the boundary of the sample accompanying the nonzero topological invariant, which is known as the bulk-boundary correspondence. Recent studies have revealed the existence of topological edge modes in various quantum and classical systems, such as cold atoms, photonics, and fluids. While the conventional theory of topology relies on the linearity of the equation of motion, classical systems and mean-field analysis of interacting bosons can be described by nonlinear equations. Nonlinear effects on the topological edge modes has also attracted growing interest, and previous studies have found topological phenomena unique to nonlinear systems, such as topological edge solitons [1] and topological synchronization [2]. However, since the nonlinear systems have no band structures in the conventional sense, the topological invariants characterizing nonlinear topology has been unclear.

In our work, we extend the Chern number to nonlinear two-dimensional systems and analyze its bulk-boundary correspondence to gapless boundary modes [3]. To extend the notion of band structures and their topological invariants, we introduce the nonlinear eigenvalue problem, whose eigenvector corresponds to a periodically oscillating state in nonlinear dynamics. Based on the nonlinear eigenvalue problem, we show that the nonzero nonlinear Chern number predicts the existence of localized zero modes, while the zero nonlinear Chern number indicates the absence of zero modes or the anti-localization of zero modes, which is the bulk-boundary correspondence in nonlinear systems. More surprisingly, the existence or absence of topological edge modes depends on the amplitude of the nonlinear wave. The nonlinear Chern number also corresponds to such amplitude dependence of nonlinear topological edge modes, which we term nonlinearity-induced topological phase transitions. Thus, our result should provide a guiding principle to fully elucidate the topological classification of nonlinear systems.

[1] D. Leykam and Y. D. Chong, Phys. Rev. Lett. **117,** 143901 (2016).
[2] K. Sone, Y. Ashida, and T. Sagawa, Phys. Rev. Research **4,** 023211 (2022).
[3] K. Sone, M. Ezawa, Y. Ashida, N. Yoshioka, and T. Sagawa, arXiv:2307.16827 (published in Nat. Phys. (2024).)

MAGNETIC EXCITATIONS OF WEAK MOTT INSULATOR

Hidemaro Suwa

Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan

Intermediate coupling systems exhibit novel phenomena emerging from the entanglement between charge, spin, and orbital degrees of freedom. In particular, 4*d* and 5*d* orbital electron systems, such as strontium iridates and associated thin films, are ideal platforms for studying the complex effect of multiple degrees of freedom. The constant development of powerful spectroscopic techniques with increasing energy and momentum resolution calls for detailed theoretical analyses. Semiclassical methodologies, exemplified by Landau-Lifshitz dynamics, are indispensable tools for studying spin models. They provide invaluable insights for interpreting phenomena observed in inelastic neutron scattering and resonant inelastic X-ray scattering experiments. However, the recent discovery of weak Mott insulators in the intermediate coupling regime demands novel approaches that can account for the influence of charge fluctuations. We have developed a semiclassical methodology facilitating large-scale computations (encompassing more than 10^4 sites) of dynamical properties at finite temperatures across a broad spectrum of U/t values. We have investigated the magnetic excitations of a half-filled bilayer Hubbard model with spin-orbit coupling, targeting the bilayer iridate $Sr_3Ir_2O_7$, an intermediately correlated antiferromagnet. On-site electron-electron repulsion creates preformed excitons in a paramagnetic band insulator and triggers a triplet exciton condensation that results in the antiferromagnetic order[1,2,3]. Raman scattering captures the characteristic longitudinal mode appearing below two-magnon excitations and detects its softening, indicating a quantum phase transition induced by pressure. We will also discuss how our semiclassical dynamical simulation calculates magnetic excitations from complex magnetic orders.

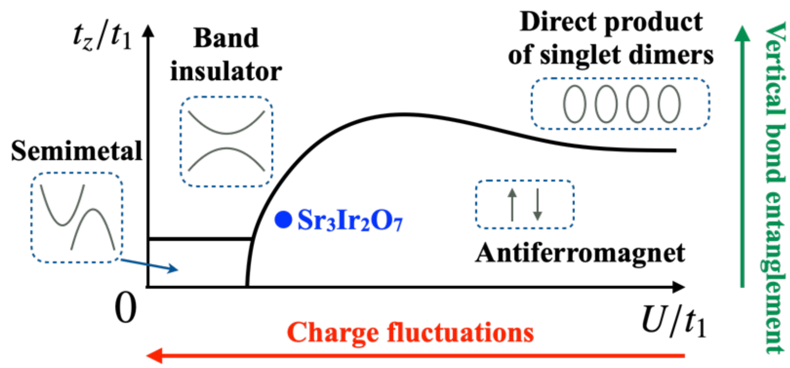

Fig. 1 Schematic phase diagram of the bilayer Hubbard model with spin-orbit coupling. The bilayer iridate $Sr_3Ir_2O_7$ is located close to the quantum critical point in the BCS-BEC crossover regime.

[1] H. Suwa, S.-S. Zhang, and C. D. Batista, Phys. Rev. Research **3**, 013224 (2021).
[2] D. G. Mazzone, Y. Shen, H. Suwa, et al., Nat. Commun. **13**, 913 (2022).
[3] H. Suwa, S.-S. Zhang, and C. D. Batista, JPS Conf. Proc. **38**, 011168 (2023).

SCANNING TUNNELING MICOSCOPY IN KITAEV QUANTUM SPIN LIQUID

Shintaro Takayoshi[1], Masafumi Udagawa[2], Takashi Oka[3]

[1]*Konan University*
[2]*Gakushuin University*
[3]*ISSP, University of Tokyo*

Kitaev's chiral spin liquid is a topological phase realized on a honeycomb lattice with anisotropic magnetic interactions and accompanied with elementary excitations of Majorana fermion. Since the topological phase is characterized by the global nature of the system, there are difficulties in detecting its excitations, the Majorana fermion, by spatially localized probes. Recently, a proposal has been made to detect the Majorana particle by utilizing the charge degrees of freedom in the Kitaev's chiral spin liquid. The setup consists of placing a thin film of Kitaev magnet on a metal substrate and measuring tunneling current as a function of bias voltage by a scanning tunneling microscope (STM). Then it can determined from the tunneling current spectra whether the excitation called Vison exists in the vicinity of the STM probe [1]. In this talk, we study the same situation and discuss whether it is possible to move the position of Vison using the STM probe like tweezers.

We consider the situation where the STM tip is located just above the spin site of a Kitaev magnet, and conduction electrons in the tip interact with the spins in the Kitaev magnet through exchange coupling. By regarding the configuration of Visons near the site on the tip as a pseudospin, a bound state similar to the Kondo singlet is formed (Figure 1). As the interaction between the electrons in the tip and the Kitaev magnet becomes stronger, the energy of the bound state decreases. This result implies that the STM tip traps Visons and Majorana fermions can be manipulated by moving the tip.

[1] M. Udagawa, S. Takayoshi, and T. Oka, Phys. Rev. Lett. **126**, 127201 (2021).

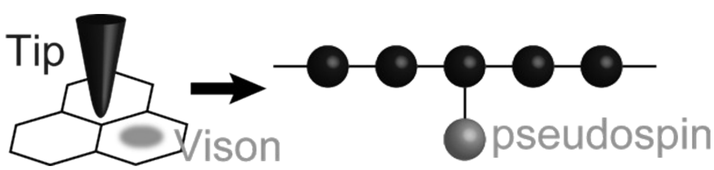

Figure 1: Modelling of interaction between the Kitaev magnet and the STM tip

QUANTUM MANY-BODY SCARS WITH UNCONVENTIONAL SUPERCONDUCTING PAIRINGS

Naoto Tsuji[1,2], Shohei Imai[1]

[1]Department of Physics, University of Tokyo
[2]RIKEN Center for Emergent Matter Science (CEMS)

There have been various attempts to realize exotic superconducting states out of equilibrium that are inaccessible within thermal equilibrium. The challenge is how to make those nonthermal states robust against thermalization. One possible mechanism to maintain nonequilibrium superconducting orders is provided by quantum many-body scars, which are exceptional energy eigenstates that do not have thermal properties in a nonintegrable system. Here we present a systematic construction of quantum many-body scar states with unconventional superconducting pairings via multi-body interactions [1]. This allows us to realize exact energy eigenstates with various unconventional pairing symmetries (p-wave, d-wave, f-wave, etc.), giving an exhaustive extension of Yang's s-wave η-pairing state. We apply our construction to the two-dimensional spinful Hubbard model on a square lattice with multi-body interactions, and show that the spin-triplet d-wave pairing state becomes a quantum many-body scar, as evidenced from numerical analysis of the pair correlation function, entanglement entropy, and level statistics. We also discuss other examples, including f-wave pairing states on a honeycomb lattice, and p-wave pairing states in one dimension.

[1] S. Imai and N. Tsuji, arXiv:2404.02914.

INTERACTING CHIRAL FERMIONS ON THE LATTICE WITH MATRIX PRODUCT OPERATOR NORMS

Atsushi Ueda[1]

[1]*Department of Physics and Astronomy, University of Ghent, 9000 Ghent, Belgium*

Naively discretizing fermionic field theory on a lattice is known to produce unwanted fermion modes. This phenomenon is often referred to as 'fermion doubling,' which has been a significant issue when simulating chiral fermionic theory. We develop a formalism for simulating one-dimensional interacting chiral fermions on the lattice without breaking any local symmetries by defining a Fock space endowed with a semi-definite norm defined in terms of matrix product operators. This formalism can be understood as a second-quantized form of Stacey fermions, hence providing a possible solution for the fermion doubling problem and circumventing the Nielsen-Ninomiya theorem. We prove that the emerging theory is hermitian by virtue of the fact that it gives rise to a hermitian generalized eigenvalue problem and that it has local features as it can be simulated using tensor network methods similar to the ones used for simulating local quantum Hamiltonians. We also show that the scaling limit of the free model recovers the chiral fermion field. As a proof of principle, we consider a single Weyl fermion on a periodic ring with Hubbard-type nearest-neighbor interactions and construct a variational generalized DMRG code demonstrating that the ground states of the system for large system sizes can be determined efficiently [1].

[1] J. Haegeman, L. Lootens, Q. Mortier, A. Stottmeister, **A. Ueda,** and F. Verstraete, arXiv:2405.10285(2024)

SPIN CORRELATIONS IN THE BI-LAYER STACK OF HUBBARD MODEL: A TWO-PARTICLE SELF-CONSISTENT STUDY

Jiawei Yan[1] and Philipp Werner[1]

[1]*Department of Physics, University of Fribourg, 1700 Fribourg, Switzerland*

In this talk, we present a nonequilibrium two-particle self-consistent theory (TPSC) tailored for studying the two-dimensional Hubbard model. In contrast to dynamical mean-field theory, which neglects spatial fluctuations that may be significant in low dimensions, TPSC incorporates them through a static vertex, which is self-consistently calculated at the two-particle level by fulfilling various local sum rules [1]. We formulated the theory using Schwinger-Keldysh technique, which enables us to study both equilibrium and nonequilibrium steady states without numerical analytical continuation [2]. Benchmarks show that the method agrees nicely with recent optical lattice experiments at equilibrium. When applying a bias, we found a decoupling of two layers under a large electric field. More interestingly, we found that inter-layer spin correlations experience a switch from anti-ferromagnetic to ferromagnetic, which is completely caused by nonequilibrium effects [3]. We recently made an extension of the method for multi-orbital Kanamori-Hubbard interactions, which is an important step towards real material simulations.

[1] Y.M. Vilk and A.-M.S. Tremblay, J. Phys. I **7**, 1309 (1997).
[2] J. Yan and V. Janiš, Phys. Rev. B. **105**, 085122 (2022).
[3] J. Yan and P. Werner, Phys. Rev. B. **109**, 155113 (2024).

NONRECIPROCAL PHENOMENA IN SUPERCONDUCTORS: EXOTIC PAIRING, TOPOLOGICAL SUPERCONDUCTIVITY, AND NONEQUILIBRIUM DIODE EFFECT

Youichi Yanase[1], Akito Daido[1], Hiroto Tanaka[1], Hikaru Watanabe[2], Naratip Nunchot[1]

[1]*Department of Physics, Kyoto University*
[2]*Research Center for Advanced Science and Technology, University of Tokyo*

We discuss nonreciprocal transport and optical phenomena in superconductors [1]. Theoretical frameworks of the intrinsic superconducting diode effect [2,3], the optical second-harmonic generation and the bulk photocurrent generation [4,5,6,7] are presented. Based on these nonreciprocal phenomena, probe of finite-momentum Cooper pairs [2], spin-triplet Cooper pairs [3,6], and mixed-parity Cooper pairs [4] are proposed. It is also shown that the topological superconductivity can be detected by utilizing the quantum geometry of Bogoliubov quasiparticles [7]. A nonequilibrium setup for unidirectional superconductivity [8], which enables the perfect superconducting diode effect, is also proposed.

[1] N. Nagaosa and Y. Yanase, Annual Review of Condensed Matter Physics, Vol. **15** (2024).
[2] A. Daido, Y. Ikeda, Y. Yanase, Phys. Rev. Lett. **128**, 037001 (2022).
[3] N. Nunchot, Y. Yanase, Phys. Rev. B **109**, 054508 (2024).
[4] H. Watanabe, Y. Yanase, Phys. Rev. X **11**, 011001 (2021).
[5] H. Watanabe, A. Daido, Y. Yanase, Phys. Rev. B **105**, 024308 (2022).
[6] H. Tanaka, H. Watanabe, Y. Yanase, Phys. Rev. B **107**, 024513 (2023).
[7] H. Tanaka, H. Watanabe, Y. Yanase, arXiv:2403.00494.
[8] A. Daido, Y. Yanase, arXiv:2310.02539.

NON-HERMITIAN SKIN EFFECTS IN A BOSONIC CHAIN WITH STRONG CORRELATIONS

Tsuneya Yoshida[1], Song-Bo Zhang[2], Titus Neupert[3], and Norio Kawakami[1,4,5]

[1]Department of Physics, Kyoto University
[2]Hefei National Center for quantum Design of Functional Materials, University of Science and Technology of China
[3]Department of Physics, University of Zurich
[4]Department of Materials Engineering Science, Osaka University
[5]Department of Physics, Ritsumeikan University

In these years, it has been elucidated that non-Hermiticity induces unique topological phenomena[1,2]. Representative examples are a non-Hermitian skin effect and the emergence of an exceptional point. The former exhibits extreme sensitivity of eigenvalues and eigenstates to boundary conditions due to the non-Hermitian topology in the bulk[3]. While the non-Hermitian topological theory has significantly developed in non-interacting cases, the non-Hermitian topology of correlated systems has not been sufficiently explored.

In this work, we analyze the interplay between strong correlations and the non-Hermitian topology with particularly focusing on non-Hermitian skin effects. Our analysis of one-dimensional bosonic open quantum systems discovers a novel type of skin effects which we dub the Mott skin effect[4]. In contrast to the ordinary skin effect in non-interacting systems, the Mott skin effect results in the extreme sensitivity to boundary conditions only in spin degree of freedom (i.e., charge degree of freedom is not sensitive to the boundary conditions). In addition, our analysis elucidates that the Mott skin effect induces dynamical spin accumulation at an edge while charge degree of freedom remains uniform.

If time allows, we also address correlation effects on exceptional points, degeneracy of energy eigenvalues protected by the non-Hermitian topology; correlations change the topological classification and results in fragility/robustness against interactions[5].

[1] Z. Gong et al., Phys. Rev. X 8, 031079 (2018).
[2] K. Kawabata et al., Phys. Rev. X 9, 041015 (2019).
[3] N. Okuma et al., Phys. Rev. Lett. 124, 086801 (2020).
[4] TY et al., arXiv:2309.14111 (2023).
[5] TY and Y. Hatsugai, Phys. Rev. B 106, 205147 (2022).

EARLY FAULT-TOLERANT QUANTUM COMPUTATION IN PRACTICE

Nobuyuki Yoshioka[1]

[1] *Department of Applied Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan*

The significant development of quantum devices in recent years has opened a path to realize quantum computation, with the aid of quantum error mitigation techniques, whose accuracy is comparable to state-of-the-art classical algorithms even without implementation of quantum error correction. The next milestones are unarguably to demonstrate the power of successive error corrected quantum gates, and subsequently practical quantum advantage in fault-tolerant quantum computation. In the first half of my talk, we argue that the target of the latter is condensed matter problems. We estimate the runtime required to simulate the ground state of notoriously difficult strongly correlated quantum many-body systems, both for classical and quantum algorithms, and estimate that the quantum-classical crossover occurs at computation of hours using hundreds of thousands of physical qubits, assuming the logical encoding of surface codes using superconducting processors. This requirement is orders of magnitude smaller than previous estimates for quantum chemistry and cryptanalysis problems, and therefore expected to provide the first goal for quantum information science community.
In the second half of my talk, we discuss how to enhance the computation accuracy of fault-tolerant quantum computation that does not perfectly suppress the errors. We argue that deep quantum circuits well-scramble the system such that the error can be phenomenologically understood by global depolarizing noise (white noise approximation), and that error mitigation can be done in a cost-optimal way in such a situation.

My talk is based on the following references:

[1] N. Yoshioka, T. Okubo, Y. Suzuki, Y. Koizumi, W. Mizukami, npj Quantum Info., in press.
[2] K. Tsubouchi*, T. Sagawa, N. Yoshioka*, Phys. Rev. Lett. 131, 210601 (2023).
^