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**Conference on Fractionalization and Emergent Gauge Fields in Quantum Matter | (SMR 3834)**

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P01

# Realization of Trimerized State in Spin-1 Square-Kagome Lattice

P02

# Vacancy-induced Curie tails in short-valence bond spin liquids

Md. Zahid Ansari

We argue that vacancy-induced Curie tails in the low-temperature susceptibility of diluted quantum magnets provides a diagnostic for short-valence bond spin liquids. Specifically, we argue that such Curie tails in spin liquid phases are a multi-vacancy effect arising from regions of the lattice that confine the monomers of any maximum matching of the diluted lattice. Further, we argue that isolated vacancies do not give rise to such susceptibility signatures in short-valence bond spin liquids. This distinguishes them from valence-bond solid phases of quantum magnets, in which iso- lated vacancies do give rise to Curie tails in the low-temperature suscepbtibility. We provide detailed quantum Monte Carlo evidence in support of these arguments using SU(N) and O(N) symmetric designer Hamiltonians that exhibit a VBS phases on the honeycomb and triangular lattices, and spin-liquid behavior on a decorated square lattice of the Lieb type and on the kagome lattice. [in collaboration with K. Damle and Souvik Kundu].

P03

# Beyond Li-Haldane Counting: A Close Look at Chiral Topological Order in the Entanglement Spectra of (2+1)-Dimensional Spin Liquid Ground States, with a Focus on PEPS

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The entanglement spectrum (ES) has been a successful tool for the exploration of (2+1)-dimensional chiral topological states, including chiral spin liquids, through Li and Haldane's method of counting degeneracies in the low-lying ES characteristic of an underlying conformal field theory (CFT) [1]. We develop a quantitative understanding of the splitting of these degeneracies in the real space ES, at fixed momentum, that occurs at finite size, based on a Generalized Gibbs Ensemble (GGE) of local conservation laws that arise directly from, and are thus controlled by, the chiral CFT. These conservation laws come from viewing the conformal boundary state description of the ES as a quantum quench.

We apply this by computing such conservation laws for chiral SU(2)-level-one and -level-two [2], and later chiral SU(3)-level-one [3], Wess-Zumino-Witten CFTs, and successfully matching these with numerically calculated entanglement spectra for corresponding chiral spin liquid states, including Projected Entangled Pair States (PEPS). For the chiral SU(2)-level-two case, we find that essential to the GGE ensemble are local integrals of operators of fractional dimension, as proposed by Cardy in Ref. [4] for quantum quenches. One such operator even has lower conformal dimension than the energy-momentum tensor, with implications for the infinite-size entanglement spectrum. Meanwhile, in the chiral SU(3)-level-one case, we find that integrals of odd-dimensional operators are available from the CFT. Only they can be responsible for breaking the degeneracy of SU(3) conjugates, but they are excluded from the ensemble for a chiral state by certain discrete symmetries.

We additionally develop a "doubled" SU(3)-level-one theory [5] to fully explain the low-lying entanglement spectrum of an SU(3) spin liquid PEPS [6] that strongly breaks time-reversal symmetry and possesses chiral SU(3)-level-one Li-Haldane counting in some ES sectors, but not others. This clarifies the non-chirality of that state. We can then clearly contrast the PEPS's sectors which exhibit Li-Haldane state counting of a chiral state, as well as breaking of the degeneracy of SU(3) conjugates, with the chiral SU(3)-level-one spin liquid state [3], and so demonstrate the utility of broken conjugate degeneracy as a diagnostic of the absence of chirality. These results show the important information about chiral topological states that can be gleaned from the detailed structure of the finite-size entanglement spectrum.

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P04

# Signatures of Confinement in Raman Spectroscopy of Ising Spin Chains

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Confinement of excitations is usually considered as a phenomenon of high-energy physics. However, over the recent years, related effects have been discussed in condensed matter settings as well. A paradigmatic example is the formation of mesonic bound states in spin chains with linear confinement between domain walls. A prominent candidate material is the quasi-one dimensional Ising magnet $CoNb_2O_6$ for which mesonic bound states have been detected by neutron scattering experiments. In this work, we study the Raman response of a twisted Kitaev chain in the presence of a magnetic field as a minimal model for confinement in $CoNb_2O_6$ and compute the response within the theory by Fleury and Loudon. We show that the bound states directly manifest themselves as sharp peaks in the Raman response, which we numerically compute using Matrix Product States. We find that the main features of the spectrum can be well understood by a trial wave-function, which contains a few solitonic excitations only. Moreover, when approaching the critical regime Raman spectroscopy can be used to directly detect Ising quantum criticality via the emergence of the famous E8 symmetry in the response spectrum.

P05

# SU(2) gauge theory of the pseudogap phase in the two-dimensional Hubbard model

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We present a SU(2) gauge theory [1] of fluctuating magnetic order in the two-dimensional Hubbard model. The theory is based on a fractionalization of electrons in fermionic chargons and bosonic spinons. The chargons undergo Néel or spiral magnetic order below a density-dependent transition temperature T*. Fluctuations of the spin orientation are described by a nonlinear sigma model obtained from a gradient expansion of the spinon action. The spin stiffnesses are computed from a renormalization group improved random phase approximation. Our approximations are designed for moderate, not for strong, Hubbard interactions. The stiffnesses are strongly doping dependent with discontinuities at half-filling and a pronounced electron-hole asymmetry. The spinon fluctuations prevent magnetic long-range order of the electrons at any finite temperature. The phase with magnetic chargon order shares characteristic features with the pseudogap regime in high-Tc cuprates: a strong reduction of charge carrier density, a spin gap, and Fermi arcs. A substantial fraction of the pseudogap regime exhibits electronic nematicity.

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P06

# Parent Hamiltonian for the Laughlin wavefunction paradigm and its integrability

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The renowned Calogero-Sutherland model (CSM), a many-body system in one spatial dimension with two-body interaction potential of inverse sine square type, is one of the simplest integrable continuum microscopic models whose quasiparticle excitations – the spinons – have abelian fractional statistics [1]. We construct the CSM as a Parent Hamiltonian for Laughlin wavefunction as the ground state. We achieve this by obtaining a destruction operator, calculating its adjoint and forming a non-negative semi-definite Hermitian operator. Further, inspired by [2] we show the integrability of the model by including a two-body particle permutation operator in this destruction operator and thereby building integrals of motion out of the resulting operator. Finally, destruction operators also for the Pfaffian continuum wavefunction and $k = 3$ Read-Rezayi series wavefunction are derived using CFT null field decoupling technique and integrability of the Pfaffian wavefunction parent Hamiltonian is speculated.

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P07

# Monopole Excitations in the Kagome Dirac Spin Liquid

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The ground state of the spin-1/2 Kagome Heisenberg Antiferromagnet (KHAF) has been a widely debated question for decades. Recently, there has been evidence pointing towards a U(1) Dirac Spin Liquid (DSL) [1], whose field theoretic description is given by compact QED in $2+1$ dimensions. In this work, we study the stability of the DSL state to perturbations, focusing on monopole excitations above this candidate ground state. In QFT, these excitations are described by monopole/instanton operators, which change the U(1) gauge flux by $2\pi$ at a specific space-time point. These operators, which describe gauge fluctuations beyond the mean-field level, are an important class of excitations of the spin-liquid state.
In our work, we modify the DSL ansatz by threading one quantum of flux uniformly throughout the whole lattice, and use the Gutzwiller-projected Variational Monte Carlo technique to study the monopole energy cost and its scaling with system size. We also study the fate of spinon particle-hole excitations. We find that both the monopole *and* the spinon excitations are gapless in the thermodynamic limit.
Further, we also study states with a finite density of monopoles $N_m$ to investigate for a possible instability of the Dirac state towards forming a chiral spin liquid, but find no signs of such an instability. [2]

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P08

# Symmetric spin liquids on the trellis lattice

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Unlike conventional magnets, long-range magnetic orders may not be realized in some highly frustrated quantum spin systems. Rather, novel phases such as quantum spin liquids may emerge as ground states. Due to strong quantum fluctuations, two-dimensional spin-1/2 magnets are more prone to exhibit such phases. Being a highly frustrated two-dimensional lattice, the trellis lattice [1] may emerge as a promising candidate to explore such phases. To this end, we perform a projective symmetry group (PSG) [2] classification of symmetric quantum spin liquids on this lattice. Employing the Abrikosov fermion representation for spin, we obtain a total of 256 algebraic PSG corresponding to the invariant gauge group (IGG) $Z_2$. However, restricting up to three symmetry inequivalent nearest neighbours, we identify 2 $SU(2)$, 5 $U(1)$ and 9 $Z_2$ mean field ansätze. Furthermore, we employ a $J_1 - J_2 - J_3$ Heisenberg model and studied phase diagram, spinon dispersion. Moreover, we calculate the dynamical structure factor which can be directly compared with the experimental observations.

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P09

# Superconductivity in Spin-Orbit coupled SU(8) Dirac Fermions on Honeycomb lattice

P10

# Quantum spin liquids on the diamond lattice

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We perform a projective symmetry group classification of spin $S = 1/2$ symmetric quantum spin liquids with different gauge groups on the diamond lattice. Employing the Abrikosov fermion representation, we obtain 8 $SU(2)$, 62 $U(1)$ and 80 $Z_2$ algebraic PSGs. Constraining these solutions to mean-field parton Ansätze with short-range amplitudes, the classification reduces to only 2 $SU(2)$, 7 $U(1)$ and 8 $Z_2$ distinctly realizable phases. We obtain both the singlet and triplet fields for all Ansätze, discuss the spinon dispersions and present the dynamical spin structure factors within a self-consistent treatment of the Heisenberg Hamiltonian with up to third-nearest neighbor couplings. Interestingly, we find that a zero-flux $SU(2)$ state and some descendent $U(1)$ and $Z_2$ states host robust gapless nodal loops in their dispersion spectrum, owing their stability at the mean-field level to the projective implementation of rotoinversion and screw symmetries. A nontrivial connection is drawn between one of our $U(1)$ spinon Hamiltonians (belonging to the nonprojective class) and the Fu-Kane-Mele model for a three-dimensional topological insulator on the diamond lattice. We show that Gutzwiller projection of the 0- and $\pi$-flux $SU(2)$ spin liquids generates long-range Néel order.

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P11

# The Saga of $\alpha$-$RuCl_3$: Relevant Models and Phase Diagrams

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We provide a comprehensive study to demonstrate that the available phenomenology significantly restricts the allowed model parameters for $\alpha$-$RuCl_3$, a honeycomb-lattice Kitaev magnet that continues to attract great interest, leading to its better understanding.[1, 2] Using Luttinger-Tisza, exact diagonalization, and density-matrix renormalization group methods, we provide a detailed investigation of the relevant phase diagrams, yielding a detailed yet physically unifying transparent vision of the nature of this material. It transpires that $\alpha$-$RuCl_3$ can be described as a fluctuating ferro-antiferromagnet with an antiferromagnetic further-neighbor and strong off-diagonal couplings. It is in a fluctuating zigzag ground state, which is proximate to an incommensurate phase that is neighboring a ferromagnetic one. We propose that the substantial anisotropic-exchange terms of the relevant models generically produce strong anharmonic couplings of magnons throughout the phase diagram and for any form of the underlying magnetic order, necessarily producing a spectrum of spin excitations that consists of a broad continuum coexisting with well-defined modes. For the much-discussed spectral properties of $\alpha$-$RuCl_3$, the conclusion of this work thus unambiguously points toward the physics of strongly interacting and mutually decaying magnons, not to that of the fractionalized excitations.

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P12

# Gravitational wave analogues in spin nematics and cold atoms

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Condensed matter systems can possess striking parallels with gauge theories that arise in the context of high-energy physics, exemplified by the Anderson-Higgs transition in superconductors [1], and emergent photons [2] and magnetic monopoles [3] in spin ice. Such examples raise the question of where else there is potential for low-energy experiments to inform physics relevant to high-energy scales.

Here we show how spin nematic phases provide a low-energy avenue for accessing the physics of linearized gravity, in particular for the realization of gravitational wave-like, relativistically dispersing spin-2 excitations. We show at the level of the action that the low-energy effective field theory for a spin nematic is in correspondence with that of linearized gravity. We then explicitly identify a microscopic model of magnetism whose Goldstone modes are relativistically dispersing, massless spin-2 bosons which are in one-to-one correspondence with gravitational waves, and outline a procedure motivated by simulation (see Fig. 1) for directly observing these analogue waves in a cold atom platform.

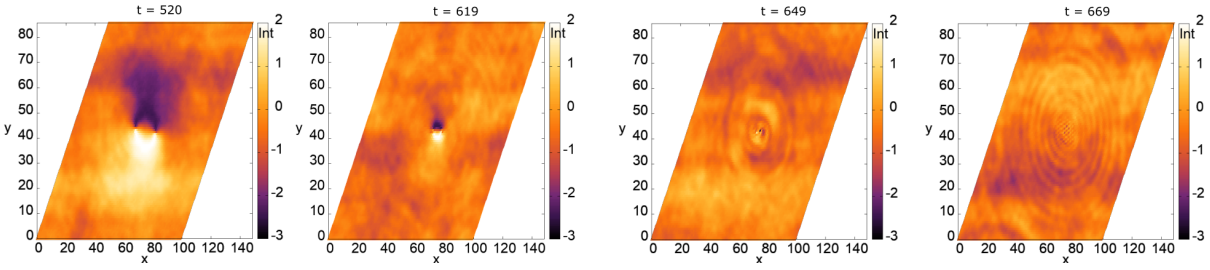


Figure 1: Simulated time evolution of a vortex-pair annihilating in a quantum spin nematic, showing the emission of quadrupolar waves in direct analogy to gravitational waves.

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# 2-Form U(1) Spin Liquids: Classical Model and Quantum Considerations

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We propose the existence of a new class of gapless spin liquids in three dimensions: 2-form U(1) quantum spin liquids. To illustrate this phase, we first introduce a minimal classical Ising model on the pyrochlore lattice, analogous to nearest-neighbor spin ice (NNSI), which we dub the *spin vorticity model*, constructed to enforce a local "zero-curl" constraint on every hexagonal loop of the lattice. We demonstrate using analytic approximation and numerical Monte Carlo simulations that this model has an extensive ground state entropy and a low-temperature Coulomb-like phase characterized by "inverted" pinch point singularities in spin-spin correlation cross sections. We give a detailed characterization of the emergent gauge structure of the ground state manifold of this model, which may be described as a *condensate of membranes*—flipping a collection of spins forming a closed surface (Fig. 1(a)) costs zero energy. Unlike established spin liquids like NNSI, this model contains no point-like quasiparticle excitations. Instead, the fractionalized excitations are extended string objects, created by flipping a collection of spins forming an open surface (Fig. 1(b)). At finite temperature, the classical model is then described by a gas of string loops in a background of fluctuating membranes. This Coulomb phase is described within the formalism of 2-form electrodynamics, where a 2-form U(1) gauge field couples to electrically charged strings. We then introduce a minimal quantum extension of the classical spin vorticity model, from which we derive an effective *membrane exchange* model of the quantum dynamics within the classical ground state manifold. This model maps directly to a frustrated 2-form U(1) lattice gauge theory. We further demonstrate how to quantize the string excitations, by coupling a 1-form *string field* to the emergent 2-form U(1) gauge field, thus mapping a spin model to a 2-form gauge-Higgs model. We discuss the stability of the gapless deconfined phase of this gauge theory, and thus the possibility of realizing a novel phase of quantum matter: a 2-form U(1) quantum spin liquid.

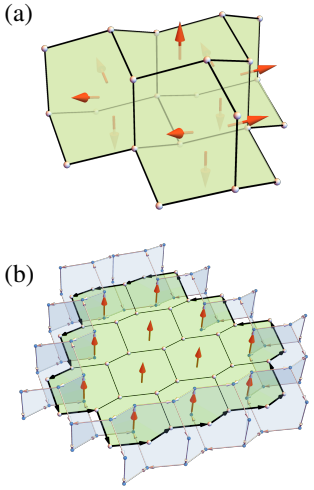


Figure 1: (a) Flipping a collection of spins (red arrows) forming a closed surface costs zero energy. (b) Flipping spins forming an open surface creates a string excitation on the boundary.

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P14

# VQE algorithm for topological one-dimentional many-body systems

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Among the many applications of quantum computation, there is the possibility to study more efficiently many- body systems and their properties. In this work I focus on systems that exhibit topological behavior, which that have attracted great attention in contemporary condensed matter physics due to their theoretical interest and technological potentiality. The aim of this work is the study of Su-Schrieffer-Heeger (SSH) and Kitaev fermonic open chains [1, 2], which are the simplest models showing topological behavior, with the use of Variational Quantum Eigensolver (VQE) algorithm [1]. The goal is to classify the topological phases through the identification of the topological ground state of the systems using topological properties, by implementing suitable objective functions for the algorithm in order to guide its convergence to the minimum energy state in the topologically non-trivial phase, where VQE fails due to the degeneracy caused by the presence of localized edge states at zero energy. This work is intended as starting point for the investigation of nontrivial interacting systems by quantum computers.

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P15

# Kondo breakdown transitions and phases

P16

# Role of interface hybridization on induced superconductivity in 1T′-$WTe_2$ and 2H-$NbSe_2$ heterostructures

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THeterostructures between two dimensional quantum spin Hall insulators (QSHI) and superconducting materials can allow for the presence of Majorana Fermions at their conducting edge states. Although a strong interface hybridization helps induce a reasonable superconducting gap on the topological material, the hybridization can modify the material's electronic structure. In this work, we utilize a realistic low energy model with tunable interlayer hybridization to study the edge state physics in a heterostructure between monolayer quantum spin Hall insulator 1T′-$WTe_2$ and s-wave superconductor 2H-$NbSe_2$. We find that even in the presence of strong inter-layer hybridization that renders the surface to become conducting, the edge state shows a significantly enhanced local density of states and induced superconductivity compared to the surface. We provide an alternate heterostructure geometry that can utilize the strong inter-layer hybridization and realize a spatial interface between a regime with a clean QSHI gap and a topological conducting edge state.

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## Abstract

A variety of analytical approaches have been developed for the study of quantum spin systems in two dimensions, the notable ones being spin-waves, slave boson/fermion parton constructions, and for lattices with one-to-one local correspondence of faces and vertices, the 2D Jordan-Wigner (JW) fermionization. Field-theoretically, JW fermionization is implemented through Chern-Simons (CS) flux attachment. For a correct fermionization of lattice quantum spin-1/2 magnets, it is necessary that the fermions obey mutual bosonic (anyonic) statistics under exchange - this is not possible to implement on arbitrary 2D lattices if fermionic matter couples only to the lattice gauge fields. Enlarging the gauge degrees of freedom to include the dual lattice allows the construction of consistent mutual Chern-Simons field theories. Here we propose a mutual CS theory where the microscopic (spin) degrees of freedom are represented as lattice fermionic matter additionally coupled to specific combinations of dual lattice gauge fields that depend on the local geometry. We illustrate the use of this method for understanding the properties of a honeycomb Kitaev model subjected to a strong Zeeman field in the $z$-direction. Our CS gauge theory framework provides an understanding why the topological phase is degraded at lower (higher) critical fields for the ferro- (antiferro-) magnetic Kitaev interaction. Additionally, we observe an effectively one-dimensional character of the low-excitations at higher fields in the $z$-direction which we also confirm by spin-wave calculations. I am currently working on Kitaev model at low fields starting with a mutual CS theory with level 2 (corresponds to 4-fold degenerate ground state on a torus) and studying how Zeeman field and other perturbations destroy the topological phases by level renormalization.

# P18

I will present the resummation-based quantum Monte Carlo (QMC) algorithm -- implemented recently for sign-problem-free SU(2)-symmetric Hamiltonians in the stochastic series expansion (SSE) framework – and show that it does not reduce the sign problem for frustrated SU(2)-symmetric Heisenberg antiferromagnets on canonical geometrically frustrated lattices composed of triangular motifs such as the triangular lattice. In the process, we demonstrate that resummation-based updates do provide an ergodic sampling of the SSE-based QMC configurations which can be an issue when using the standard SSE updates, however, severely limited by the sign problem as previously mentioned. The notions laid out in these notes may be useful in the design of better algorithms for geometrically frustrated magnets. These algorithms are useful to simulate in an unbiased way microscopic models that can host interesting phenomena that form the theme of this conference.

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# Competition between electron solid and fractional quantum Hall liquid phases in the Landau levels of multilayer graphene

P20

# Classical spin models on the distorted windmill lattice and their applicability to $PbCuTe_2O_6$

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Inspired by the experimental results on the spin-liquid candidate $PbCuTe_2O_6$ [1], we characterize the classical Heisenberg models on the distorted windmill lattice and discuss to which extent they are able to reproduce the experimental findings. First, we consider the general case of antiferromagnetic interactions, up to fourth neighbors. Setting $J_1 = J_2$, as approximately in $PbCuTe_2O_6$, we map out the classical magnetic phase diagram at zero temperature as function of $J_3$ and $J_4$. The competition between $J_3$ and $J_4$ opens up interesting scenarios. We found two distinct magnetically ordered ground states, according to the condition $J_3 \lesseqgtr J_4$. Along the phase boundary $J_3 = J_4$ we found a ground state manifold with subextensive, that becomes extensive at the special point where all the four interactions are equal. The ground states forming the subexstensive degeneracy are the same as the ones found for the $J_1 = J_2$ case [2]. In the case of extensive degeneracy, we uncover a possibly-new type of classical spin liquid defined on a lattice of corner sharing octahedra, with the underlying lattice formed by the octahedra being non-bipartite [3]. Then, we fix the $J_n$ to the values proposed for $PbCuTe_2O_6$. In this case, the system exhibits a phase transition at finite temperature towards an incommensurate magnetically ordered ground state, that was not observed for $PbCuTe_2O_6$. This indicates that quantum fluctuations play an important role in determining the magnetic properties of this material. Finally we simulated the dynamical structure factor for several temperatures and compared it with the published data on $PbCuTe_2O_6$ at low temperatures. Our results show that the simulated structure factor in the paramagnetic regime is able to reproduce the signal distribution found in the experiments. This indicates that broad spin-liquid features determined by quantum fluctuations found in experiments are overall well reproduced by thermal fluctuations.

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P21

# Topological phase diagram of two-band fermionic chain in presence of Hubbard interaction

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We explore the ground-state properties of a two-band fermionic chain supporting a symmetry-protected topological insulator phase, in the presence of Hubbard interaction, inspired by the model proposed in [1]. Starting from the non-interacting ground state, we define a two-orbital Jastrow-Slater wave function which provides a proper variational description of the topological phase diagram. The topological phase transition, which is controlled by the on-site term only, is shifted to greater values of the parameter, with respect to the non-interacting limit, as the repulsion U between electrons on the same orbital is increased. The topological properties in presence of interaction are detected by the many-body marker introduced by Resta and Sorella [2]. Furthermore, the topological non-trivial behaviour of the system persists in the large U limit, where the spin-1 Haldane chain, characterized by string order, emerges as effective spin Hamiltonian.

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P22

# Fractional (and conventional) excitations on the kagome lattice

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Motivated by recent experiments on $Cs_2Cu_3SnF_{12}$ and $YCu_3(OH)_6Cl_3$, we consider the $S = 1/2$ Heisenberg model on the kagome lattice with nearest-neighbor superexchange and Dzyaloshinskii-Moriya interaction, which favors $Q = (0, 0)$ magnetic order [1]. By using both variational Monte Carlo and tensor network approaches, we determine the transition point between the spin liquid phase and the 120° antiferromagnetic order. We assess the spin dynamical structure factor and the corresponding low-energy spectrum, by using the variational Monte Carlo technique, unveiling a strong renormalization of the spin-wave dispersion and a continuum of excitations above the magnon modes, which share remarkable similarities with the inelastic neutron scattering spectra of $Cs_2Cu_3SnF_{12}$ [2]. Furthermore, we investigate the characteristic signatures of the chiral spin liquid state which can be stabilized by introducing a three-spin chiral interaction on the kagome lattice [3].

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P23

# Irrational moments and higher-rank gauge theories in diluted classical spin liquids

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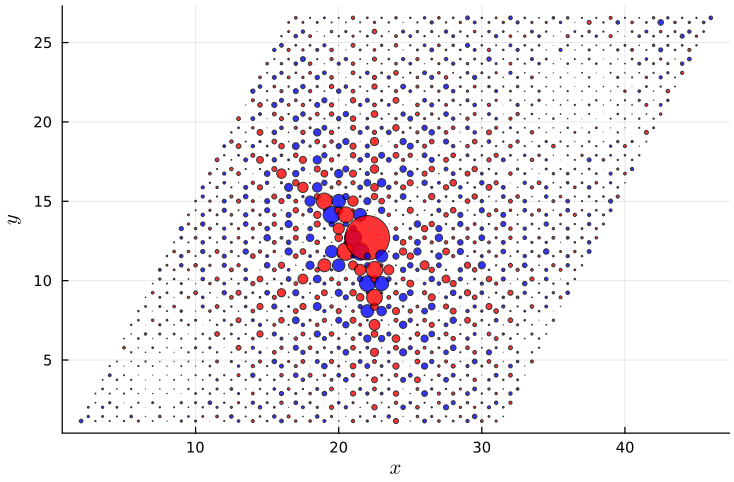
Classical spin liquids have proved to be very fruitful platforms for studying exotic emergent gauge theories. As such gauge charges generically carry information of the underlying system, one such way to implement these charges is by introducing vacancies. We show that dilution with nonmagnetic ions can lead to the emergence of effective free spins with irrational size. We analyse these effects in two distinct models of classical spin liquids in the checkerboard and honeycomb lattices. We find a relationship between the irrational moment size and either spatially anisotropic or beyond nearest-neighbour couplings. The latter honeycomb model has been shown to realise a higher-rank U(1) spin liquid with multifold pinch-point singularities in the structure factor [1]. We demonstrate that the long-range and exotic scaling properties of the spin texture and spin correlations of the diluted clusters are mediated by the underlying higher rank spin liquid.

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P24

# Bond disorder in the high-field regime of extended Heisenberg-Kitaev models

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We study the effect of quenched disorder in extended Heisenberg-Kitaev models on the honeycomb lattice, focusing on bond disorder in the high-field regime for model parameters relevant to $\alpha$-$RuCl_3$. In the clean limit, an asymptotic high-field phase with gapped magnon excitations is realized above a critical field. Here, isolated impurities can induce both spin textures and magnetic in-gap states. For a finite impurity concentration, we find a field regime above the critical field where low-energy impurity-induced states fill the bulk gap, while also smearing the bulk transition to the low-field ordered state. Finally, we discuss the relevance for $\alpha$-$RuCl_3$.

P25

# Spin vestigial orders in extended Heisenberg-Kitaev models near hidden SU(2) points: Application to $Na_2Co_2TeO_6$

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The honeycomb magnet $Na_2Co_2TeO_6$ has recently been argued to realize an approximate hidden SU(2) symmetry that can be understood by means of a duality transformation. Using large-scale classical Monte Carlo simulations, we study the finite-temperature phase diagram of the pertinent Heisenberg-Kitaev-$\Gamma$-$\Gamma'$ model near the hidden-SU(2)-symmetric point, in the presence of a six-spin ring exchange perturbation. At low temperatures, the model features collinear single-**q** zigzag and noncollinear triple-**q** ground states, depending on the sign of the ring exchange coupling. We show that in the vicinity of the hidden-SU(2)-symmetric point, the magnetic long-range orders melt in two stages. The corresponding finite-temperature transitions are continuous and fall into 2D Ising and 2D Potts universality classes, respectively. The two fluctuation-induced phases at intermediate temperatures spontaneously break spin rotational and lattice translational symmetries, respectively, but both leave time reversal symmetry intact. They are characterized by finite expectation values of a real, symmetric, traceless, second-rank tensor, and are naturally understood as vestigial orders of the underlying magnetic states. We identify these vestigial orders as $\mathbb{Z}_3$ spin nematic and $\mathbb{Z}_4$ spin current density wave phases, respectively. For increasing ring exchange perturbations, the width of the vestigial phases decreases, eventually giving rise to a direct first-order transition from the magnetically-ordered phase to the disordered paramagnet. We propose the $\mathbb{Z}_4$ spin current density wave phase, which is the vestigial phase of the primary triple-**q** magnetic order, as a natural candidate for the paramagnetic 2D long-range-ordered state observed in $Na_2Co_2TeO_6$ in a small window above the antiferromagnetic ordering temperature.

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P26

# Simulating two-dimensional spin systems with tensor networks

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In this poster I will present the recent advances in the broad programme aiming at the description of both chiral and non-chiral spin liquids (SL) through tensor network (TN) wavefunctions. Within the last few years, several works demonstrated the ability of TNs to describe abelian and non-abelian chiral SL with high fidelity, despite the no-go theorem precluding an exact construction with finite bond dimension TNs. Instead, the non-chiral SL and in particular their gapless variants conjectured in frustrated antiferromagnets on square or kagome lattices are proving difficult. Here, the technical developments stemming from the gradient optimization of TNs and scaling analysis via correlation lengths proved instrumental in recognizing such phases.

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P27

# Fractional Chern Insulator in Twisted Bilayer $MoTe_2$

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A recent experiment has reported the first observation of a zero-field fractional Chern insulator (FCI) phase in twisted bilayer $MoTe_2$ moiré superlattices [1]. The experimental observation is at an unexpected large twist angle 3.7° and calls for a better understanding of the FCI in real materials. In this work, weperform large-scale density functional theory calculation for the twisted bilayer $MoTe_2$, and find that lattice reconstruction is crucial for the appearance of an isolated flat Chern band. The existence of the FCI state at $\nu = -2/3$ is confirmed by exact diagonalization. We establish phase diagrams with respect to the twist angle and electron interaction, which reveal an optimal twist angle of 3.5° for the observation of FCI. We further demonstrate that an external electric field can destroy the FCI state by changing band geometry and show evidence of the $\nu = -3/5$ FCI state in this system. Our research highlights the importance of accurate single particle band structure in the quest for strong correlated electronic states and provides insights into engineering fractional Chern insulator in moiré superlattices.

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P28

# Frustrated Ferromagnets: Incommensurate Spin Spirals and Quantum Disordered Phases

P29

# Synthetic spacetime in periodic structures

P30

# Dynamics of visons and their signatures in perturbed Kitaev models

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In the paradigmatic Kitaev honeycomb model, spins fractionalize into immobile visons that carry a $\mathbf{Z}_2$ gauge flux and itinerant Majorana fermions with a gapless spectrum. However, in the presence of perturbations, visons become dynamical degrees of freedom. We study an isolated vison in the isotropic Kitaev model perturbed by a small magnetic field, off diagonal exchange ($\Gamma$) and a Heisenberg interaction ($J$)[1]. Visons acquire dispersion linear in $h$ and $\Gamma$ in the ferromagnetic model, strikingly different to the antiferromagnetic case. The singular scattering of Majorana fermions from visons leads to friction for the vison with a fully universal low-$T$ mobility $\mu \propto v_m/T^2$ where $v_m$ is the Majorana fermion velocity.

In an antiferromagnetic Kitaev model perturbed by a magnetic field, visons form Chern bands and may lead to characteristic features in the thermal Hall effects of Kitaev materials. We also predict that vison diffusion gives rise to universal features in quench experiments. The dynamics of visons in the chiral spin liquid phase can be probed by Raman spectroscopy which shows characteristic polarization dependence. Furthermore, we argue that the Raman spectrosopy of visons may also carry signatures of their anyonic nature.

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P31

# Emergent glassiness in disorder-free Kitaev model

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The complete phase diagram of the Kitaev model with a magnetic field remains elusive, as do the experimental results in the candidate material $\alpha$-$RuCl_3$. Here we study the Kitaev model on a one-dimensional ladder setting in the density-matrix renormalization group (DMRG) method in the presence of a magnetic field at zero temperature. We find five distinct phases with increasing magnetic field, which are characterized by a homogeneous flux phase, the $Z_2$ vortex gas, solid and emergent *glass* phase in the so-called $U(1)$ spin liquid region, and finally a spin-polarized phase. The emergent glassiness is confirmed by calculating correlation functions showing quasi-long range behaviour, and ground state fidelity, showing a plethora of energetically accessible orthogonal saddle points corresponding to different flux configurations. This glassy behaviour seems to arise from the slow dynamics of the $Z_2$ fluxes, which is a consequence of the local constraints present in the underlying theory. This phenomenon can also be explored in other spin-liquid systems where the corresponding low-energy excitations are similarly retarded due to constraints.

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P32

# Edge state behavior in a Su-Schrieffer-Heeger like model with periodically modulated hopping

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Su-Schrieffer-Heeger (SSH) model is one of the simplest model to show topological end/edge states and the existance of Majorana fermions. Here we consider a SSH like model both in one and two dimensions where a nearest neighbor hopping features spatially periodic modulations. In the 1D chain, Majorana bound states (MBS) undergo a transition between single-end and both-ends existance as hopping detuning strength is varied through. We also witness appearance of new in-gap end states apart from the zero energy MBS when the hopping periodicity go beyond two lattice spacings. Contrarily in a 2D SSH model with symmetric hopping that we consider, both non-zero and zero energy topological states appear in a finite square lattice even with a simple staggered hopping, though the zero energy modes disappear in a ribbon configuration. Apart from edge modes, the 2D system also features corner modes as well as modes with satellite peaks distributed non-randomly within the lattice. In both the dimensions, an increase in the periodicity of hopping modulation causes the zero energy majorana modes to become avalable for either sign of the detuning. But interestingly with different periodicity for hopping modulations in the two directions, the zero energy modes in a 2D model become rarer and does not appear for all strength and sign of the detuning.

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# Multiboson exchange embedding for the Hubbard model

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In condensed matter physics, strongly correlated electrons are paradigmatic examples of quantum many-body systems that defy a description in terms of simple band theory, due to their strong interactions with each other and with the atomic lattice. Their study is both exciting and challenging, not only because the construction of accurate theoretical models requires the consideration of many different factors, such as spin, charge, and orbital degrees of freedom, as well as disorder, frustration, and fluctuations, but also because of the scarcity of exactly solvable reference Hamiltonians. For example, the single-band Hubbard model in more than one dimension has remained at the forefront of computational condensed matter physics for decades, although in many respects it can be regarded as the simplest incarnation of a reasonably realistic correlated electron system.

We present a novel quantum-embedding approach based on the single-boson exchange (SBE) decomposition [1, 2] of the parquet equations. In the SBE formalism, all diagrams contributing to the two-particle vertex $F$ are grouped according to their interaction reducibility, i.e. the way in which they can be split into disconnected parts by removing a bare vertex instead of a pair of single-particle Green's functions, as it is usually done in the parquet decomposition. This way, unphysical divergences in two-particle irreducible quantities are efficiently mitigated and only the well-conditioned multiboson vertex $\Lambda_U$ is needed to determine all other (single-boson and single-particle) functions self-consistently. Using the dynamical cluster approximation (DCA) with statistically exact CT-QMC simulations, we determine $\Lambda_U$ for small Hubbard clusters coupled to a metallic environment and solve the self-consistent equations on periodic lattices with up to $32 \times 32$ sites, preserving the full frequency and momentum dependence of all single-boson exchange diagrams. We benchmark our approach against established many-body methods at half-filling and in the hole-doped regime of the square lattice Hubbard model.

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# Interplay of gauge fields and matter

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Motivated by the synergies of quantum information science, modern quantum emulators and quantum materials, in this poster I will present recent results on the interplay between gauge fields and fermionic matter. First, I will study exactly soluble toy models displaying orthogonal (semi-)metallic behavior, Fermi surface reconstruction without symmetry breaking, (topological) zeros of the fermionic Green's function[1, 2, 3]. Second, I will present the interplay of metallic leads with quantum spin liquid candidate materials as a way to access signatures of gauge fields and spinons in all-electric transport probes[4, 5]. Finally I will discuss the role of fluctuating gauge fields in the context of newly proposed type-II heavy Fermi liquids as an explanation of magnetic memory in the unconventional superconductor 4Hb-TaS2[6].

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P35

# Crystalline phases and devil's staircase in qubit spin ice

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Motivated by the recent realization of an artificial quantum spin ice in an array of superconducting qubits with tunable parameters [1], we scrutinize a quantum six-vertex model on the square lattice that distinguishes two types of vertices. We map the zero-temperature phase diagram using numerical (exact diagonalization) and analytical (perturbation expansion, Gerschgorin theorem) methods [2]. Following a symmetry classification, we identify three crystalline phases alongside a subextensive manifold of isolated configurations. Monte Carlo simulations at the multicritical Rokhsar-Kivelson point reveal a quantum phase exhibiting a cascade of transitions with increasing flux. By comparing structure factors, we find evidence for the emergence of the fully flippable and plaquette phases in the artificial quantum spin ice.

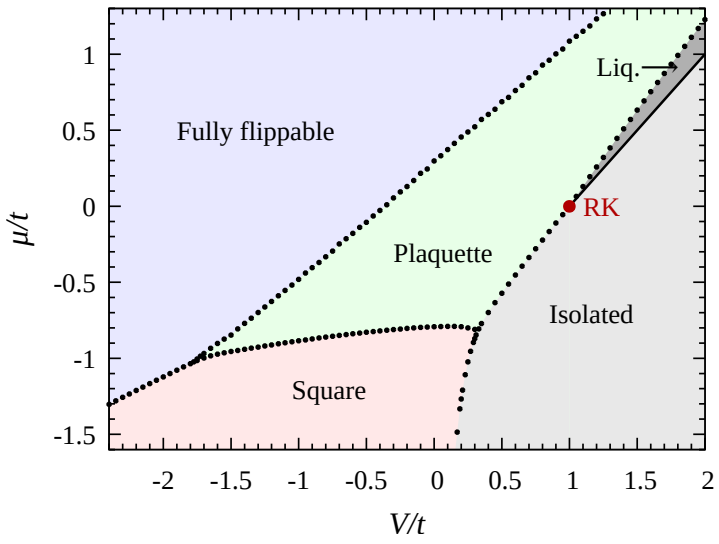


Figure 1: The phase diagram of the model as a function of the kinetic term ($t$), the energy of flippable plaquettes ($V$), and a chemical potential ($\mu$). The three crystalline phases are the fully flippable, the square, and the resonating plaquette phases. The isolated manifold maximizes a topological flux corresponding to total magnetization. A gapless liquid phase emanates from the multicritical Rokhsar-Kivelson point in which we observe a cascade in the flux.

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# Lower bound energy for the spin-1/2 Heisenberg pyrochlore antiferromagnet

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The nature of the ground state of the spin-1/2 antiferromagnetic Heisenberg model on the pyrochlore lattice is an open and difficult question. A growing number of numerical approaches have been developed in recent years to tackle the problem, narrowing down the possible scenarios. Some of them are variational methods, that provide an upper bound for the ground state energy. A way to see how close these are to the true ground state is to compare them with a lower bound for the ground state energy.

We calculated lower bounds following Anderson's method [1] in this work. We write the Hamiltonian as a sum of sub-Hamiltonians defined on an 18-site open cluster formed by six tetrahedra around a hexagon. We allow all possible two-site exchanges with weights respecting the $D_{3d}$ point group of the cluster so that the nearest neighbor Hamiltonian is the sum of the translated and rotated specified sub-Hamiltonian according to the space group. Observing these constraints, we determine the relations between the coefficients of the exchanges which leave ten free parameters in the sub-Hamiltonian. To get a lower bound, we numerically calculate the ground state energy of the cluster with the Lánczos algorithm and maximize its value by varying the free parameters.

This procedure revealed a lower bound of $-0.5498J$ for ground state energy per site, where $J$ is the nearest neighbor exchange. This result is comparable with $-0.56J$ [2], $-0.572J$ [3] predicted energies and raises the possibility of a lower ground state energy than $-0.4917J$ determined by NLCE [4].

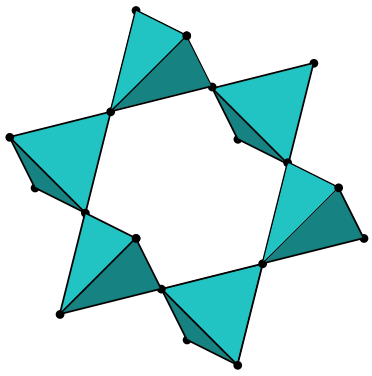

Figure 1: The 18-site cluster.

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P37

# Local quenches in a confining spin chain

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Our work is motivated by the recent discovery of real time confinement in the quantum Ising spin chain [1]. We investigate the effect of confinement on the dynamics of local quenches using time evolving block decimation (TEBD) method to simulate the time evolution. For the case of closed systems, we observe enhanced magnitude of fronts escaping confinement. Theoretical understanding of this phenomenon is in progress [2].
For a more realistic description of experimental systems, it is often necessary to consider an open system by coupling the model to an environment which can be accomplished by applying the Lindblad formalism [3]. The time evolution can be implemented in the TEBD protocol by vectorising the Lindblad equation and the density operators in Liouville space. It turns out that the escaping fronts are strongly suppressed compared to the case of local quenches of closed systems.

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P38

# Manipulating flat bands through spin-orbit interaction in pentagon-based conducting polymers

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Flat bands have garnered significant interest today due to the wide range of applications facilitated by their high degeneracy. Notably, flat bands manifest in various scenarios such as diffraction-free photonics via collective excited states of atoms in Creutz super-radiance lattices [1], interaction-enhanced group velocity in optical Kagome lattices [2], production of topological states in 1D optical lattices [3].

I explored flat band conditions for pentagon-based conducting polymer chains, considering the presence of spin-orbit interaction (SOI) in the Hamiltonian of the studied system [4]. Two spin-orbit couplings were considered: one within the base and another representing inter-base contributions. Additionally, an external magnetic field was introduced through Peierls phase factors to gather more insights.

In my exploration, I present the studied system, analyze the band structure, and identify flat bands. My investigation delves into the mathematical strictness of flat band conditions [5] and demonstrates how these conditions can be relaxed by spin-orbit interactions while either maintaining or altering the position of the flat bands. This comprehensive approach provides a nuanced understanding of the interplay between spin-orbit coupling, external magnetic fields, and the structural characteristics of conducting polymers, offering valuable insights into the manipulation of flat bands.

In my study, I demonstrate that incorporating spin-orbit coupling in the system Hamiltonian allows for a significant relaxation of the strict flat band conditions. This approach is particularly enticing due to the controllable nature of SOI strength through an externally applied electric field. As a result, engineering a flat band in a real system becomes more easily achievable than previously considered. Dispersive bands, which deviate from parameters set by flat band conditions, can be effectively transformed back into flat bands through the modulation of SOI strength. My findings suggest that the modulation of SOI strength offers a promising option for manipulating flat bands, with potential applications in the broad spectrum of phenomena related to flat bands.

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# Thermal Hall conductivity near field-suppressed magnetic order in a Kitaev-Heisenberg model

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We investigate thermal Hall conductivity $\kappa_{xy}$ of a $J$-$K$ Kitaev-Heisenberg model with a Zeeman field in the (111) direction in the light of the recent debate surrounding the possible re-emergence of Ising topological order (ITO) and half-quantized $\kappa_{xy}/T$ upon field-suppression of long-range magnetic order in Kitaev materials. We use the purification-based finite temperature Tensor Network approach making no prior assumptions about the nature of the excitations: Majorana, visons or spin waves. For purely Kitaev interactions and fields $h/K \gtrsim 0.02$ sufficient to degrade ITO, the peak $\kappa_{xy}/T$ monotonously decreases from half-quantization associated with lower fields - a behavior reminiscent of vison fluctuation corrections. For higher fields $h/K \gtrsim 0.1$, we find the results qualitatively consistent with a spin-wave treatment. In our $J$-$K$ model (with ferro-$K$ and antiferro-$J$), in the vicinity of field-suppressed magnetic order, we found $\kappa_{xy}/T$ to be significant, with peak magnitudes exceeding half-quantization followed by a monotonous decrease with increasing $h$. We thus conclude that half-quantized thermal Hall effect in the vicinity of field suppressed magnetic order in our model, is a fine-tuning effect and is not associated with a Majorana Hall state with ITO.

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# A continuous-$N$ quantum Monte Carlo study of SU($N$) Heisenberg model with two-column representation

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We study the SU($N$) symmetric Heisenberg model with a two-column representation ($S = 1$ for $N = 2$) on the square lattice. We use the resummation-based stochastic series expansion quantum Monte Carlo technique which can treat $N$ as a *continuous* parameter. For the one-column case ($S = \frac{1}{2}$ for $N = 2$), we find a continuous-$N$ quantum phase transition from a magnetically ordered phase to a magnetically disordered phase at $N_c = 4.47(9)$ in good agreement with a previous study by *Beach et al.* [1]. For the two-column case which is of our interest, we find a continuous-$N$ quantum phase transition at $N_c = 9.35(4)$. This is consistent with an earlier integer-$N$ numerical study by *Kawashima et al.* [2] which found a magnetically ordered phase for $N \leq 9$ and a magnetically disordered phase for $N \geq 10$. We find the exponents at this transition to be $z = 1, \nu = 1.08(7)$.

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# Flux fractionalization transition in anisotropic $S = 1$ antiferromagnets and dimer-loop models

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We demonstrate that the low temperature ($T$) properties of a class of anisotropic spin $S = 1$ kagome (planar pyrochlore) antiferromagnets on a field-induced $\frac{1}{3}$-magnetization ($\frac{1}{2}$-magnetization) plateau are described by a model of fully-packed dimers and loops on the honeycomb (square) lattice, with a temperature-dependent relative fugacity $w(T)$ for the dimers. The fully-packed O(1) loop model ($w = 0$) and the fully-packed dimer model ($w = \infty$) limits of this dimer-loop model are found to be separated by a phase transition at a finite and nonzero critical fugacity $w_c$, with interesting consequences for the spin correlations of the frustrated magnet. The $w > w_c$ phase has short loops and spin correlations dominated by power-law columnar order (with subdominant dipolar correlations), while the $w < w_c$ phase has dominant dipolar spin correlations and long loops governed by a power-law distribution of loop sizes. Away from $w_c$, both phases are described by a long-wavelength Gaussian effective action for a scalar height field that represents the coarse-grained electrostatic potential of fluctuating dipoles. The destruction of power-law columnar spin order below $w_c$ is driven by an unusual *flux fractionalization* mechanism, topological in character but quite distinct from the usual Kosterlitz-Thouless mechanism for such transitions: Fractional electric fluxes which are bound into integer values for $w > w_c$, proliferate in the $w < w_c$ phase and destroy power-law columnar order.

# Spreading entanglement through pairwise exchange interactions

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(Dated: March 28, 2023)

The spread of entanglement is a problem of great interest. It is particularly relevant to quantum state synthesis, where an initial direct-product state is sought to be converted into a highly entangled target state. In devices based on pairwise exchange interactions, such a process can be carried out and optimized in various ways. As a benchmark problem, we consider the task of spreading one excitation among $N$ two-level atoms or qubits. Starting from an initial state where one qubit is excited, we seek a target state where all qubits have the same excitation-amplitude – a generalized-W state. This target is to be reached by suitably chosen pairwise exchange interactions. For example, we may have a a setup where any pair of qubits can be brought into proximity for a controllable period of time. We describe three protocols that accomplish this task, each with $N-1$ tightly-constrained steps. In the first, one atom acts as a flying qubit that sequentially interacts with all others. In the second, qubits interact pairwise in sequential order. In these two cases, the required interaction times follow a pattern with an elegant geometric interpretation. They correspond to angles within the spiral of Theodorus – a construction known for more than two millennia. The third protocol follows a divide-and-conquer approach – dividing equally between two qubits at each step. For large $N$, the flying-qubit protocol yields a total interaction time that scales as $\sqrt{N}$, while the sequential approach scales linearly with $N$. For the divide-and-conquer approach, the time has a lower bound that scales as $\log N$. With any such protocol, we show that the phase differences in the final state cannot be independently controlled. For instance, a W-state (where all phases are equal) cannot be generated by pairwise exchange.



## I. INTRODUCTION

The synthesis of entangled states is an enduring problem in quantum science. This requires systematic protocols for transforming a direct-product state into a desired superposition of states. To mitigate decoherence effects, any such process must be optimized to minimize operation time. This has inspired several studies on time-optimized protocols[1–7]. At the same time, it is important to ensure scalability. As quantum devices grow in qubit-number, entangling protocols must be able to operate within reasonable timeframes. This requires optimization with respect to qubit-number-complexity (operating time vs. number of qubits). Motivated by these ideas, we consider the simplest entanglement-spreading task – that of spreading a single excitation equally among $N$ participating qubits. We impose a constraint informed by the design of multiple quantum architectures: this task is to be achieved solely by pairwise exchange interactions. We present three solutions and discuss their scaling with qubit number.

The interest in entanglement spreading can be gauged from the large number of studies on the W state – a prototypical entangled state where an excitation is equally spread over $N$ qubits[8]. Many proposals have been put forward to synthesize the W-state[9, 10] and many experiments have succeeded in creating it[11–14]. The challenge in these protocols can be stated as follows: starting from an unentangled initial state with only one qubit excited, how can the excitation be spread equally among all qubits? In this article, we take an approach that is inspired by *mancala* games – a family of games with a long history and wide geographical spread[15]. They are played on a board with pits that contain pieces. In a typical game, a player picks pieces from one pit and distributes them over the other pits. Here, we have $N$ qubits that are analogous to $N$ pits. An excitation (an $\uparrow$ state or a 1-state) is initially stored in one qubit, analogous to pieces stored in a pit. The goal of the game is to spread the pieces evenly among $N$ pits. Below, we describe three protocols to achieve this goal and characterize their scaling with $N$.

We assume an architecture where qubits can undergo pairwise exchange interactions. Exchange interactions have been proposed as a mechanism for designing logic gates[16]. They can be achieved in many settings. For example, with ultracold atoms in an optical lattice, a lattice-modulation can be used to induce an XXZ-exchange interaction[17]. The time period and the strength of the interaction can both be controlled by tuning the modulation. In semiconductor qubits, exchange interactions can be induced in a similar fashion by tuning tunnelling barriers[18–20]. Alternatively, they can be mediated by a cavity-mode[21] where the strength and duration can be controlled by varying the detuning.

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## II. ENTANGLEMENT BY EXCHANGE

To set the stage, we begin by considering two two-level atoms (qubits), labelled A and B. They undergo an exchange interaction which entangles them. The degree of entanglement can be tuned by varying the interaction time, $t$.

We first discuss Heisenberg exchange as it leads to a simple form for the time-evolution operator. We then generalize to anisotropic exchange of the XXZ type. The results discussed in subsequent sections hold for any value of the XXZ anisotropy, including the Heisenberg limit. A Heisenberg exchange interaction between two qubits is described by the Hamiltonian

$$\hat{H}_{AB} = J\Big[\sigma_x^A\sigma_x^B + \sigma_y^A\sigma_y^B + \sigma_z^A\sigma_z^B\Big], \tag{1}$$

where $\sigma$'s are single-qubit operators encoded by Pauli matrices. With the two qubits interacting for time $t$, the wavefunction undergoes unitary evolution. The time-evolution operator can be written in various forms. For our purposes, it is best written as

$$\hat{U}_{AB}(t) = e^{it/2}\Big\{\cos(t)\ \hat{\mathbb{1}}_{AB} - i\sin(t)\ \hat{\Pi}_{AB}\Big\}, \tag{2}$$

where time $t$ is measured in units of $2\hbar/J$. The identity operator, $\hat{\mathbb{1}}_{AB}$, leaves both qubits unchanged. In contrast, $\hat{\Pi}_{AB}$ is the permutation operator that switches the states of A and B. In the $S_z$ basis ($\{\uparrow\uparrow,\uparrow\downarrow,\downarrow\uparrow,\downarrow\downarrow\}$), it is given by

$$\hat{\Pi}_{AB} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{3}$$

If one qubit is initially excited and the other is in the ground state, the permutation operator transfers the excitation from the former to the latter. As seen from Eq. 2, the amplitude for excitation transfer is $\sin(t)$, while that for retaining the excitation at the same qubit is $\cos(t)$. By tuning the interaction time $t$, the 'transferred weight' can be tuned. For a generic value of $t$, the final state is entangled with the excitation spread over two qubits.

We next consider a more general interaction Hamiltonian of the XXZ form,

$$\hat{H}^{\lambda}_{AB} = J\Big[\sigma_x^A\sigma_x^B + \sigma_y^A\sigma_y^B + \lambda\sigma_z^A\sigma_z^B\Big], \tag{4}$$

where $\lambda$ is an anisotropy parameter. This Hamiltonian leads to the unitary time-evolution operator,

$$\hat{U}^{\lambda}_{AB}(t) = e^{i\lambda t/2}\hat{P}_{\sigma_A\neq\sigma_B}\Big\{\cos(t)\ \hat{\mathbb{1}}_{AB} - i\sin(t)\ \hat{\Pi}_{AB}\Big\} + e^{-i\lambda t/2}\hat{P}_{\sigma_A=\sigma_B}, \tag{5}$$

Here, $\hat{P}_{\sigma_A=\sigma_B}$ is a projection operator onto the $\sigma_A = \sigma_B$ sector, where both qubits are in the same state. In this case, $\hat{U}^{\lambda}_{AB}(t)$ leaves the state unchanged (up to a global phase). In contrast, $\hat{P}_{\sigma_A\neq\sigma_B}$ selects states where the qubits are in opposite states. Acting on such states, $\hat{U}^{\lambda}_{AB}(t)$ exchanges their states with probability amplitude $\sin(t)$. If the initial state had one qubit excited and one in the ground state, the final state will generically be entangled. The interaction time, $t$, controls the spread of the excitation across the two qubits.

Before stating the problem of interest, we note that the amplitudes in Eqs. 2 and 5 are periodic in time with period $2\pi$. In the following discussion, we always choose the shortest time that can effect a desired operation.

## III. PROBLEM STATEMENT

We consider $N$ two-level atoms (qubits). We assume a setup where pairs of atoms can be selected and made to interact for a specified period of time. For instance, this may involve bringing two atoms close to one other – at a certain fixed distance and for a chosen time interval. Initially, the $N$ qubits are in a direct-product state represented as

$$|\psi_{initial}\rangle = |\uparrow_1\downarrow_2\downarrow_3\ldots\downarrow_N\rangle. \tag{6}$$

The first qubit is in the excited state while others are in the ground state. This can be viewed as one quantum of information stored in qubit-1.

The target state is a generalized W-state given by

$$|\psi_{target}\rangle = \frac{1}{\sqrt{N}}\sum_{j=1}^{N} e^{i\phi_j}|\downarrow_1\ldots\downarrow_{j-1}\uparrow_j\downarrow_{j+1}\ldots\downarrow_N\rangle. \tag{7}$$

This is a sum of $N$ components, each having the excitation positioned at a different qubit. Each component has the same probability amplitude, but not necessarily the same phase. If all $\phi_j$'s were equal, this would be the well-known W-state[8]. We do not place any restriction on $\phi_j$'s here. In fact, we will see below that $\phi_j$'s cannot be independently tuned.

In the following sections, we propose three protocols that take the initial state of Eq. 6 to the target state of Eq. 7. Our arguments hold for interactions of the XXZ type with any value for the anisotropy parameter, $\lambda$.

## IV. PROTOCOL WITH A SINGLE FLYING QUBIT

We assume that one of the qubits can move freely and interact with each of the others. The qubit could be a photon or a vibration mode that can selectively couple to static qubits. In fact, the protocol discussed below was successfully used to generate a generalized W-state with trapped ions in 2005[11]. In this study, the role of the flying qubit was played by a vibration mode of a trapped-ion-chain. In the following discussion, we assume that this flying qubit is labelled as $j = 1$. We further assume that this qubit is initially in the excited state while all other qubits ($j = 2, 3, \ldots, N$) are in the ground state.

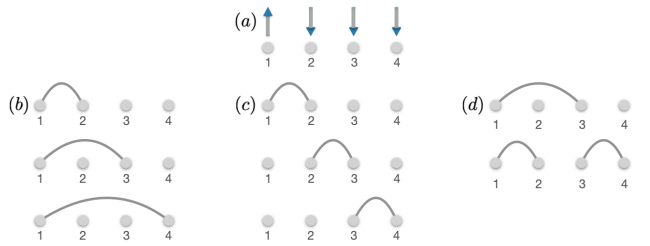


FIG. 1. Three protocols illustrated for a system with $N = 4$ qubits. (a) The initial direct product state with one qubit excited and $N-1$ qubits in the ground state. (b) A flying-qubit protocol where qubit-1 interacts with each of the other qubits in order. (c) A sequential protocol where pairs of neighbouring qubits interact in succession. (d) A divide-and-conquer protocol where the system is arranged hierarchically in units of two qubits. At each stage, interactions act at one level of the hierarchy.

We propose a protocol where qubit-pairs interact in the following order: qubits 1 and 2 interact for time $t_{1,2}$, qubits 1 and 3 interact for time $t_{1,3}$, ..., qubits 1 and $N$ interact for time $t_{1,N}$. Initially, qubits 1 and 2 begin in the state $|\uparrow_1\downarrow_2\rangle$. As they interact for time $t_{1,2}$, their state is acted upon by the time-evolution operator of Eq. 2 or 5. The resulting state is (up to a global phase)

$$\cos(t_{1,2})|\uparrow_1\downarrow_2\downarrow_3\ldots\downarrow_N\rangle - i\sin(t_{1,2})|\downarrow_1\uparrow_2\downarrow_3\ldots\downarrow_N\rangle.$$

After time $t_{1,2}$, qubit 2 does not interact with any of the other qubits. The component that is proportional to $\sin(t_{1,2})$ remains unchanged in amplitude, although it may accrue a phase. Therefore, in the final state, the probability amplitude for qubit 2 to be excited is $\sin(t_{1,2})$. Upon comparing with the target state of Eq. 7, we must have

$$\sin(t_{1,2}) = \frac{1}{\sqrt{N}}. \tag{8}$$

This fixes $t_{1,2}$. Subsequently, qubit 1 interacts with qubit 3 for time $t_{1,3}$. At the start of this process, the amplitude for qubit 1 to be excited is $\cos(t_{1,2}) = \sqrt{\frac{N-1}{N}}$. The probability amplitude for the excitation to be transferred to qubit 3 is given by a product of two amplitudes: (i) that for qubit 1 to be initially excited and (ii) that for the excitation to be transferred during the interaction. This is given by

$$\sqrt{\frac{N-1}{N}} \times \sin(t_{1,3}) = \frac{1}{\sqrt{N}}. \tag{9}$$

We have set the amplitude to $1/\sqrt{N}$ in order to match the target state of Eq. 7. As qubit 3 does not interact after this step, it will always retain its amplitude through to the end. We obtain

$$\sin(t_{1,3}) = \frac{1}{\sqrt{N-1}}. \tag{10}$$

At this point, the amplitude for qubit-1 to be excited is

$$\sqrt{\frac{N-1}{N}} \times \cos(t_{1,3}) = \sqrt{\frac{N-1}{N}} \times \sqrt{\frac{N-2}{N-1}} = \sqrt{\frac{N-2}{N}}. \tag{11}$$

At the next step, qubits 1 and 4 interact. The amplitude for an excitation to be transferred to qubit 4 is given by

$$\sqrt{\frac{N-2}{N}} \times \sin(t_{1,4}) = \frac{1}{\sqrt{N}}. \tag{12}$$

This fixes $\sin(t_{1,4}) = \frac{1}{\sqrt{N-2}}$. Proceeding in this manner, we find

$$\sin(t_{1,5}) = \frac{1}{\sqrt{N-3}}, \quad \ldots, \quad \sin(t_{1,N}) = \frac{1}{\sqrt{2}}. \tag{13}$$

These relations can be gathered into a general expression for the $j^{\text{th}}$ time interval,

$$t_{1,j+1} = \sin^{-1}\{1/\sqrt{N-j+1}\}. \tag{14}$$

Remarkably, these time periods have an elegant geometric interpretation. These are angles within the spiral of Theodorus, a geometric construction known since the 5th century BCE[22, 23]. The spiral is constructed as a series of right-angled triangles. At each step, a unit line segment is drawn perpendicular to the hypotenuse of the previous step. This forms one side of a new right-angled triangle with a longer hypotenuse. This procedure leads to a sequence of points spiralling outwards. The $\text{n}^{\text{th}}$ point is given as $(r_n, \theta_n)$ in polar coordinates. Here, $r_n = \sqrt{n}$ and $\theta_n$ is a monotonically increasing function of $n$. For large $n$, it is known[22, 24] that $\theta_n \sim 2\sqrt{n}$, with corrections that are subleading in powers of $n$.

Fig. 2 shows the angles as they appear in the spiral. The 'interior angles', denoted as $\alpha_n$'s, are precisely the time intervals given in Eq. 14,

$$\alpha_1 = t_{1,N}; \quad \alpha_2 = t_{1,N-1}; \quad \ldots; \quad \alpha_{N-1} = t_{1,2}. \tag{15}$$

From the figure, it is clear that the interior angles decrease progressively, i.e., $\alpha_n$ monotonically decreases with $n$. We deduce that the time intervals increase progressively, with $t_{1,2} < t_{1,3} < \ldots < t_{1,N}$. The total process time, excluding overheads such as rearranging qubits, is given by

$$t_{flying} = t_{1,2} + t_{1,3} + \ldots + t_{1,N} = \sum_{j=1}^{N-1} \alpha_j = \theta_N \approx 2\sqrt{N}. \tag{16}$$

where $\alpha_j$'s are angles as shown in Fig. 2. The sum over $\alpha_j$'s yields $\theta_N$, the angular coordinate of the $N^{\text{th}}$ point of the Theodorus spiral. In the last step, we have used the approximate form for $\theta_N$ when $N$ is large. We arrive at the following result: this protocol yields a generalized W-state with the operation time scaling as $\sqrt{N}$ for large $N$.

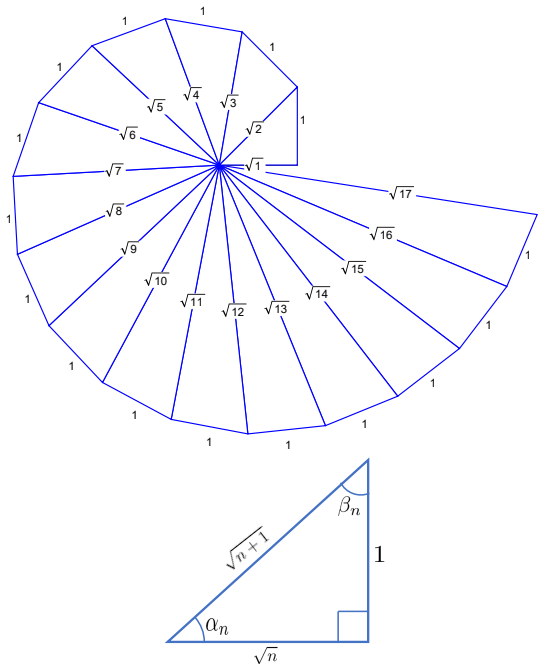


FIG. 2. Top: The spiral of Theodorus, constructed as a series of right-angled triangles. Bottom: The $n^{\text{th}}$ triangle in the spiral, with sides 1, $\sqrt{n}$ and $\sqrt{n+1}$.

## V. PROTOCOL WITH SEQUENTIAL PAIRWISE INTERACTIONS

We next consider a protocol where qubit-pairs interact in the following order: qubits 1 and 2 interact for time $t_{1,2}$, qubits 2 and 3 interact for time $t_{2,3}$, ..., qubits $N-1$ and $N$ interact for time $t_{N-1,N}$. Initially, qubit 1 is taken to be excited while all others are in the ground state. As qubits 1 and 2 interact, their state is acted upon by the time-evolution operator of Eq. 2 or Eq. 5. A portion of the excitation can be transferred from qubit 1 to 2. At the next step, a portion of the excitation in qubit 2 is transferred to 3 and so on.

Qubit 1 is only modified during the first step. As a result, its final excitation-amplitude is determined at the first step alone. From Eq. 2 or 5, this is given by $\cos(t_{1,2})$ – the amplitude for no excitation transfer occurring during the first step. In the final target state, the amplitude for qubit-1 to be excited must be $1/\sqrt{N}$, so that

$$\cos(t_{1,2}) = \frac{1}{\sqrt{N}}. \tag{17}$$

This fixes time $t_{1,2}$. After the first step, the amplitude for qubit-2 to be excited is given by $\sin(t_{1,2}) = \sqrt{\frac{N-1}{N}}$. During the second step, this excitation may be passed onto qubit-3. Beyond the second step, qubit-2 remains unchanged. As a result, the final amplitude for qubit-2 to be excited is given by $\sin(t_{1,2}) \times \cos(t_{2,3})$. In the final target state, the amplitude for qubit-2 to be excited must be $1/\sqrt{N}$, so that

$$\sqrt{\frac{N-1}{N}}\cos(t_{2,3}) = \frac{1}{\sqrt{N}} \implies \cos(t_{2,3}) = \frac{1}{\sqrt{N-1}}. \tag{18}$$

This fixes $t_{2,3}$. Considering each following step in the same fashion, we arrive at

$$\cos(t_{3,4}) = \frac{1}{\sqrt{N-2}}, \quad \ldots, \quad \cos(t_{N-1,N}) = \frac{1}{\sqrt{2}}. \tag{19}$$

These relations determine all time intervals in the problem, with $t_{j,j+1} = \cos^{-1}(1/\sqrt{N-j+1})$. These times are, once again, angles that appear in the spiral of Theodorus. As shown in Fig. 2, they are 'exterior angles' denoted as $\beta_n$'s. We have $\beta_1 = t_{N-1,N}$, $\beta_2 = t_{N-2,N-1}$, ..., $\beta_{N-1} = t_{1,2}$.

From Fig. 2, we see that $\beta$'s increase monotonically with $n$. We conclude that the time intervals in this protocol are arranged in descending order: $t_{1,2} > t_{2,3} > \ldots > t_{N-1,N}$.

As seen from Fig. 2, $\beta_j$ and $\alpha_j$ form a pair of complementary angles for any $j$. In Sec. IV, the total operation time was written as a sum over $\alpha$-angles. Here, the total operating time is

$$t_{sequential} = t_{1,2} + t_{2,3} + \ldots + t_{N-1,N} = \sum_{j=1}^{N-1} \beta_j$$
$$= (N-1)\frac{\pi}{2} - \sum_{j=1}^{N-1} \alpha_j \approx (N-1)\frac{\pi}{2} - 2\sqrt{N}. \tag{20}$$

We have used the result quoted in Eq. 16 for the sum over $\alpha_j$. We conclude that the total operating time scales linearly with $N$ in this protocol.

## VI. DIVIDE-AND-CONQUER PROTOCOL

The previous two sections present two protocols. In both, an initial excitation in one qubit is spread over $N$ qubits in serial fashion – through a sequence of exchange interactions that must be executed in serial order. We now consider a third protocol that allows for parallel operations. At each step, we consider two qubits. One has a certain probability of being in the excited state, while the other is entirely in the ground state. An exchange interaction is carried out to equally spread the excitation-amplitude between the two qubits.

This protocol is particularly suited for $N$'s that are powers of 2, i.e., $N = 2^M$ where $M$ is an integer. The protocol proceeds through $M$ stages where each stage may involve multiple pairwise interactions. For illustration, we take the example of 4 qubits ($M = 2$). Initially, qubit-1 is excited while all others are in the ground state. During the first stage, qubit-1 and qubit-3 are made to interact. The interaction time is chosen such that the qubit-1 and 3 both acquire the same excitation-amplitude. That is, $\cos(t_{1,3}) = \sin(t_{1,3}) = 1/\sqrt{2}$.

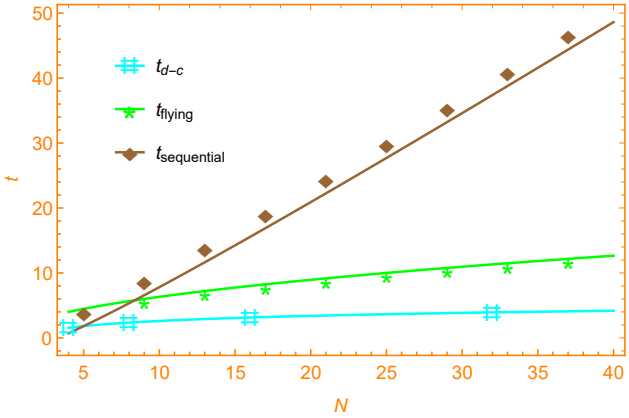


FIG. 3. The total interaction time $t$ vs. the number of qubits, $N$, for the three protocols discussed here. The lines show the approximate scaling form for large $N$ (see text).

During the second stage, qubit-1 interacts with qubit-2 while qubit-3 interacts with qubit-4. These two interactions may take place at the same time, in parallel. For each interaction, the time period is fixed such that the likelihood of excitation-transfer is equal to that of excitation-retention, i.e., $\cos(t_{1,2}) = \sin(t_{1,2}) = \cos(t_{3,4}) = \sin(t_{3,4}) = 1/\sqrt{2}$. This yields the target state, with each qubit having the same amplitude $(1/2)$ for carrying an excitation.

For any larger value of $M$, we have $M$ stages. It can be easily seen that the total number of pairwise interactions is still $N-1$, the same as for the previous two protocols. However, all interactions within a stage may take place in parallel. Each of these interactions takes place over a time period given by $\cos(t) = 1/\sqrt{2}$, i.e., $t = \pi/4$.

If the setup is such that only one pairwise interaction can take place at a time, the total operating time would be $(N-1)\pi/4$, scaling linearly with $N$. If parallel pairwise interactions are possible, they significantly reduce operating time. We have $M$ distinct stages in the problem, each involving pairwise interactions over a time period of $\pi/4$. The lowest time is achieved if all interactions of a stage are performed simultaneously. This yields a lower bound for the operating time, $t_{lower\ bound} = M\pi/4$. This quantity scales as $M \sim \log_2 N$.

## VII. PHASE DIFFERENCES IN THE TARGET STATE

The target state, as defined in Eq. 7, has $N$ phases denoted as $\phi_j$'s. These phases cannot be independently controlled. With the exchange interactions of Eqs. 2 and 5, every excitation-transfer carries a phase of $3\pi/2$ (a factor of $-i$). As a result, in any of the three protocols, the final state corresponds to Eq. 7 with disparate values of $\phi_j$'s. To illustrate this, we formally show that a W state (with all $\phi_j$'s being equal) cannot be synthesized using pairwise exchange interactions.

Our argument is based on two observations: (i) Pairwise exchange interactions are unitary operations and therefore, reversible. (ii) The W state is invariant under any permutation. As a result, it is unchanged (up to a global phase) by operators of the form Eq. 2 or Eq. 5. Suppose the W state could be synthesized starting from a direct product state via pairwise interactions. It must be possible to reverse the process – to start from a W state and to arrive at a direct product state with only pairwise interactions. However, this is not possible, as any operation of the form of Eqs. 2 or 5 does not change the W state. We conclude that the W state cannot be produced within this approach.

## VIII. DISCUSSION

We have discussed protocols to generate highly entangled generalized W-states starting from a direct product state. The entanglement is generated by pairwise interactions: at each step, two qubits are brought together and allowed to interact for a controlled period of time. This setup imposes strong constraints on the protocol and on the final state. For example, while it allows for an equal-weight superposition, the phase difference across components cannot be tuned. However, these constraints lead to highly-structured solutions. The time-intervals involved have a geometric interpretation, as angles of the spiral of Theodorus.

Our first protocol assumes a flying-qubit setup. This could be realized as a cavity-photon-mode that can be tuned into resonance with a series of static qubits[25, 26]. In fact, this protocol has been used in Ref. 11 to create a generalized-W state with trapped ions. The second protocol involves sequential inter-qubit interactions. A similar protocol has been realized in Ref. 27 with semiconductor spin-qubits, but with the goal of transferring a qubit-state between the ends of a chain. The same setup can employ our sequential-protocol to generate a generalized W-state. Other studies have considered a qubit-chain with all interactions present concurrently. They have examined the transport of a qubit-state from one end of the chain to the other[28].

We have discussed three protocols and compared them in terms of the time required.Fig. 3 shows how the time required for each protocol scales with the number of qubits. In our analysis, we have only considered the total interaction time. An experimental realization will invariably have overheads associated with moving qubits, reconfiguring interaction circuits, etc. Future realization-specific studies could take these times into account. We have also ignored issues of adiabaticity, assuming that exchange interactions evolve the system with perfect fidelity. In practice, errors may arise from varying the interactions with time (e.g., see Ref. 29). Despite these limitations, our study provides estimates that could inform protocol design. On a given quantum-computing platform, all the protocols considered here may not be

accessible. For example, in ultracold atoms in optical lattices, qubits are arranged along a line. The divide-and-conquer algorithm may be ill-suited to such a setup as it requires qubits to be moved by large distances. Nevertheless, our results provide an estimate for the time involved.

## ACKNOWLEDGMENTS

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# Abstract template for … Contributed Poster …

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Following nearly a century of research, it remains a puzzle that the low-lying excitations of metals are remarkably well explained by effective single-particle theories of non-interacting bands. The abundance of interactions in real materials raises the question of direct spectroscopic signatures of phenomena beyond effective single-particle, single-band behaviour. Here we report the identification of quantum oscillations (QOs) in the three-dimensional topological semimetal CoSi, which defy the standard description in two fundamental aspects. First, the oscillation frequency corresponds to the difference of semi-classical quasi-particle (QP) orbits of two bands, which are forbidden as half of the trajectory would oppose the Lorentz force. Second, the oscillations exist up to above 50K - in stark contrast to all other oscillatory components - which vanish below a few K. Our findings are in excellent agreement with generic model calculations of QOs of the QP lifetime. Since the only precondition for their existence is a non-linear coupling of at least two electronic orbits, e.g., due to QP scattering on defects or collective excitations, such QOs of the QP lifetime are generic for any metal featuring Landau quantization with multiple orbits. They are consistent with certain frequencies in topological semi-metals, unconventional superconductors, rare-earth compounds, and Rashba-systems, and permit to identify and gauge correlation phenomena, e.g., in two-dimensional materials and multiband metals.

P44

**Title:** Lieb-Schultz-Mattis theorem and symmetry protected topological states: application to the pyrochlore, diamond, and breathing pyrochlore lattices

**Presenter:** Chunxiao Liu

**Abstract:** In this work, we discuss the Lieb-Schultz-Mattis (LSM) theorems and filling constraints relevant to the pyrochlore, diamond, and breathing pyrochlore lattices in the recently developed framework of crystalline symmetry protected topological (cSPT) phases. We reproduce many classification results of cSPT obtained in previous works. Furthermore, we go beyond the existing classification results by giving a detailed analysis of the microscopic origin for the nontrivial topological classes. This analysis allows us to obtain the LSM and LSM-cSPT anomalies and track the trivialization and formation of topological classes under the breaking of inversion symmetry. Finally, we discuss the matching of the LSM and low energy anomalies. The principles and calculation methods presented in this work can be applied to all cSPT systems.

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# Entropically-Driven Spin-Liquid to Spin-Liquid Thermal Crossover in a Pyrochlore Magnet

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One of the foremost goals in the study of pyrochlore magnetism is the search for spin-liquid phases composed of highly-disordered yet strongly correlated states. These phases are usually found in Hamiltonians possessing a highly degenerate ground state manifold preventing the onset of long-range order. In this work, we present a spin model on the pyrochlore lattice that realizes a novel classical spin-liquid at intermediate temperatures, collapsing into another spin-liquid phase at low temperatures. We demonstrate that the spin-liquid phase at intermediate temperatures is described by an emerging long-wavelength theory involving both vector and tensor fields, leading to the observation of twofold and fourfold pinch points, as well as, pinch-line singularities in the spin correlation functions. On the other hand, for the low-temperature spin-liquid, an effective long-wavelength theory describing a Coulomb phase is obtained. We demonstrate that the crossover between both phases has an entropic origin, providing the first realization of an entropically-driven selection of a spin-liquid.

P46

# A model of d-wave superconductivity, antiferromagnetism, and charge order on the square lattice

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We describe the confining instabilities of a proposed quantum spin liquid underlying the pseudogap metal state of the hole-doped cuprates. The spin liquid can be described by a SU(2) gauge theory of Nf = 2 massless Dirac fermions carrying fundamental gauge charges — this is the low energy theory of a mean-field state of fermionic spinons moving on the square lattice with π-flux per plaquette in the Z2 center of SU(2). This theory has an emergent SO(5)f global symmetry, and is presumed to confine at low energies to the Néel state. At non-zero doping (or smaller Hubbard repulsion U at half-filling) we argue that confinement occurs via the Higgs condensation of bosonic chargons carrying fundamental SU(2) gauge charges also moving in π Z2-flux. At half-filling, the low energy theory of the Higgs sector has Nb = 2 relativistic bosons with a possible emergent SO(5)b global symmetry describing rotations between a d-wave superconductor, period-2 charge stripes, and the time-reversal breaking 'd-density wave' state. We propose a conformal SU(2) gauge theory with Nf = 2 fundamental fermions, Nb = 2 fundamental bosons, and a SO(5)f ×SO(5)b global symmetry, which describes a deconfined quantum critical point between a confining state which breaks SO(5)f , and a confining state which breaks SO(5)b . The pattern of symmetry breaking within both SO(5)s is determined by terms likely irrelevant at the critical point, which can be chosen to obtain a transition between Néel order and d-wave superconductivity. A similar theory applies at non-zero doping and large U, with longer-range couplings of the chargons leading to charge order with longer periods.

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I have proved that the ground state of the half-integer spin Kitaev model is always a Z2 spin liquid no matter what the interaction strengths are. A general exact parton construction is introduced to demonstrate that there are extensive local conserved Z2 fluxes in the higher spin Kitaev model.

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# Classification of quantum spin liquid mean field Ansätze in $S \leq 1$ Diamond lattice : Projective Symmetry Group approach

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In geometrically frustrated spin systems, novel phases such as quantum spin liquids (QSL) appear due to the quantum mechanical melting of long-range orders. The low dimensional spin $S = 1/2$ systems are the breeding grounds for such phases due to strong quantum fluctuations. However, some recent findings [1, 2, 3, 4] show the existence of QSLs in three-dimensional spin $S = 1$ systems. One of the powerful known approaches for $S = \frac{1}{2}$ systems, is Abrikosov fermion mean field theory (AF-MFT) where one can classify all possible mean field Ansätze owing to lattice space group and time reversal symmetries using projective symmetry group (PSG) [5]. Utilizing spin-$S$ AF-MFT [6], we generalized the PSG approach and implemented it on $S = 1$ Diamond lattice and made a systematic comparison with $S = \frac{1}{2}$ case [7]. The fundamental difference arises from their internal symmetry groups $U(1)\bar{\otimes}Z_2$ and $SU(2)$ for $S = 1$ and $S = \frac{1}{2}$ respectively. Due to the even parity of the hopping term, the hopping-only Ansätze remains the same for both cases. We find seven such cases in the Diamond lattice when restricted up to the second nearest neighbour. Among these, five appear with invariant gauge group (IGG) $U(1)$ while the other two appear with IGG $SU(2)$ in $S = \frac{1}{2}$ and $U(1)\bar{\otimes}Z_2$ in $S = 1$. But due to the odd parity of the pairing term, the $Z_2$ Ansätze are not same for the two cases. There are a total of eight $Z_2$ Ansätze in $S = \frac{1}{2}$ system while the number is only one in $S = 1$ case. Also, in $S = 1$ case there is an additional IGG $Z_2\bar{\otimes}Z_2$ where we find two more Ansätze. Furthermore, we carried out a mean-field theoretical analysis with $J_1 - J_2$ Heisenberg model [4] and study the phase diagram and the dispersion spectrum. Interestingly, we obtain a nontrivial multi-nodal-loop band structure in one $SU(2)$ and one $U(1)$ Ansätze. These nodal loops are robust and protected by projective symmetries.

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P49

# Thermal Hall effect in kagome antiferromagnet

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Quantum spin liquids (QSLs) are highly entangled quantum states that remain disordered even at zero temperature, and these systems exhibit fractionalized excitations with neutral spin-1/2 quantum numbers. Thermal transport has emerged as a valuable tool for investigating the properties of these charge-neutral excitations. The spin-1/2 Heisenberg antiferromagnet on a kagome lattice is a well-known system that has the potential to host QSL phases. While the exact ground state nature of this system is still unknown, numerical studies have suggested a gapless $U(1)$ Dirac spin liquid (DSL). In this work, we aim to investigate the potential of scalar spin chirality, which is induced by orbital coupling of the applied magnetic field to induce a transition from DSL to a chiral spin liquid (CSL). Describing the spins in terms of neutral fermionic spinons, we start our analysis from the $\pi$-flux model on the kagome lattice whose low-energy continuum theory is given by $QED_3$ with $N_f = 4$. After turning on spin chirality, we calculate the Chern number numerically and find gapped Chern bands have nonzero Chern numbers, the emergent gauge field is gapped by an effective Chern-Simons (CS) term, demonstrating the existence of a CSL. Additionally, we compute the thermal Hall conductivity at nonzero scalar spin chirality and show that it is quantized at zero temperature. As a continuation of our analysis, we aim to calculate the corrections to the thermal Hall conductivity due to gauge interaction.

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# Evidence of two-spinon bound states in the magnetic spectrum of $Ba_3CoSb_2O_9$

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Recent inelastic neutron scattering (INS) experiments of the triangular antiferromagnet $Ba_3CoSb_2O_9$ revealed strong deviations from semiclassical theories. We demonstrate that key features of the INS data are well reproduced by a parton Schwinger boson theory beyond the saddle-point approximation. The measured magnon dispersion is well reproduced by the dispersion of two-spinon bound states (poles of the emergent gauge fields propagator), while the low-energy continuum scattering is reproduced by a quasifree two-spinon continuum, suggesting that a free spinon gas is a good initial framework to study magnetically ordered states near a quantum melting point.

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# Valence-Bond Solid phases in the spin-1/2 Kekulé-Heisenberg model

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One of the main goals in condensed matter physics is searching for systems with ground state exhibiting quantum paramagnetic phases such as spin liquid phases and valance bond solids. Although these phases are magnetically disordered, they possess unique features crucial in applied physics[1,2]. In this paper we have considered a spin-1/2 Kekulé-Heisenberg (KH) model, and examined its ground state phase diagram. The KH model under our study is a generalization of the Kitaev spin model on a two dimensional honeycomb lattice [3]. By utilizing a graph-based projected entangled pair state (gPEPS) approach in the thermodynamic limit, we obtained the ground state phase diagram of our KH model and demonstrated that it exhibits a plethora of magnetically ordered and disordered phases, including a valance bond solid (VBS) phase with vanishing magnetization, two magnetically ordered phases with ferromagnetic and Neél orders, and a Kitaev spin liquid phase introduced in the Kitaev-Heisenberg model [4]. In the VBS phase all symmetries of the initial Hamiltonian are maintained. In this respect, this phase is the same as quantum spin liquid phases, however, the VBS phase seen in our system exhibits a distinct feature. It has a plaquette order showing an arrangement of decorated plaquettes.

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P52

# Dimensional reduction of the Luttinger-Ward functional for spin-degenerate D-dimensional electron gases

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Strongly correlated electron liquids encompass large variety of collective and emergent quantum phenomena observed in condensed matter systems. Reliable theoretical treatment of such systems remains an extremely challenging ordeal for condensed matter community due to extreme complexity of an interacting many-body problem. Except specially constructed exactly solvable models, approximations are always required to approach interacting many-body problems. Here, I am going to present the semiclassical limit of an interacting $D$-dimensional electron gas (DDEG) with a spherical Fermi surface and a spatial dimension $D > 1$ [1]. The semiclassical limit here corresponds to the most relevant infrared sector near the Fermi surface, where quantum fluctuations of the electron occupation are the strongest at very low temperature, they are responsible for emergent quantum phenomena in interacting electron liquids. We show that in the semiclassical limit, fermion loops as well as fermion lines constructed from any number of electron Green's functions can be represented in terms of their one-dimensional analogues. For this reason, we call our approach the dimensional reduction. We apply the dimensional reduction to the entire Luttinger-Ward functional and find an explicit expression for an arbitrary skeleton diagram, the diagrams for electron Green's function and the self-energy then follow from the variational principle. If we apply the assumptions behind the multidimensional bosonization (linear spectrum and forward scattering interaction), we restore all results of the multidimensional bosonization. However, these assumptions are not necessary within our approach, we include non-linearity of the electron dispersion near the Fermi surface as well as the backscattering interaction. We also find the contribution of the non-collinear scattering (when momenta of interacting electrons are neither aligned nor anti-aligned), this contribution is missing within the multidimensional bosonization approach. The dimensional reduction approach is extremely versatile and can be applied to any strongly interacting electron system with well-defined Fermi surfaces (a surface where the electron distribution function is discontinuous/non-analytic), from conventional semiconducting electron systems to high-temperature superconductors.

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P53

# Emergent SU(8) Dirac semimetal and novel proximate phases of spin-orbit coupled fermions on a honeycomb lattice

Conference on Fractionalization and Emergent Gauge Fields in Quantum Matter — (smr 3834)

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Emergent Dirac fermions provide the starting point for understanding the plethora of novel condensed matter phases. The nature of the associated phases and phase transitions crucially depends on both the emergent symmetries as well as the implementation of the microscopic ones on the low-energy Dirac fermions. Here, we show that $j = 3/2$ electrons in spin-orbit coupled materials on honeycomb lattice can give rise to SU(8) symmetric Dirac semimetals with symmetry implementation very different from that of graphene. This non-trivial embedding of the microscopic symmetries in the low energy is reflected in the nature of phases proximate to the Dirac semimetal. Such phases can arise from finite short-range electron-electron interactions. In particular, we identify 24 such phases – divided into three classes – and their low energy properties obtained by condensing particle-number conserving fermion bilinears that break very different microscopic symmetries and/or are topologically protected by symmetries. The latter includes interesting generalisations of quantum spin-Hall phases. Remarkably some of the resultant phases still support a sub-set of gapless fermions– protected by a sub-group of SU(8) – resulting in interesting density wave semimetals. Near the phase transitions to such density wave semimetals, the surviving gapless fermions strongly interact with the bosonic order parameter field and give rise to novel quantum critical points. Our study is applicable to a wide class of $d^1$ and $d^3$ transition metals with strong spin-orbit coupling and predicts that such materials can harbour a very rich interplay of symmetries and competing interactions in the intermediate correlation regime.

P54

# Quasiuniversality from all-in-all-out Weyl quantum criticality in pyrochlore iridates

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We identify an exotic quasiuniversal behavior near the all-in-all-out Weyl quantum critical point in three-dimensional Luttinger semimetals, such as the pyrochlore iridates $R_2\mathrm{Ir}_2\mathrm{O}_7$, with $R$ a rare-earth element. The quasiuniversal behavior is characterized by power laws with exponents that vary slowly over several orders of magnitude in energy or length. However, in contrast to the quasiuniversality discussed in the context of deconfined criticality, the present case is characterized by a genuinely-universal ultra-low-temperature behavior. In this limit, the pertinent critical exponents can be computed exactly within a renormalization group analysis. Experimental implications for the pyrochlore iridates are outlined.

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P55

# Renormalization group for fluctuating loops – U(1) gauge theory and XY model

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It was shown by Polyakov [1,2] that Maxwell theory in 3+1 dimensions can go through a deconfinement – confinement phase transition if the U(1) gauge field is compact. This happens due to a non-perturbative mechanism where monopoles proliferate when the Maxwell coupling exceeds a critical value. In this work, we revisit this phase transition using a renormalization group (RG) approach. The key players in our approach are fields defined on closed strings as opposed to points. This description is obtained by performing a duality transformation on the original theory. We then explore the phase diagram as a function of the Maxwell coupling. We make connection to the viewpoint of the deconfined phase as a one-form symmetry broken state. We then study the XY model in 2+1 D using the same procedure. We highlight curious aspects of this RG on closed strings that have no analog in conventional field theory.

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P56

# Quantum Effects on Unconventional Pinch Point Singularities

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Fractons, fractionalized quasiparticles characterized by their lack of kinetic degrees of freedom, have attracted increasing attention in the study of frustrated spin systems. Mathematically, they are best described via higher-rank tensor gauge theories, which can be effectively realized as low-temperature phases of frustrated spin models. While most quantum fracton models are based on complicated multi-spin interactions that are difficult to realize in realistic settings, it has recently been found how classical models with emergent tensor gauge theories can be constructed from a simple rule of two-body interactions [1]. One of the most promising, but challenging routes is to investigate whether classical fracton phases dressed with quantum fluctuations survive in favor of quantum fractonic phases. In this poster we will present our recent work on the corresponding $SU(2)$ symmetric quantum analogue of the classical fracton model, which we analyze by the appearance of multifold pinch points in the magnetic structure factor. The poster is based on the work in [2].

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# Dynamics of a single dopant in a gapless Z2 spin liquid

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# Magnetic superconductors in Metal-Organic framework hybrids

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Crafting synthetic two-dimensional (2D) functional materials with novel quantum characteristics is a key focus of contemporary condensed matter physics. The adaptability to manipulate both the lattice arrangements and electronic band configurations of these artificially designed materials presents a distinct opportunity to control their properties externally. Among these, the Metal-Organic Framework (MOF) and Covalent Organic Framework (COF) have attracted substantial attention due to their potential applications in organic electronics, spintronics, and topological materials [1]. Characterized by a pair of dispersive bands, a Fermi level-linked flat energy band, and a Dirac cone at the M-point, the Lieb lattice [3] design has been experimentally realized recently in $sp^2$C-COF and $sp^2$N-COF [2]. In addition to the topologically nontrivial band structures, this lattice model exhibits flat bands, which could give rise to exotic strongly correlated electron states even for relatively weak interaction strength [3].

Our investigation explores the distinct quantum phases that result from the interplay of the electronic and spin degrees of freedom in the Lieb lattice. Our approach involves coupling an s-wave superconductor to a lattice of localized magnetic spins using Kondo interactions. This interplay creates a "*Magnetic Superconductor*" characterized by the coexistence of magnetic and superconducting orders. Using a comprehensive model that unifies a 2D attractive Hubbard framework with Kondo interactions, we harness the spectroscopic signatures to explore the evolution of the Fermi surface across distinct parameter regimes. By analyzing the ground state phase diagram with precision, we observe the emergence and coexistence of gapped and gapless superconducting states with anti-ferromagnetic and non-collinear magnetic orders, as well as the transition from anti-ferromagnetic to non-collinear magnetic phases.

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# Transport properties near the semimetal-insulator transition in higher-order topological materials

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Recently, a new class of topological materials called higher-order topological materials and their non-equilibrium properties are being studied extensively. Depending on the strength of intra-cell hopping amplitudes, systems hosting higher-order Weyl semimetal phases can undergo a phase transition to such a topological insulating phase. In this study, we perform classical-statistical lattice simulations to extract transport properties near this semimetal-insulator phase transition.

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# An order fractionalization route to spinor ordering and triplet superconductivity

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Quantum Materials such as $UTe_2$[4] and 4-Hb $TaS_2$[5], have been proposed to be time-reversal symmetry broken triplet superconductors. Experimental signatures like the simultaneous condensation of two-component ordering in these systems suggest the possibility of spinor ordering in these quantum materials, motivating us to ask, "What kinds of microscopic physics could lead to spinor ordering?" To this end, we propose a Kondo Lattice model, where the coupling of $\mathbb{Z}_2$ Yao Lee spin liquids to conduction electrons results in the condensation of fractionalized Majoranas with conduction electrons[1, 2] leading to a spinor ordering. This model is exactly solvable in 3D and exhibits a second-order phase transition at small Kondo coupling into a spinor-ordered state, with odd-frequency triplet pairing with PDW behaviour between conduction electrons. Investigation of various phases of the model reveals a superconductor-Kondo insulator phase transition. Here the Kondo insulator phase has a decoupled gapless Kitaev spin liquid formed by the orbital degree of freedom. To understand the critical point between the superconductor and Kondo insulator, we examine the gauge fluctuations generated due to spinor ordering by analytically calculating the vison gap energy[3] in the ordered state. This allows us to determining the role of confinement-deconfinement of Majorana fermions in the spinor ordered state as one approaches the quantum critical point. Finally, we propose experimental signatures one would expect if the Majorana-conduction electron condensation played a role in the formation of spinor order parameter.

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P61

# The dynamical structure factor of the SU(4) algebraic spin liquid on the honeycomb lattice

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We compute the momentum resolved dynamical spin structure factor $S(k,\omega)$ of the SU(4) Heisenberg model on the honeycomb lattice assuming the $\pi$-flux Dirac spin liquid ground state by two methods: (i) variationally using Gutzwiller projected particle-hole excitations of the $\pi$-flux Fermi sea and (ii) in the non-interacting parton mean-field picture [1]. The two approaches produce qualitatively similar results. Based on this analogy, we argue that the energy spectrum of the projected excitations is a gapless continuum of fractional excitations. Quantitatively, the Gutzwiller projection shifts the weight from higher to lower energies, thus emphasizing the lower edge of the continuum. In the mean-field approach, we obtained the 1/distance$^4$ decay of the spin correlation function, and the local correlations show $S^{33}_{\mathrm{MF}}(\omega) \propto \omega^3$ behavior.

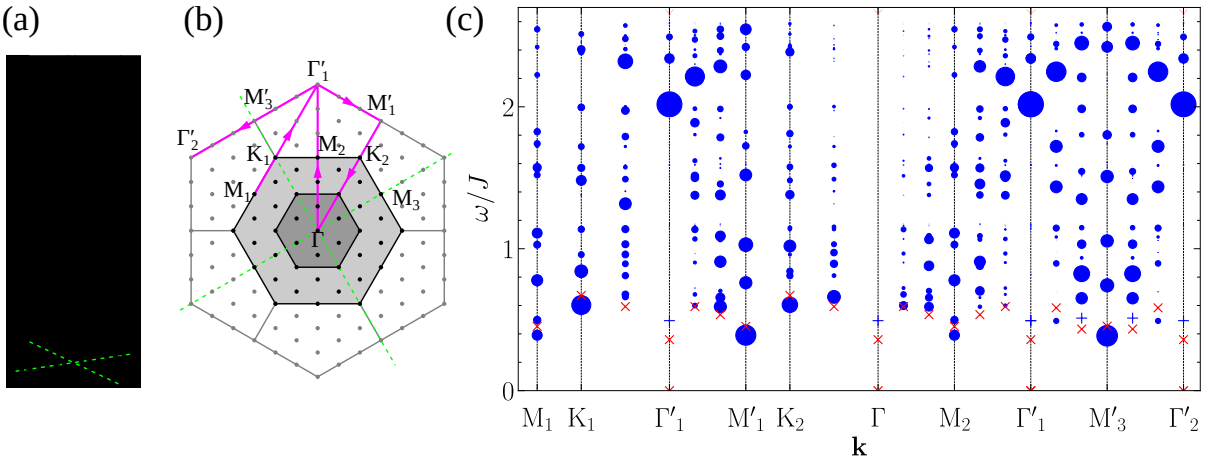


Figure 1: (a) The twofold degenerate bands defined of the $\pi$-flux state in the reduced Brillouin zone, with the Dirac cones at the $\Gamma$ point. The Fermi sea of the variational wave function fills the lowest (green) band. The tiny spheres represent the energies and momenta for the 72-site cluster with antiperiodic boundary conditions. The arrows indicate the lowest energy particle-hole excitations with nonvanishing weight at the M and $\Gamma'$ momenta. (b) The reciprocal space of the honeycomb lattice. The reduced Brillouin zone corresponds to the 8-site unit cell of the $\pi$-flux state, a quarter of the Brillouin zone of the honeycomb lattice. The structure factor is fully characterized by its behavior in the extended zone. The dots are the $k$-points of the 72-site cluster. (c) The dynamical structure factor $S^{33}(\mathbf{k},\omega)$ for a 72-site cluster from the variational calculation, along the magenta path in the reciprocal space. The area of the circles is proportional to the weights in $S^{33}(\mathbf{k},\omega)$.

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P62

# Deciphering competing interactions of Kitaev-Heisenberg-Γ system in clusters

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We study Kitaev-Heisenberg-Γ Hamiltonian on finite size clusters and investigate various zero and finite temperature properties in detail and explore the key differences due to relative sign and magnitude of Kitaev($K$), Heisenberg ($J$) and Γ interaction in the presence of magnetic field. Nearest-neighbor spin-spin correlation function shows step like character when $J$ is positive only irrespective of sign of $K$. Similarly the low energy spectrum under magnetic field depends on the sign of $K$. Dynamics of Majorana fermions depend greatly on external magnetic field which can even stabilize the gauge fields to Kitaev limit in the presence of $J$. Majorana dynamics also shows that $K-J-\Gamma$ model to be a testbed to manipulate quantum speed limit. For small magnetic field, magnetization shows a dome like structure for an intermediate temperature range for positive $K$. However a positive $J$ can cause this for negative $K$ also. The zero temperature magnetization and susceptibility shows large dependence on external magnetic field and relative sign and magnitude of $K$ and $J$. Either a negative $K$ or $J$ is shown to give qualitatively similar susceptibility for different magnetic field only. For the specific heat a negative $K$ or $J$ favors mostly single peak structure while a two peak structure is favored for positive $K$ or $J$, though the magnitude of magnetic field can causes re-entrant behavior also.

[1] arXiv:2306.14839

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# Spin Nematics Meet Spin Liquids: Exotic Phases in the Spin-1 Bilinear-Biquadratic Model with Kitaev Interactions

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New discoveries are often made on the border between different disciplines. One major discipline in solid state physics is dedicated to quantum spin liquids, an unconventional state of matter accompanied by emergent gauge fields, topological order and fractionalized excitations [**1**]. Another concept is that of spin nematics, a magnetically ordered state dominated by quadrupole moments, which breaks spin-rotation symmetry by selecting an axis, while not choosing a particular direction [**2**]. Usually seen as two separate areas of study, we are interested in connecting those two disciplines, by asking the question: "What happens, when a spin nematic and a spin liquid meet?"

To answer this question, we adopt the newly developed U(3) formalism [**3**] and investigate the $S$=1 Kitaev model under the influence of bilinear-biquadratic interactions. We obtain a comprehensive phase diagram including triple-$q$ chiral ordered and quadrupolar ordered phases, in addition to already known ferro, antiferro, zigzag and stripy phases [**4**] (see Fig.1). Intriguingly, next to quadrupolar ordered and semi-ordered phases, the competition between Kitaev and positive biquadratic interactions also promotes a noncoplanar finite-temperature chiral spin liquid (CSL) state with macroscopic degeneracy and finite spin scalar chirality, which can be transparently understood, on an effective eight-color model.

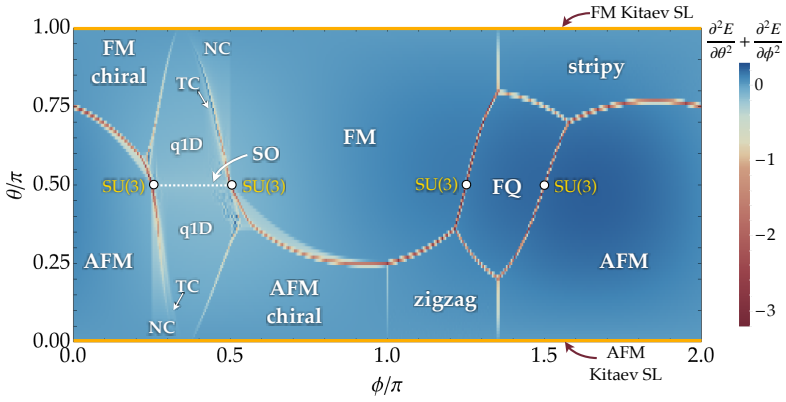


Fig.1: Semiclassical ground state phase diagram of the $S$=1 bilinear-biquadratic model with Kitaev interactions on the honeycomb lattice. The model stabilizes ferromagnetic (FM), antiferromagnetic (AFM), zigzag, stripy, and spin-nematic ferroquadrupolar (FQ) phases. The competition between chiral order, the Kitaev spin liquid (SL), and quadrupolar semi-order (SO) gives rise to unconventional twisted conical (TC), quasi-one-dimensional (q1D) coplanar, and noncoplanar (NC) ordered phases.

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P64

# Two dimensional coherent spectroscopy of quantum pyrochlore spin chains: predictions for $Ce_2Zr_2O_7$ and $Nd_2Zr_2O_7$

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Two dimensional cohererent spectroscopy (2DCS) is a powerful tool, probing the nonlinear optical response of correlated systems [1]. An interesting application of this tool is in studying fractionalized excitations in quantum phases of matter, which are challenging to distinguish unambiguously in linear response. Frustrated rare-earth pyrochlore oxides, $R_2M_2O_7$, have long been of interest as potential realizations of fractionalized quantum phases, and the application of 2DCS to these systems has the potential to bring new insight into the nature of their excitations. Here we present theoretical predictions for the 2DCS response of rare-earth pyrochlore magnets subject to a [110] magnetic field. This field direction is of particular interest because it splits the system into a set of effective 1-dimensional spin chains [2]. This enables a controlled theoretical approach to the problem, while retaining fractionalized excitations in the spectrum. We present two worked examples, based on the modelling of real materials, $Ce_2Zr_2O_7$ and $Nd_2Zr_2O_7$. We show how the use of different photon polarizations in the 2DCS experiment can be used as a filter to either pick out fractionalized spinons or conventional magnons from the spectrum. We find that a [001] polarization of the probe field is particularly sensitive to lower band edge of the spinon continuum and can be used as a measure of the proximity of a quantum critical point in $Ce_2Zr_2O_7$. We also show that the parameter $\theta$, which controls the mixing of dipolar and octupolar degrees of freedom in the microscopic Hamiltonian, has significant influence on the 2DCS response: modifying the intensity of the rephasing signal of the fractionalized spinons on unpolarized chains; and controlling the relative intensity of one- and two- magnon signals on the polarized chains.

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# Abstract for poster

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We propose and implement here an approximate, nonperturbative, self consistent equation of motion approach to the strong correlation problem for the case of an extremely strongly correlated Fermi liquid (ECFL; $U = \infty$ in the single orbital lattice model of Hubbard) for large spatial dimension $d$. We obtain an equation of motion for the single particle Green's function $G$ and for the associated self energy $\Sigma$; the latter involves the (number) density correlation function $D_N$ and the spin correlation function $D_S$. We obtain coupled closed form equations for $G$, $D_N$, $D_S$ and solve them self consistently. The imaginary part $-\operatorname{Im}\Sigma(0,T)$ has a low temperature coherent Fermi liquid regime with well defined low energy quasiparticle excitations crossing over smoothly into the high temperature incoherent Fermi liquid regime with no quasiparticles; these two limiting regimes are characterized by $-\operatorname{Im}\Sigma(0,T)$ going as $T^2$ and $T$ respectively. We also obtain results for dc resistivity $\rho(T)$, which also is seen to cross over from a $T^2$ behaviour at low temperatures to being linear in $T$ at high temperatures.

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# Hyper-magic manifold in twisted Kitaev bilayers

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# Emergent spin-vortex crystal order in disordered J1-J2 XY model on a square lattice

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We investigate the frustrated classical J1-J2 XY model defined on a square lattice in the presence of quenched disorder. Previous studies [1] hinted that the model, in a frustrated regime ($|J2|/|J1| > 0.5$), supports a nematic phase along with a KT transition. With the use of large-scale Monte Carlo simulations, we show that the introduction of a small number of impurities leads to an emergent random field that destroys the ordered state of the translationally invariant model. Moreover, we show that this disorder results in stabilizing a non-collinear spin-vortex state at low temperatures. We further provide a detailed analysis of the critical behaviour that typifies the transition from this spin-vortex state to the paramagnetic state.

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P68

# Low-temperature theory of inversion and quantum oscillations in Kondo insulators

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We present a low temperature self-consistent theory of the half-filled Kondo lattice model (KLM) [1] in Kumar representation [2]. The half-filled KLM is found to show three phases in the temperature-hopping ($T$-$t$) plane: the strong coupling Kondo singlet phase (KS), the inverted Kondo singlet (iKS) phase, and the antiferromagnetic (AFM) phase. The KS and iKS phases are differentiated by the inversion of the charge quasiparticle dispersion, as discovered in Ref.[3]. Interestingly, we note that the density of states (DoS) of the charge quasiparticles exhibits dimensional reduction across the inversion transition; the DoS clearly changes from being 3D-like in the KS phase to 1D-like in the iKS phase, near the charge gap ($\Delta_c$). The calculated specific heat is found to neatly distinguishes the two Kondo singlet phases when plotted as $C_v/\Delta_c^2$ vs. $T/\Delta_c$. These features can be used as experimental markers for the inversion transition. The calculated magnetisation is found to show clear oscillations with inverse magnetic field in the intermediate to low Kondo coupling regimes, at finite low temperatures. Notably, these magnetic quantum oscillations are found to exhibit Lifshitz-Kosevich like behaviour with temperature as well as quantum fluctuations induced by Kondo interactions (i.e. $J^2/t$ behaves similar to temperature).

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P69

# Entropic selection in frustrated magnets: ordering on self-intersecting space

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Frustrated magnets may have large degenerate ground state spaces of which some may be 'picked out' by thermal fluctuations. This is the well known 'Order by Disorder' (ObD) phenomenon. We bring out the role of ground state space geometry in this mechanism. In particular, self-intersections in the space lead to a qualitative difference with stronger selection. We present results for two prototype models of frustrated magnets. The work is based on [1].

The first model has a smooth ground state manifold (a torus). Collinear states are 'selected' as they allow greater scope for fluctuations. Indeed, as the magnet evolves, it spends a greater amount of time in the vicinity of collinear states. Crucially, the degree of selection is energy independent. When coupled to a thermal reservoir, the same collinear states are selected. The degree of selection is temperature independent.

The second model has a classical ground state space that is not smooth. It consists of three tori that intersect one another. Fluctuations favour the lines of intersection which correspond to collinear states. However, the degree of selection varies with energy $\epsilon$. In fact, it grows as $\epsilon^{-1/2}$ as $\epsilon \to 0$. When this system is coupled to a reservoir of temperature $T$, selection grows as $T^{-1/2}$ as $T \to 0$. This enhanced selection can be understood from geometry. Near an intersection point, the available phase space expands dramatically and surpasses the volumes elsewhere. This is the classical analogue of 'Order by Singularity' (ObS), a mechanism previously proposed in quantum spin clusters.

We support our analytic arguments with numerical simulations. We simulate energy-preserving spin dynamics using the Landau-Lifshitz equations. To describe contact with a reservoir, we carry out Monte Carlo simulations.

Our key result is that fluctuations play a stronger role in magnets with self-intersecting ground state spaces. This can lead to observable consequences in macroscopic models and materials. This is particularly relevant to systems with weak state selection such as spiral liquids (e.g., $MnSc_2S_4$) or those with intersecting ground state spaces (e.g., $ErSn_2O_7$). Our results provide a starting point to analyze temperature dependence in neutron intensities.

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P70

# Quantum spin liquids in dipolar-octupolar pyrochlore magnets

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We study quantum spin liquid (QSL) with low-energy fermionic quasi-particles for pyrochlore magnets with dipolar-octupolar symmetry. We classify the possible U(1) and $Z_2$ fermionic QSLs in such a system and compare their characteristics. Our study provides a possible way to understand the possible signatures of fermionic quasiparticles in a recent experiment on Ising pyrochlore magnet $Nd_2ScNbO_7$. We further calculate the dynamic spin structure factor and thermal characteristics to understand the nature of these fermionic quasiparticles through neutron scattering and linear response experiments.

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# Emergent gauge theories and fractionalized excitations in synthetic quantum systems

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In recent years, programmable quantum simulators based on ultracold atomic systems have emerged as versatile platforms to probe strongly correlated phases of matter, including quantum spin liquids. Motivated by experiments realizing a $Z_2$ quantum spin liquid (QSL) in an array of strongly interacting Rydberg atoms, we formulate a gauge-theoretic description of this system and demonstrate how the QSL can be understood as the deconfined phase of such an emergent $Z_2$ gauge theory. We characterize this state in terms of its fractionalized spinon and vison excitations and discuss their relevance to experimental verifications of the topological ground state.

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# Thermal Expansion Anomalies in Spinels: $CdCr_2O_4$ and Beyond

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Although most materials tend to expand when heated, a select few, such as water ice, elastic bands, and invar alloy, display an anomalous phenomenon known as negative thermal expansion (NTE). Recently, it was discovered that $CdCr_2O_4$, a chromium spinel oxide, exhibits NTE within its ordered half-magnetization plateau phase. This phenomenon was also observed in an effective spin-lattice coupled bond-phonon model on the pyrochlore lattice [1].

In this study, we revisit $CdCr_2O_4$ using a more realistic site-phonon model that includes intra- and inter-tetrahedra interactions on the pyrochlore lattice [2]. We construct order parameters from the irreducible representations of the possible ground state spin configurations to map the temperature and magnetic field phase diagram through classical Monte Carlo simulations.

Our results demonstrate the presence of NTE in the half-magnetization plateau phase of the site-phonon model, thereby confirming the entropy-driven NTE mechanism presented in [1]. We further investigate the model's ability to explain other types of NTE observed in spinels, including at zero field.

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P73

# A simple model for strange metallic behavior

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We present an effective semi-holographic approach for non-Fermi liquids which reproduces strange metallic behavior robustly. Building on the work by Faulkner and Polchinski [1], it was shown in [2] that semi-holography can provide a theory of generalized quasi-particles on the Fermi surface in the large $N$ limit. Here carrier electrons hybridize with fermionic operators of a critical sector. Crucially, even after introducing arbitrary interactions both within and between the two sectors with particular large $N$ scaling, the spectral function has a robust and simple low energy behavior on the Fermi surface, given by a scaling exponent $\nu$, as can be obtained with just linear hybridization.

Recently, we have refined the above model that allows it to be studied at finite temperature reliably [3, 4]. The self-energy of the carrier electrons receive two type of local contributions with specific temperature dependence, one which is given by the Green's function of a fermion in a two-dimensional black hole, and another which is Fermi liquid-like. The model has two effective couplings and a few other parameters, like the exponent $\nu$.

Remarkably, for a specific ratio of the two couplings determined by $\nu$, the model has a universal spectral function valid for a large range of temperatures and frequencies near the Fermi surface. This form also fits nodal photoemission data [5] obtained from copper oxide samples under different doping conditions and different temperatures very well with a very few parameters.

We can analytically show and numerically verify that the universal form of the spectral function of our model leads to linear-in-T dc-resistivity over a wide range of temperatures. It also reproduces a refined picture of Planckian dissipation where the scattering time $\tau$ is given by $\tau = f \cdot \hbar/(k_B T)$ – while $f = \mathcal{O}(1)$, while at weak coupling, it becomes $f = \mathcal{O}(10)$ at strong coupling agreeing with the interpretation of experimental data discussed in [6].

We will present new results on optical conductivity where we reproduce specific universal characteristics of temperature dependent non-Drude low frequency behavior in agreement with the experimental analysis in [7].

We will also discuss how our model is related to other approaches involving a lattice of Sachdev-Yi-Kitaev type quantum dots.

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# Fermionic parton construction for dipolar-octupolar pyrochlore and bilayer kagome magnets

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We study possible fractionalisation in dipolar-octupolar pyrochlore magnets and bilayer kagome magnets. We employ a fermionic parton construction to classify all the possible $U(1)$ and $Z_2$ quantum spin liquid states in these systems. We further predict the neutron scattering structure factor and the specific heat of these states. For the dipolar-octupolar pyrochlore magnets, we find a symmetric monopole flux state and linear temperature dependence of specific heat due to the fermionic spinons in some of the QSL phases, we speculate this might explain the metallic specific heat response observed in recent experiments on $Nd_2ScNbO_7$.

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# Spin point groups for weakly spin-orbit coupled materials

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# Quantum spin ice in three-dimensional Rydberg atom arrays

-Jeet Shah, Gautam Nambiar, Alexey V. Gorshkov, and Victor Galitski

Quantum spin liquids are exotic phases of matter whose low-energy physics is described as the deconfined phase of an emergent gauge theory. With recent theory proposals and an experiment showing preliminary signs of $Z_2$ topological order [G. Semeghini et al., Science **374**, 1242 (2021)], Rydberg atom arrays have emerged as a promising platform to realize a quantum spin liquid. In this work, we propose a way to realize a U(1) quantum spin liquid in three spatial dimensions, described by the deconfined phase of U(1) gauge theory in a pyrochlore lattice Rydberg atom array. We study the ground state phase diagram of the proposed Rydberg system as a function of experimentally relevant parameters. Within our calculation, we find that by tuning the Rabi frequency, one can access both the confinement-deconfinement transition driven by a proliferation of "magnetic" monopoles and the Higgs transition driven by a proliferation of "electric" charges of the emergent gauge theory. We suggest experimental probes for distinguishing the deconfined phase from ordered phases. This work serves as a proposal to access a confinement-deconfinement transition in three spatial dimensions on a Rydberg-based quantum simulator.

P77

# Eigenvalue spectrum of 2+1 flavor QCD in the continuum limit

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**Abstract**

The transition from hadron to the quark-gluon plasma phase is a smooth crossover in QCD with physical quark masses, nevertheless, the (almost) chiral nature of the light quarks is believed to drive such a transition. This phenomenon can be studied using lattice QCD techniques and the most popularly used fermion discretization, the staggered fermions only have a remnant of the full chiral symmetry of QCD, which is believed to be recovered in the continuum limit. We for the first time, study the eigenvalue spectrum of the QCD Dirac operator with highly improved staggered quark (HISQ) discretization for three different lattice spacings at $0.9 - 1.1$ $T_c$ ($T_c$ is the pseudo-critical temperature) and perform the continuum extrapolation. From the features of the eigenvalue spectrum, we can conclude that though the flavor nonsinglet part of the chiral symmetry is restored at $T_c$ the flavor singlet $U_A(1)$ part of it is effectively restored only above 1.15 $T_c$. Moreover, we observe a level repulsion between the infrared eigenvalues which has a quadratic dependence on the spacing similar to the Gaussian unitary ensemble (GuE) of random matrix theory, unlike the near-zero modes. The $U_A(1)$ restoration happens around the same temperature at which a separation between the localized near-zero modes and the delocalized bulk modes occur similar to an Anderson like transition. Our results have interesting connections to a strongly interacting electron system moving in a disordered potential.

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# Tensor Network Phase Diagram of the Spin-1/2 Antiferromagnetic Heisenberg Model on the Square-Kagome Lattice

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**Abstract:**

Using large-scale tensor network simulations based on infinite projected entangled-pair states (iPEPS) we investigated the ground state phase diagram of the spin-1/2 antiferromagnetic Heisenberg model on the square-kagome lattice in the thermodynamic limit. We mapped out the phase diagram of the model as an interplay between the strength of the Heisenberg interactions on different bonds of the lattice. Our results reveal the presence of diverse intriguing phases, encompassing the plaquette state, distinct families of valance-bond crystals (VBS) characterized by different bond correlation patterns, as well as Ferrimagnetic states. We have further characterized the underlying phases and phase transitions in the phase diagram through detailed analysis of the local observables such as magnetization, and spin correlation as well as with entanglement measures such as bond entropy. The tensor network simulations enabled us to not only accurately capture the ground state properties of the model in previously known regimes, but also shed light on the nature of the unknown phases in the phase diagram of the system.

**Keywords**: tensor network, infinite projected entangled-pair states, quantum phase transitions, Heisenberg antiferromagnets.

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# Classification and emergence of quantum spin liquids in chiral Rydberg models

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We investigate the nature of quantum phases arising in chiral interacting Hamiltonians recently realized in Rydberg atom arrays. To this end, we classify all possible fermionic chiral spin liquids with U(1) global symmetry using parton construction on the honeycomb lattice. The corresponding variational wave functions accurately describe the Rydberg many-body ground state at 1/2 and 1/4 particle density. Complementing this analysis with tensor network simulations, we conclude that both particle filling sectors host a spin liquid with the same topological order of a $\nu = 1/2$ fractional quantum Hall effect. At density 1/2, our results clarify the phase diagram of the model, while at density 1/4, they provide an explicit construction of the ground state wave function with almost unit overlap with the microscopic one. These findings pave the way to the use of parton wave functions to guide the discovery of quantum spin liquids in chiral Rydberg models.

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# Abstract template for Poster in Conference on Fractionalization and Emergent Gauge Fields in Quantum Matter

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The Transformer architecture has become the state-of-art model for natural language processing tasks, avoiding recurrent and convolutional structures. Its key feature is the ability to describe long-range correlations among the elements of the input sequences. This approach has also been adapted to computer vision tasks, thus defining the Vision Transformer (ViT) architecture, obtaining competitive results compared to state-of-art deep Convolutional-Neural Networks. Motivated by these achievements, we propose an adaptation of the ViT architecture to define a new class of variational neural-network states for quantum many-body systems, the ViT wave function. First, we apply this idea the one-dimensional $J_1-J_2$ Heisenberg model, demonstrating its effectiveness in capturing long-range correlations and accurately characterizing gapped and gapless phases. Subsequently, we extend our investigation to the two-dimensional Shastry Sutherland model, aiming to determine its phase diagram. Notably, our findings reveal a region within the phase diagram that is consistent with a spin liquid phase. The success of the ViT wave function relies on mixing both local and global operations, thus enabling the study of large systems with high accuracy.

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P81

# Dissipation-induced order in quantum spin chains

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The one-dimensional spin-1/2 Heisenberg model with antiferromagnetic exchange coupling is one of the best studied systems in quantum magnetism. The ground state of the isolated spin chain is a Luttinger liquid with critical spin and dimer correlations. It is an open question how these properties are affected by a coupling to the environment. Here, we consider the effects of local site and bond dissipation on the quantum spin chain. Using a recently developed quantum Monte Carlo method for retarded interactions [1, 2], we first show that ohmic site dissipation spontaneously breaks the SO(3) spin symmetry and induces long-range antiferromagnetic order in the 1D chain beyond the applicability of the Mermin-Wagner theorem [3]. Ohmic site dissipation is a marginally relevant perturbation so that exponentially large system sizes are required to observe long-range order at small couplings. Below this length scale, our numerics is dominated by a crossover regime where spin correlations show different power-law behaviors in space and time. Secondly, we study the effects of bond dissipation as a function of the interaction range of the corresponding retarded interaction [4]. For a slow power-law decay, we find that bond dissipation immediately induces valence-bond-solid order, whereas for a fast decay the critical phase remains stable up to a critical coupling. We discuss the properties of the critical phase and the quantum phase transition under the influence of the dissipative bath.

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# Spin-Peierls instability of the U(1) Dirac spin liquid

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Quantum spin liquids are tantalizing phases of frustrated quantum magnets. A complicating factor in their realization and observation in materials is the ubiquitous presence of other degrees of freedom, in particular lattice distortion modes (phonons), that provide additional mechanisms for relieving magnetic frustration, thereby possibly spoiling spin-liquid ground states. In this work, we focus on triangular-lattice Heisenberg antiferromagnets, where recent numerical evidence suggests the presence of an extended U(1) Dirac spin liquid phase which is described by compact quantum electrodynamics in 2+1 dimensions ($QED_3$), featuring gapless spinons and monopoles as gauge excitations. The theory is believed to flow to a strongly-coupled fixed point with conformal symmetries at low energies. Using complementary perturbation theory and scaling arguments, we show that a symmetry-allowed coupling between finite-wavevector lattice distortions and monopole operators of the U(1) DSL induces a spin-Peierls instability towards a (confining) 12-site valence-bond solid state. We support our theoretical analysis with state-of-the-art iDMRG simulations. Away from the limit of static distortions, we demonstrate that the phonon energy gap establishes a parameter regime where the spin liquid is expected to be stable.

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# The formalism of conformal Hilbert spaces and the fractionalization of anyons in fractional quantum Hall systems

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The fractional quantum Hall (FQH) effect is a family of strongly correlated topological systems in two-dimension, with exotic low lying charge excitations that are anyonic and even non-Abelian. Here we propose a unified framework in understanding the integer and fractional quantum Hall systems via Hilbert space truncation. This framework is closely related to the well-known microscopic pseudopotential and Jack polynomial formalism, and we show a more general method in constructing Hilbert spaces within a single Landau level with emergent conformal symmetry[1]. These conformal Hilbert spaces (CHS) have well-defined topological properties with anyons as "elementary particles". The hierarchical structure of the CHS allows us to reveal internal structures of anyons of the familiar FQH phases (e.g. the Laughlin and Moore-Read phases), and to derive experimentally relevant conditions for such anyons or quasiholes to undergo fractionalisation with the same topological phase[2].

More interestingly, the fractionalisation of and the interaction between anyons are mediated by the quantum geometric fluctuations of the topological quantum fluids, which can also be systematically understood via the hierarchy of the CHS. Expanding on this hidden connections between the interplay of geometry and topology in FQH systems, I will briefly discuss the emergence of multiple gravitons and the spin-statistics theorem of (deformable) anyons[3, 4]. The CHS formalism can also be generalised to the sub-Hilbert spaces of multiple LLs, and I will discuss a number of experimental ramifications.

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# Abstract for "Randomness-induced Spin Liquid in the Square-Lattice Compounds $Sr_2CuTe_{1-x}W_xO_6$"

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We apply a plaquette-disorder $J_1$-$J_2$ model to describe the physics of a series of $S = \frac{1}{2}$ Heisenberg antiferromagnet compounds $Sr_2CuTe_{1-x}W_xO_6$ on the square lattice. Based on coupling strengths from quantum chemistry calculations [1], our exact diagonalization study probes the ground states beyond previous spin-wave analysis [2]. Here, we identify the range of $x$ for the non-magnetic phases where both AFM and stripe order parameters vanish. The spin freezing parameter drops to zero around $x = 0.5$, indicating a randomness-induced phase transition to a gapless spin-liquid-like phase. A broad continuum of the dynamical spin structure factor is also observed.

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# (3+1)D gauge theories of topological orders with non-Abelian fusion rules, shrinking rules, and braiding statistics

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Braiding and fusion rules of topological excitations are indispensable topological invariants in topological quantum computation and topological orders. While excitations in two dimensions (2D) are always particlelike anyons, those in three dimensions (3D) incorporate not only particles but also loops, spatially nonlocal objects, making it novel and challenging to study topological invariants in higher dimensions. While 2D fusion rules have been well understood from bulk Chern-Simons field theory and edge conformal field theory, it is yet to be thoroughly explored for 3D fusion rules from higher-dimensional bulk topological field theory. Here, we perform a field-theoretical study on (i) how loops that carry Abelian gauge fluxes fuse and (ii) how loops are shrunk into particles in the path integral, which generates fusion rules, loop-shrinking rules, and descendent invariants, e.g., quantum dimensions. We first assign a gauge-invariant Wilson operator to each excitation and determine the number of distinct excitations through equivalence classes of Wilson operators. Then, we adiabatically shift two Wilson operators together to observe how they fuse and are split in the path integral; despite the Abelian nature of the gauge fluxes carried by loops, their fusions may be of non-Abelian nature. Meanwhile, we adiabatically deform world sheets of unknotted loops into world lines and examine the shrinking outcomes; we find that the resulting loop-shrinking rules are algebraically consistent to fusion rules. Interestingly, fusing a pair of loop and antiloop may generate multiple vacua, but fusing a pair of anyon and antianyon in 2D has one vacuum only. By establishing a field-theoretical ground for fusion and shrinking in 3D, this work leaves intriguing directions for future exploration, e.g., symmetry enrichment, quantum gates, and topological order of braided monoidal 2-category of 2-group.

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# Fractonic Phases in a Constrained Bose-Hubbard Model

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Quantum many-body systems with fracton constraints are widely conjectured to exhibit unconventional low-energy phases of matter. In this work, we demonstrate the existence of a variety of such exotic quantum phases in the ground states of a dipole-moment conserving Bose-Hubbard model in one dimension. For integer boson fillings, we perform a mapping of the system to a model of microscopic local dipoles, which are composites of fractons. We apply a combination of low-energy field theory and large-scale tensor network simulations to demonstrate the emergence of a dipole Luttinger liquid phase. At non-integer fillings our numerical approach shows an intriguing compressible state described by a quantum Lifshitz model in which charge density-wave order coexists with dipole long-range order and superfluidity – a "dipole supersolid". Moreover, we study low-energy excitations of these fractonic phases by numerically computing spectral functions and investigating the dynamics after a quench, which shows signatures reminiscent of a gauge theory. We discuss potential experimental implications of our results.