OCPA 10

THE 2026 OCPA CONFERENCE

ABSTRACT

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Efimov Effect in Long-range Quantum Spin Chains

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ABSTRACT

When two non-relativistic particles interact resonantly in three dimensions, an infinite tower of three-body bound states emerges, exhibiting a discrete scale invariance. This universal phenomenon, known as the Efimov effect, has garnered extensive attention across various fields. However, it remains an open question how analogous universal few-body physics can emerge in low-dimensional quantum platforms. In this work, we demonstrate that the Efimov effect also manifests in long-range quantum spin chains. The long-range coupling modifies the low-energy dispersion of magnons, enabling the emergence of continuous scale invariance for two-magnon states at resonance. This invariance is subsequently broken to discrete scale invariance for the three-magnon problem, leading to the celebrated Efimov effect. We further discuss generalizations to arbitrary spatial dimensions, where the traditional Efimov effect serves as a special case. Our results reveal universal physics in dilute quantum gases of magnons that can be experimentally tested in trapped-ion systems.

REFERENCE

Efimov Effect in Long-range Quantum Spin Chains, arXiv:2502.20759.

KEYWORDS

Efimov effect, Few-body physics, Long-range spin systems

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WIDE-BAND MOIRE SUPERCHIRAL OPTICAL FIELD

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ABSTRACT

On-chip optical superchiral fields are usually generated using nanostructures. Here we demonstrate superchiral field generation using surface waves in a one-dimensional photonic crystal (PhC). The PhC supports nodal rings featuring a bandwidth-enhanced, all-angle degenerate dispersion for transverse magnetic (TM) and transverse electric (TE) surface modes. This unique degeneracy is harnessed to create simultaneous electric field and magnetic field skyrmion bags, resulting in a moiré superchiral field superlattice on the flat crystal surface. We show that the distribution of the superchirality can be modulated by the moiré angle and orbital angular momentum (OAM) of the excitation scheme and the handedness of chirality is determined by the phase difference between TM and TE waves. This work proposes a simple platform for on-chip chiral sensing using tailored superchiral fields.

REFERENCE STYLE

Observation of strong spin-orbit couplings in plasmonic spin-twistronics topological lattices, *Nature Communications*, 17, 1905, 2026, P. Shi, X. Gou, Q. Zhang, W. Wei, H. Wu, Z. Zhu, Y. Shen, X. Yuan.

Bandwidth-enhanced moiré superchiral optical field in a nodal ring photonic crystal, *Physical Review B*, in press, 2026, Q. Zhang, R. Chen, X. Yuan.

KEYWORDS

Near-field optics, Photonic crystals, Chirality

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Stabilizer Rényi Entropy in SYK-like Models

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ABSTRACT

Quantum entanglement and quantum magic are two distinct fundamental resources that enable quantum systems to exhibit complex phenomena beyond the capabilities of classical computer simulations. While quantum entanglement has been extensively used to characterize both equilibrium and dynamical phases, the study of quantum magic, typically quantified by the stabilizer Rényi entropy (SRE), remains less explored. In this talk, I will introduce our recent work on investigating the SRE in SYK-like models by representing the corresponding partition function using auxiliary spin degrees of freedom. We apply this method to three examples: (1) the single-site SYK model, (2) the coupled SYK model, and (3) thermofield double dynamics. Our results reveal various transitions in the SRE that are not visible in conventional observables or Rényi entropies of density matrices.

REFERENCE STYLE

[1]. Stabilizer Renyi Entropy and Its Transition in the Coupled Sachdev-Ye-Kitaev Model, *PHYSICAL REVIEW LETTERS*, 136, 080201 (2026), P. Zhang, S. Zhou, and N. Sun.

[2]. Connecting Magic Dynamics in Thermofield Double States to Spectral Form Factors, *arXiv*:2601.12787, N. Sun and P. Zhang.

KEYWORDS

Sachdev-Ye-Kitaev model, Quantum magic, Stabilizer Rényi entropy

Application of AI-based methods to quantum metrology and quantum algorithm optimization

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ABSTRACT

Recent advances in Artificial Intelligence have profoundly influenced science and technology, in particular quantum technologies. In this talk, we present our recent works illustrating how reinforcement learning (RL) and physics-informed neural networks (PINN) can be applied to quantum metrology and quantum algorithm optimization while improving resource efficiency across the quantum workflow.

First, we proposed RL algorithm which can discover generalizable quantum control strategies for parameter estimation tasks. By learning policies that remain effective across a range of parameter values, it enables adaptive control protocols that avoid repeated recalculation of optimal strategies during iterative estimation procedures [1]. Building on this idea, we introduce a reinforcement-learning-based framework for automated circuit architecture discovery in variational quantum sensing. By treating circuit structure as a trainable object and enabling distributed architecture search under hardware constraints, the method adaptively explores state preparation and measurement designs, achieving improved sensitivity and resource efficiency compared with fixed ansatzes [2].

We then present PINN approaches that enhance quantum system characterization and variational algorithm optimization. For Hamiltonian learning, we propose inverse physics-informed neural networks that incorporate the Schrödinger equation into the training objective, enabling accurate inference of system parameters from limited noisy measurements while maintaining physical consistency [3]. Finally, for noisy variational quantum algorithms, we introduce a physics-informed denoising network that learns the effective optimization dynamics under an error-mitigated cost landscape, significantly reducing the number of required circuit executions while preserving the correct optimization trajectory [4].

These results illustrate how AI-driven approaches can improve efficiency across multiple layers of the quantum computing stack and highlight the growing role of AI as a key enabler for scalable quantum technologies.

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REFERENCE STYLE

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[3] Hamiltonian learning via inverse physics-informed neural networks, *Phys. Rev. Research*, 7, 043137, 2025, J. Liu, X. Wang.

[4] Accelerating Noisy Variational Quantum Algorithms with Physics-Informed Denoising Networks, in preparation, J. Liu, X. Wang.

KEYWORDS

reinforcement learning, physics-informed neural networks, quantum metrology, quantum algorithm, quantum control

Scalable and efficient generation of graph states in cavity QED

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ABSTRACT

Scalable graph states constitute a fundamental resource for measurement-based quantum computation and a wide range of entanglement-assisted quantum technologies. Their generation requires controllable quantum platforms and efficient, high-fidelity preparation protocols. Here, we propose a systematic approach to generate scalable graph states in one- and two-dimensional geometries using atom–cavity interfaces. Our method is based on the state-carving technique, which enables selective projection of desired entangled states by removing unwanted state components.

We develop a multiqubit state-carving protocol that, combined with the adiabatic transport of a controlled number of atoms in optical tweezers, allows flexible and scalable generation of graph states with tailored geometries. We further analyze the achievable state fidelity and demonstrate that the preparation probability can be optimized through sequential single-photon probing. A key advance of our work is a simple yet powerful modification of the conventional state-carving scheme, which enables entanglement generation with unit probability in principle.

This efficient and experimentally feasible protocol significantly enhances the practicality of entanglement generation in atom–cavity interfaces, even in regimes of moderate cooperativity. Our results establish atom–nanophotonic platforms as a promising route toward large-scale graph-state generation, with direct implications for modular quantum computing, quantum repeaters, and the realization of arbitrarily structured graph states. These capabilities are essential for scalable one-way quantum computation and future quantum network architectures.

REFERENCE STYLE

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KEYWORDS

Scalable graph states; Efficient entanglement generation; cavity QED

Quantum magnonics and quantum nonlinear magnonics

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ABSTRACT

Quantum magnonics has emerged as a new direction of research in both quantum physics and condensed matter physics. This talk introduces the background in this area and the very recent progress in my group. First, I will demonstrate the quantum control of a single magnon, including the deterministic generation of a single-magnon state and its coherent superposition with the vacuum (zero-magnon state). Second, I will show some new results on magnon squeezing in the quantum regime, a novel phenomenon in quantum nonlinear magnonics.

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KEYWORDS

Cavity magnonics, Single-magnon control, Magnon squeezing

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Universal quantum control by time-dependent Hamiltonian: Hermitian and non-Hermitian

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ABSTRACT

Conventional manipulations over quantum systems for such as coherent population trapping and unidirectional transfer focus on Hamiltonian engineering while regarding the system's manifold geometry and constraint as secondary causes. Here, we treat them on equal footing in controlling time-dependent quantum systems under either Hermitian or non-Hermitian Hamiltonian. The idea is inspired by the D'Alembert principle of regarding active force, constraint force, and inertial force in an unbiased way. For the Hermitian Hamiltonian, we prove that multiple nonadiabatic paths can be obtained by the von Neumann equation for the projection operators of ancillary bases, that serves as dynamical invariants. For the non-Hermitian Hamiltonian, we prove that the Hamiltonian triangularization in the stationary ancillary picture is sufficient to construct at least one nonadiabatic passage in both bra and ket spaces. The passage ends up with a desired target state that is automatically normalized without artificial normalization. Our works demystify and unify the popular protocols on quantum state engineering, including stimulated Raman adiabatic passage, the Lewis-Riesenfeld invariants, quantum transitionless driving, and holonomic transformation. We establish a universal quantum-control framework with a clear motivation inspired by analytical mechanics.

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Universal quantum control by non-Hermitian Hamiltonian, *Physical Review A*, 112, 032605, 2025, Z. Jin, J. Jing.

Universal quantum control over bosonic networks, *Physical Review A* 113, 012426, 2026, Z. Jin, J. Jing.

KEYWORDS

universal quantum control, nonadiabatic passage, non-Hermitian Hamiltonian

SU(3) color-orbit coupling in ultracold strontium

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ABSTRACT

Strontium-87, with its zero electronic spin and a large nuclear spin of 9/2, possesses a large Zeeman manifold within its magnetic-insensitive $^1S_0$ ground state. This makes ultracold strontium-87 a suitable platform to explore SU(N) physics. We have previously realized uniform SU(2) synthetic gauge field in a tripod configuration, where spin-orbit coupling was observed. Our study reveals particle dynamics in the non-abelian SU(2) gauge field that is similar to Zitterbewegung effect. We extend our study to the SU(3) case by coupling the internal states in a double-tripod configuration. We experimentally demonstrate the all-state connectivity that is inherent in an SU(3) system. As a central result of our work, we study the generalization of spin-orbit coupling to SU(3) color-orbit coupling, where we find three distinct oscillation frequencies with rich dynamics.

REFERENCE STYLE

Experimental realization of a SU(3) color-orbit coupling in an ultracold gas, *Nature Communications*, 16, 8448, 2025, C.S. Madasu, C. Mitra, L. Gabardos, K.D. Rathod, T. Zanon-Willette, C. Miniatura, F. Chevy, C.C. Kwong and D. Wilkowski.

KEYWORDS

Cold atoms, non-abelian gauge field, tripod system, spin-orbit coupling, SU(3)

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Dissipative Phase Transition in a Generalized Quantum Rabi Model

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ABSTRACT

We investigate dissipative phase transitions (DPTs) in a parametrically amplified open quantum Rabi model (QRM) with both single- and two-photon decay. In the classical oscillator limit, four composite phases emerge, arising from the possible normal or superradiant regimes across the upper and lower spin branches. A mean-field analysis reveals an "inverted" regime where superradiance emerges only at sufficiently low spin-boson coupling. This regime features first- and second-order DPTs separated by a tricritical point, with two-photon dissipation preserving the stability of the superradiant phase. We further study the steady-state structure beyond the mean-field level and show that the tricriticality stems from the intrinsic nonlinearity of the QRM, unveiled by the interplay of coherent and dissipative two-photon processes. The universality classes of the DPTs are identified, with the corresponding critical and finite-size scaling exponents derived and a scaling ansatz proposed to describe the critical behavior.

REFERENCE STYLE

Dissipative Phase Transition in a Parametrically Amplified Quantum Rabi Model with Two-photon decay, *arXiv:2603.18188*, 2026, M. Zhu, H. Pu.

KEYWORDS

Rabi model, phase transition, superradiance, open quantum system

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FROM NEAR-TERM QUANTUM SIMULATION TO EARLY FAULT-TOLERANCE

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ABSTRACT

Recent years have witnessed incredible advancements in quantum simulation and computation across both hardware and algorithm fronts. The field stands at an exciting threshold, as an imminent transition from the noisy intermediate-scale quantum era to early fault tolerance promises new capabilities.

In the first part of this talk, I plan to discuss a line of work exploring digital quantum simulation of condensed-matter systems on superconducting quantum processors. Thematically, these studies demonstrate that existing capabilities have already supported scientifically interesting studies. These works probe symmetry-protected topological phases in one dimension [1], interacting Chern insulators hosting chiral modes in two dimensions [2], and higher-order topology in three or more dimensions [3]. The latter studies employ mappings that trade spatial dimensions for interactions, playing to the strength of many-body simulation on a quantum device. More recent work has extended simulation methods to non-Hermitian systems exhibiting anomalous boundary physics [4].

Beyond Hamiltonian physics, digital quantum processors have also enabled direct studies of quantum dynamics. In particular, I highlight a realization of measurement-induced entanglement phase transitions [5], where volume- and area-law phases emerge in random circuits with mid-circuit measurements.

Yet, it has become universally clear that physical noise rates have become limiting, motivating the urgent need for fault-tolerant quantum computation. In the second part of my talk, I therefore introduce a recent work that establishes a class of quantum error-correcting codes that support all-to-all entangling connectivity at near zero cost and perfect fidelity [6]. On state preparation and digital quantum simulation benchmarks, these codes provide substantial logical error rate advantages against the surface code at comparable footprint. This efficiency improvement in error-corrected quantum computation accelerates the timeline to accessing novel, meaningful science beyond classical reach.

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KEYWORDS
Quantum simulation, condensed-matter physics, quantum computation, quantum error correction, quantum dynamics

NOTE TO ORGANIZERS
Due to constraints in my travel plans, I would like to request avoiding scheduling my invited talk on Monday and Tuesday (June 22 and 23), if at all possible.

Assembling, entangling, and probing NaCs molecule arrays

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ABSTRACT

Ultracold polar molecules offer an exciting platform for quantum science due to their strong, tunable long-range dipolar interactions and rich internal structure. When assembled into molecule arrays with full quantum control, they can enable the exploration of highly coherent, low-entropy many-body systems in previously inaccessible regimes.

In the Ni group at Harvard, we have been developing a bottom-up approach to assemble, control, and read out ultracold NaCs molecules in optical tweezer arrays starting from individual atoms. In this talk, I will present how ground-state molecules are synthesized in the motional ground state of optical tweezers [1-4], and how long-lived rotational coherence is achieved by engineering the tweezer polarization [5, 6], enabling controlled entanglement between molecules and the realization of an iSWAP gate [7, 8].

I will also discuss recent progress toward non-destructive readout of molecular rotational states using Rydberg atoms, as well as new approaches for scaling to large, defect-free arrays of molecules leveraging electric-field dipolar shielding, paving the way for ultracold molecule arrays to become a scalable quantum simulation platform.

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KEYWORDS
Ultracold Molecules, Quantum Simulation, Optical Tweezers, Dipolar Shielding

Continuous field tracking with machine learning and steady state spin squeezing

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ABSTRACT

Steady-state entanglement is an important resource for continuous quantum sensing, yet maintaining such entanglement in spin systems remains challenging, particularly in the presence of environmental decoherence and unknown signal perturbations. In this work, we experimentally implement continuous quantum non-demolition measurements with optical pumping on a hot atomic ensemble containing more than 10^{10} atoms, and realize a steady-state spin-squeezed state that can be maintained for more than one day under laboratory conditions.

The sustained spin-squeezed state is then employed for sensing continuously time-varying magnetic fields. To infer the time-dependent signals from the optical measurement records, we utilize recurrent neural network (Long Short-Term Memory) and demonstrated reconstruction of different types of stochastic magnetic fields. The approach demonstrates reliable performance for tracking signals with both Gaussian and non-Gaussian characteristics. Furthermore, we recently implemented deterministic steady state spin squeezing via measurement-based feedback protocol, which enabled quantum-enhanced real-time field tracking. These results provide a pathway toward quantum-enhanced sensing in realistic environments.

REFERENCE

Concurrent spin squeezing and field tracking with machine learning, *Nature Physics*, 21, 909–915, 2025, J. Duan, Z. Hu, X. Lu, L. Xiao, S. Jia, K. Mølmer, Y. Xiao.

KEYWORDS

Spin squeezing, Continuous sensing, Optical magnetometer, Quantum metrology

Occupation-selective topological pumping from Floquet gauge fields

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ABSTRACT
Topological pumping is conventionally governed by single-particle band topology. Here we show that promoting tunneling to a dynamical, occupation-conditioned variable fundamentally reshapes this paradigm, leading to occupation-selective topological pumping. In a periodically driven one-dimensional superlattice with density-dependent hopping, two-body bound states (doublons) acquire Chern numbers distinct from those of single particles and exhibit quantized transport even when the single-particle pump is trivial, including counter-propagating responses. We identify a dynamical-gauge-field mechanism that induces topological phase transitions in the bound-state sector absent from the single-particle spectrum. Furthermore, the gauge field concentrates Berry curvature into sharply localized resonant regions without compromising adiabatic quantization. A Floquet realization with ultracold atoms is proposed to realize such occupation-selective pumping. Our results reveal a mechanism for occupation-selective topological responses that can persist across higher-occupancy bound states.

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KEYWORDS
Topological pumping, Dynamical gauge field, Doublon states, Floquet systems, Cold atoms

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Propagation-invariant spatiotemporal vortices

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ABSTRACT

Diffraction, inherently linked to angular spectrum and affected by spatiotemporal coupling effects, imposes a fundamental limit on wave packets propagation. This limitation is particularly acute for spatiotemporal vortex beams, where diffraction distorts the beam profile and splits topological charges. While spatiotemporal coupling engineering has enabled diffraction-free (or propagation-invariant) wave packet propagation, achieving stable vortex propagation remains a significant challenge due to inherent constraints of regular wave dispersion. Here, we overcome this challenge by tailoring the wave system's dispersion to achieve both propagation-invariant behavior and stable vortex structures. We present the first experimental demonstration of propagation-invariant spatiotemporal vortex beams that maintain their spatiotemporal profiles and topological charges over extended propagation distances. The ability of these wave packets to stably carry diverse topological charges without splitting or deformation provides critical insights into spatiotemporal vortex dynamics and unlocks new possibilities for applications across optics, acoustics, and beyond.

REFERENCE STYLE

Propagation-invariant Spatiotemporal Vortices, *Science Bulletin*, 70, 3758-3763, 2025, J. Ye, Z. Che, J. Wang, Y. Zhang, B. Wang, W. Liu, L. Shi, J. Zi.

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KEYWORDS
Spatiotemporal vortices, Propagation-invariant, Spatiotemporal coupling, Liquid surface waves

Macroscopic Spin GHZ State in Levitated Ferromagnets

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ABSTRACT

Macroscopic quantum states bridge quantum and classical physics and are central to quantum-enhanced sensing. Among these states, a many-body entangled Greenberger-Horne-Zeilinger (GHZ) state provides maximal entanglement and leads to Heisenberg scaling in quantum sensing. Generating a macroscopic spin GHZ state in a spin system is challenging due to the requirement for coherent control over a large number of particles and complex control sequences. Here, we propose a promising method for generating a macroscopic spin GHZ-like state in a levitated ferromagnet, where the magnetic anisotropy of ferromagnets causes the collective spin and lattice to form strongly dependent degrees of freedom. This strong spin-lattice locking enables mechanical control of the collective spin and defines a constrained Hilbert space where quantum coherence is shared across these coupled degrees of freedom. The resulting GHZ-like state of the collective spins is verified through the Wigner quasi-probability distribution. We further quantify the metrological advantage of the state by demonstrating Heisenberg scaling of the quantum Fisher information. Furthermore, we analyze the roles of symmetry and geometry in decoherence due to gas collisions, identifying experimentally accessible conditions for state realization. Our work addresses the challenge of efficiently generating macroscopic spin GHZ states, reveals a novel form of macroscopic quantum superposition in systems with coupled degrees of freedom, and motivates the platform to test fundamental physics including collapse models into the spin basis.

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KEYWORDS

Macroscopic Superposition, GHZ States, Levitated Ferromagnet, Quantum Sensing

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Large-scale array of squeezed light and synchronization using atomic vapor

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ABSTRACT

Quantum light sources such as squeezed light are essential for quantum information science and technologies, but the scalable production of multiple beams of such states remains a challenge. Here, we experimentally demonstrate a novel approach for generating a large spatial array of polarization-squeezed light beams via atomic-coherence-enhanced nonlinear optical processes in a single atomic vapor cell. Unlike schemes based on independent squeezing generators, the squeezing dynamics of each channel are governed here by a common collective ground-state atomic coherence, produced by all input beams, homogenized by the thermal motion of the atoms, and protected against wall collisions by a paraffin coating. Consequently, the optical states of all channels are coupled and mutually regulated via the moving atoms, leading to synchronization behavior. We realized a 30-beam array of polarization-squeezed states with 2.03 $\pm$ 0.02 dB of squeezing, experimentally verified the synchronization in both the steady-state and temporal domains, and observed improved purity of the squeezed states as well as the system's response to perturbations, including the temporal response of the squeezing level, as the size of the array increases. This work provides a pathway toward scalable, high-performance quantum light sources for applications in precision measurement, quantum imaging, and quantum information processing.

KEYWORDS

Squeezed state, Optical array, Dissipative coupling

Orientation-Insensitive Spin Amplification for Quantum Metrology

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ABSTRACT
In quantum metrology based on atom-light interactions, while spin squeezing can be used to reduce atomic projection noise, its metrological gain is often limited by detection noises including photon shot noise. Quantum amplification of the spin signal provides an alternative to spin squeezing, enhancing the system's tolerance to detection noises. However, existing amplification protocols typically restrict the optimal gain to a particular spin direction. Here, we propose a protocol for isotropic quantum amplification of a collective transverse spin and report proof-of-principle experiments in a hot atomic ensemble of $N \sim 10^{11}$ atoms. By combining the vector and tensor atom-light interactions, we engineer an effective Hamiltonian that enables orientation-insensitive spin amplification. By optimizing the amplification process against spin relaxation and decoherences, we experimentally verify its isotropy and obtain about 20% improvement in the signal-to-noise ratio when the system is dominated by detection noises. Our work provides a new perspective for quantum amplification of phase measurements and should find applications in various quantum metrology experiment platforms using collective spins.

KEYWORDS
Quantum Metrology, Quantum Spin Amplification, Orientation-Insensitive

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Irreducible Randomness and Apparent Memory in Quantum Stochastic Processes

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ABSTRACT

Distinguishing apparent from true irreducible randomness reveals a stochastic process's memory structure—a feature vital for optimal prediction and control. While well-understood classically, quantum analogs remain underdeveloped due to the inherent interactive nature of quantum dynamics. By mapping multi-time input-output relations to temporal Choi states representing quantum stochastic processes, we formulate the quantum entropy rate as a measure of irreducible randomness—expressed as the asymptotic quantum conditional entropy of such temporal states. We prove that causality ensures its non-negativity and convergence of the quantum entropy rate for stationary processes. We show that the quantum entropy rate physically lower bounds the average randomness in the future system evolution no matter how much information an experimenter collects about the process. Furthermore, it directly leads to a quantum excess entropy as the apparent memory which dictates the minimum memory cost for any recurrent quantum circuit model of the process.

KEYWORDS

Quantum Stochastic Processes, Quantum Memory, Non-Markovianity

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Cold-atom quantum sensing via Bayesian quantum estimation

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ABSTRACT

Quantum sensors based on frequentist interferometry face a trade-off between sensitivity and dynamic range. Bayesian quantum estimation, which integrates Bayesian statistics with quantum metrology, overcomes this limitation and enables performance beyond conventional frequentist measurements. In this talk, we present a Bayesian quantum estimation framework for cold atomic ensembles and validate it using cold-atom CPT-Ramsey interferometry. For cold-atom CPT clocks, our adaptive Bayesian protocol achieves Heisenberg-limited sensitivity in integration time and improves fractional frequency stability by 5.1(4) dB over conventional PID locking while enhancing robustness against technical noise [1]. In CPT magnetometry, we optimize measurement sequences to improve precision scaling from T^(-0.5) to T^(-0.85). By tailoring the interferometry sequence via Bayesian quantum estimation, we obtain a dynamic range of 145.6 nT (14.6 dB higher than frequentist counterpart of 5.0 nT) with a sensitivity of 6.8 ± 0.1 pT/Hz^(1/2) (a 3.3 dB improvement over the frequentist counterpart of 14.7 ± 0.4 pT/Hz^(1/2)) [2]. Furthermore, we develop a credible-interval-based adaptive Bayesian quantum frequency estimation protocol for GHZ-state-based atomic clocks, achieving dual Heisenberg-limited precision scaling with respect to both total particle number and total interrogation time [3]. In addition to atomic clocks and magnetometers, this framework may bridge high sensitivity and broad dynamic range for other interferometry-based quantum sensors, such as atomic gravimeters [4].

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KEYWORDS
Bayesian quantum estimation, cold-atom quantum sensing, atomic clock, atomic magnetometer, atomic gravimeter

A Robust Laser-Ablated Strontium Cold Atom Source for Compact and Long-Term Operation

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ABSTRACT

Cold atom sources are fundamental to the advancement of modern quantum technologies, playing a critical role in fields ranging from quantum computing to precision metrology. However, traditional cold atom platforms, beyond the standard alkaline atoms, typically rely on thermal ovens combined with extensive pre-cooling stages, such as Zeeman slowers or two-dimensional magneto-optical traps (2D MOTs). These conventional setups are characterized by large volumes, high power consumption, and demanding maintenance, making them not suitable for widespread deployment in field applications or space-borne quantum sensors where extreme compactness and low energy consumption are required. To address this challenge, we present a compact, laser-induced cold atom source for strontium-88 that eliminates the need for oven, Zeeman slower, and 2D MOT. Our approach utilizes laser ablation, where the focused laser heating a micrometer-sized region compared to the centimeter-sized bulk strontium granule in oven. The bulk material acts as an effective thermal reservoir; once the ablation laser is turned off, the spot cools rapidly, leading to a fast drop in background vapor pressure and the swift recovery of the ultra-high vacuum (UHV) environment. To ensure long-term usability, we implemented an internal mirror to reflect the ablation beam onto the target. This critical design breaks the direct line-of-sight between the strontium vapor and the optical viewports, significantly reducing the probability of atomic deposition and window coating. Furthermore, the mirror prevents the hot atomic flux from directly colliding with the 3D MOT, thereby preserving the trap lifetime. Currently, our highly portable apparatus is capable of loading 1.2 million atoms within 400 ms, achieving a trapping lifetime of 1.5 s. Ongoing optimizations are expected to further enhance the

system's performance, paving the way for next-generation deployable quantum devices.

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KEYWORDS

Laser Ablation, Cold Atom Source, Strontium, Magneto-Optical Trap, Compact Setup.

FLOQUET DYNAMICS IN DISPERSIVE AND DISSIPATIVE TIME-VARYING MEDIA

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ABSTRACT

Photonics in media with time-varying properties, such as permittivity, have emerged as promising platforms to break the intrinsic limitations of conventional static photonic systems. The periodic dynamic modulation of the permittivity has unlocked the temporal degree of freedom in the photonic system, thereby giving rise to the generation of Floquet harmonics with frequencies spaced equidistantly by modulation frequency in the spectrum. The periodic dynamic modulation has also facilitated energy exchange between the electromagnetic field and the media, leading to the parametric amplification or coherent absorption of the electromagnetic field. However, the lack of computational techniques has hindered the experimental realization and implementation of the photonic systems with time-varying media.

We start from the first principles, and present a systematic framework for photonic systems with time-varying media. It not only enables previously prohibitive computations, but fosters an insight into the underlying mechanism that provides guidance for the design of realistic photonic systems.

We first focus on the closed Floquet photonic systems, such as photonic time crystal, characterized by the continuous energy bands. The proposed framework enables the fast and robust computation of energy band in complex spatial distributions. This framework further helps reveal novel topological phenomena in the Floquet photonic systems.

In parallel, we focus on the open Floquet photonic scattering systems, such as the leaky cavity, which is essential for the experimental observables. The proposed analytical framework enables modal analysis of the scattering field and establishes the correspondence between the Floquet quasienergy levels and the resonance peaks in spectra. We further introduce a hybrid numerical-analytical simulation algorithm based on the theoretical framework. The open-source software package by the hybrid framework enables the computationally inaccessible simulation of complex Floquet photonic systems with high precision.

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Quasinormal mode basis for open Floquet photonic systems. *Physical Review Letters,* 2026, Yuchen Sun, Shanhui Fan, and Guangwei Hu. (in press, DOI: 10.1103/175n-lksd)

KEYWORDS
Time-varying photonics, Quasinormal mode, Floquet matrix, Green's function, Scattering theory

Quantum Process Tensors, Combs and Link Product on Infinite Dimensions

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ABSTRACT
Continuous variable (CV) quantum systems can exhibit non-Markovian behavior, and in such cases, a Markovian description discards valuable information that may otherwise have been put to use in the enhancement of quantum control. To alleviate these issues, we extend the framework of quantum combs—a formalism for the characterization and utilization of non-Markovian multi-time processes developed in discrete variable systems—into CV non-Markovian processes. Our key contributions are generalizing the notion of a link product to CV systems and presenting an efficient algorithm to evaluate this for Gaussian processes using covariance matrices. The latter scales polynomially with the number of timesteps of a non-Markovian process, providing a unique advantage over non-Gaussian as well as general DV processes. In doing so, we provide a framework to characterize these non-Markovian processes, and powerful tools with which to study them.

KEYWORDS
Quantum information, quantum foundations, non-Markovian multi-time processes, quantum continuous variables, quantum process tensors

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Hybrid Optical Lattice-Tweezer Platform

for Ultracold Ytterbium Atoms

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ABSTRACT

Optical lattices and optical tweezers have enabled a series of breakthroughs in quantum simulation and computing. However, conventional optical lattices provide excellent scalability but limited local control, whereas optical tweezers allow flexible and precise manipulation of individual atoms but are limited in system size by the finite field of view of the objective lens.

In this talk, I will present a hybrid optical lattice-tweezer platform for ultracold ytterbium atoms that combines the large-scale scalability of optical lattices with the precise control offered by optical tweezers. This approach enables the preparation and manipulation of large, reconfigurable atomic arrays with high flexibility. I will also report on a two-color magneto-optical trap for ytterbium atoms and rapid optical transport to quantum degeneracy using a moving optical lattice.

Finally, I will discuss our recent progress in fast quantum gas microscopy. In contrast to conventional fluorescence imaging techniques, which typically require exposure times on the order of tens of milliseconds, our approach achieves site-resolved detection with microsecond-scale exposure times. Beyond conventional parity-projection measurements that infer multiple occupancy indirectly, our method enables direct detection of multiple atoms in a single lattice site, paving the way for studying quantum many-body dynamics with high temporal and spatial resolution.

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KEYWORDS

Optical Lattice, Optical Tweezer, Ultracold Ytterbium Atoms, Quantum Gas Microscopy.

Long-range nonstabilizerness and quantum codes, phases, and complexity

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ABSTRACT

As a necessary resource for quantum computational advantage, quantum magic (nonstabilizerness) is of fundamental importance in the study of quantum computation and physics. We develop a systematic theory of *long-range magic (LRM)*---nonstabilizerness that cannot be erased by shallow unitary circuits---and demonstrate its broad relevance. By bridging LRM with fault-tolerant logical gate theory, we show the emergence of LRM families from quantum error-correcting codes and devise a simple yet powerful method for testing transversal logical gates. Further, we introduce and characterize *LRM phases* in which all ground states throughout the phase exhibit LRM, and identify certain non-Abelian topological orders as representative examples. Then, adopting a complexity theory perspective, we demonstrate the classicality of non-LRM systems in e.g. preparation and learning settings, and present a "no low-energy trivial magic" (NLTM) conjecture with key motivation in the quantum PCP context, for which our LRM results suggest a compelling route. Additionally, we demonstrate how to diagnose LRM with correlation functions. The concepts and results admit substantive extensions to approximate (robust) and nongeometric scenarios. Our LRM theory illuminates profound new connections among quantum resources, computational advantage, error correction and fault tolerance, many-body physics, and complexity theory.

REFERENCE STYLE

Long-range nonstabilizerness and quantum codes, phases, and complexity, arXiv: 2503.04566, F. Wei, Z.-W. Liu.

KEYWORDS

Topological order, Quantum computational resources, Quantum error correction, Quantum complexity theory, Many-body quantum computation

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Room-Temperature Vector Atomic Magnetometer and brain magnetic field sensing

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ABSTRACT

Precision measurement of magnetic fields has important applications in brain science, biomedicine, geomagnetic navigation, magnetic anomaly detection etc. Atomic magnetometers are currently the most sensitive tools for magnetic field measurement; however, most high-sensitivity atomic magnetometers are scalar ones that can only measure the magnitude of the field. Vector magnetometers are capable of measuring both the magnitude and the direction of magnetic fields, and therefore can provide more information about the orientation and location of the field source. Yet, due to constraints from the operating principles, most vector magnetometers cannot simultaneously meet the requirements of high sensitivity, real-time, high spatial resolution, single-laser-beam and room temperature for device applications. We demonstrate a room-temperature all-optical vector magnetometer and triaxial brain field sensing using atomic magnetometer based on Electromagnetically induced transparency (EIT) in rubidium vapor cell with anti-relaxation wall coating. Employing the neural-network-based decoding techniques, we achieve the magnetic field amplitude sensitivity of $16.33\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$ and directional sensitivities of $0.015\ \mathrm{mrad}/\sqrt{\mathrm{Hz}}$ for polar angle and $0.032\ \mathrm{mrad}/\sqrt{\mathrm{Hz}}$ for azimuth angle for a magnetic field about 140 nT. We further employ the magnetometer to develop a triaxial magnetoencephalography prototype device, which can sense the brain magnetic field signal in three orthogonal directions of evoked responses from auditory stimulation. Our approach of machine learning assisted vector atomic magnetometry can be extended to high-sensitivity detection of vector geomagnetic field and anomaly magnetic field detection. Meanwhile, our prototype device provides an important technical foundation for room-temperature, non-invasive triaxial bio-magnetic-field measurements.

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KEYWORDS
Atomic magnetometer, Vector magnetometry, Magnetoencephalography, Electromagnetically induced transparency, Anti-relaxation coating

Electric Bias-induced Reversible Configuration of Single and Heteronuclear Dual-Atom Catalysts on 1T′-MoS2

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ABSTRACT

The development of substrates capable of anchoring single-atom catalysts (SACs) while enabling their dynamic reconfiguration into heteronuclear dual-atom catalysts (DACs) holds significant promise for electrochemical synthesis, yet remains underexplored. Here, we show that electrochemical desulfurization of MoS_2 generates vacancy-rich 1T′ domains, which support high loadings of Cu (7.9 wt%) and Pt (6.7 wt%) SACs that are well positioned for dynamic sintering to form DACs. Operando X-ray absorption spectroscopy and density functional theory calculations reveal a voltage-driven, reversible transformation between individual Pt/Cu SACs and Cu-Pt DAC configurations during hydrogen evolution reaction (HER) potentials. The electric field-induced Cu-Pt DACs exhibit superior performance in the selective hydrogenation of alkynes compared to their monometallic SAC counterparts. This work underscores vacancy-enriched 1T′-MoS_2 as a versatile platform for high-density SAC deposition,

enabling on-demand structural reconfiguration and paving the way for tailored catalyst design in electrosynthesis.

REFERENCE STYLE

Electric bias-induced reversible configuration of single and heteronuclear dual-atom catalysts on 1T′-MoS_2. *Nat. Nanotechnol.* 20, 1043–1051, 2025, J.H. Wu, Z.X. Chen, K. Yang, X. Zhou.

KEYWORDS

Bimetallic single-atom catalysts, dual atom catalyst, vacancy engineering, MoS_2, dynamic reconfiguration

Quantum trajectory of a spin oscillator, continuous retrodiction beyond the Heisenberg uncertainty relation

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ABSTRACT
The Heisenberg uncertainty relation imposes a fundamental limit on the measurement precision of non-commuting observables, constraining the performance of quantum sensors and measurement devices. Here, we experimentally demonstrate effectively "simultaneous" sub-SQL (standard quantum limit) estimation of two non-commuting observables in a macroscopic spin oscillator by combining predictive and retrodictive information within the past quantum state formalism. Using a rubidium-87 atomic ensemble of about 10^{10} spins, we perform continuous quantum non-demolition measurements of the canonical quadratures x and p. By synthesizing the forward-evolving quantum state and the backward-propagating effect matrix, we achieve conditional variances for both observables that both lie about 1 dB below the Heisenberg uncertainty bound, with the squeezing maintained over two hours. Moreover, the noise reduction extends to arbitrary quadratures in phase space, all with sub-SQL fluctuations. This work establishes a general framework for surpassing fundamental quantum limits in multi-parameter estimation, with direct applications in quantum-enhanced sensing and continuous-variable quantum information.

KEYWORDS
Quantum trajectory, Past quantum state, Spin oscillator, Heisenberg uncertainty relation, Quantum non-demolition measurement

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A Unified Framework for Sequential Quantum Correlation Sharing

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ABSTRACT

Quantum measurements not only extract information but also reshape quantum states through measurement backaction, thereby determining how quantum resources can be distributed and recycled. In this talk, recent progress on the sequential sharing of quantum correlations will be reviewed from the perspective of generalized quantum measurements and quantum instruments. Particular emphasis will be placed on Bell nonlocality, EPR steering, entanglement, network nonlocality, and contextuality under sequential and weak-measurement scenarios. Recent advances on complementarity-based correlation sharing and unified measurement frameworks beyond conventional POVM descriptions will also be discussed, highlighting how different Kraus structures govern resource dissipation, robustness, and quantum resource recycling in multipartite and sequential quantum information protocols.

REFERENCE STYLE

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KEYWORDS

Quantum correlation sharing, Sequential quantum measurements, Measurement backaction

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NEW FRONTIERS IN SYNTHETIC GAUGE FIELDS: COMPLEX AND HIGHER-RANK TENSORS

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THE STUDY OF SYNTHETIC GAUGE FIELDS HAS DRIVEN MAJOR ADVANCES ACROSS MANY AREAS OF PHYSICS OVER THE PAST TWO DECADES. MOST OF THESE WORKS, HOWEVER, HAVE FOCUSED ON REAL VECTOR GAUGE FIELDS. IN THIS TALK, I WILL DISCUSS HOW THIS FRAMEWORK CAN BE GENERALIZED TO A LARGELY UNEXPLORED SETTING INVOLVING COMPLEX AND HIGHER-RANK TENSOR GAUGE FIELDS. I WILL PRESENT EXPERIMENTALLY FEASIBLE APPROACHES FOR REALIZING THESE FIELDS AND HIGHLIGHT THE QUALITATIVELY NEW PHENOMENA THAT ARISE WHEN THEY COUPLE TO EXOTIC QUANTUM PHASES.

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KEYWORDS
Gauge fields, macroscopic quantum phenomena, non-Hermitian phenomena

Scalable generation of massive Schrödinger cat states via quantum tunnelling

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ABSTRACT

Massive spatial quantum superposition states are an important resource for quantum-enhanced metrology and for investigating the interplay between quantum mechanics and gravity. However, generating controllable high-mass spatial superpositions beyond single atoms remains a major experimental challenge. In this work, we report the scalable realization of massive Schrödinger cat states through coherent quantum tunnelling of ultracold atomic clusters in optical lattices. By engineering strongly interacting bosonic atoms in a double-well optical lattice, we observe coherent tunnelling dynamics of bound atomic clusters with an effective mass reaching 608 atomic mass units (AMU). The suppression of tunnelling strength associated with increasing particle number is mitigated through full control of the model parameters. Furthermore, we implement an interferometric protocol to verify the generated spatial entanglement and demonstrate quantum-enhanced phase sensitivity using the resulting cat states. Our results establish a versatile platform for creating and manipulating massive entangled matter-wave states, opening new opportunities for quantum simulation, precision measurement, and experimental studies of macroscopic quantum phenomena.

REFERENCE STYLE

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KEYWORDS

Quantum tunnelling, Schrödinger cat states, Optical lattices, Ultracold atoms, Quantum interferometry.

Wideband pulse shaping for matterwave interferometry and atomic spectroscopy

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ABSTRACT

In atomic physics, controlling atomic states with light is often challenged by intensity inhomogeneity, while probing atoms with light is constrained by phase information loss. By carefully designing optical pulses at suitable time scales, these constraints can be alleviated, enabling new experimental possibilities. In this talk, I will present two examples, both enabled by wideband optical arbitrary waveform generation (OAWG) [1].

First, by shaping nanosecond pulses according to optimal control theory [2], we achieve $\mathcal{F} \approx 99.2\%$ Raman beam-splitting fidelity with ±50% laser intensity-error resilience. We demonstrate high-contrast, $34\hbar k$ recoil-transfer Raman interferometry operating simultaneously on three pairs of atomic spin states. This technique should be useful for wideband precision inertial sensing in the presence of magnetic field noise.

Second, we develop a frequency-jump approach to coherent atomic spectroscopy. By sending precisely known, rapidly modulated optical waveforms to atoms, wideband spectral information is extracted from transient transmission in a single shot. The method is substantially more data-efficient than traditional frequency-scan methods, ideal for atomic spectroscopy with limited interrogation time window. We demonstrate the technique at an optical nanofiber interface [3], where transmission data is constrained by atomic motion.

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KEYWORDS
Atom Interferometry, Robust Quantum Control, Coherent Atomic Spectroscopy

Tailoring Rydberg interactions for expanding quantum capabilities

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ABSTRACT

Rydberg atoms provide a uniquely versatile platform for engineering strong, tunable interactions in otherwise weakly interacting neutral-atom systems. They couple strongly to each other and to external fields. The former enables controllable atom-atom, atom-photon and even photon-photon interactions, while the latter promises exceptionally sensitive and broadband microwave (MW) and radio frequency (RF) sensing capabilities. Typically, the Rydberg-Rydberg interactions are leveraged as a blockade mechanism. In contrast, we explore the antiblockade regime in atom arrays, where interactions facilitate rather than suppress excitation. I will present our numerical studies demonstrating directional quantum information and entanglement transfer [1], as well as robust avalanche amplification for weak signal detection [2]. For atom-field coupling, I will present our experimental work expanding MW sensing capabilities with cold atomic ensembles. First, we demonstrate 3D field characterization via multi-parameter extraction, which holds potential as a testbed for machine-learning-enhanced measurement protocols and has broad implications for information extraction from complex measurements. Second, we address the intersection of atom-atom and atom-field interactions by investigating the role of nonlinear atomic interactions in probing external fields [3]. Together, these studies show how tailoring Rydberg interactions expands the accessible measurement and dynamical capabilities of cold-atom platforms.

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KEYWORDS

Rydberg atom, electromagnetically induced transparency, quantum information transfer, photon-photon interaction, microwave sensing

Hardware-Aware XZZX Surface-Code Compilation and Dual-Rail Concatenation for Silicon-Atom Architectures

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ABSTRACT

We study surface-code memory experiments tailored to silicon donor-cluster hardware, where gates are dense within each cluster but sparse and noisier between clusters. Starting from a planar Tanner graph, we compile a rectangular XZZX surface-code patch onto a triangular\rectangular cluster graph with finite cluster capacity, minimizing inter-cluster ancilla-data interactions. Using explicit circuit-level simulations with a silicon-inspired biased noise model, a fixed d_x = 3 XZZX family shows decreasing X-memory logical error as d_z increases, with the current 20,000-shot data crossing

an average primitive-noise reference near d_z ≈ 4.69.

We also extend this framework to simulate dual-rail qubits concatenated with surface codes. The first implementation models each dual-rail block as an effective outer-code qubit with heralded erasure plus residual biased Pauli noise, enabling direct comparison between direct physical-qubit and dual-rail-concatenated surface-code memories. This provides a route to quantify how hardware bias, erasure information, and cluster-aware compilation combine in silicon-compatible fault-tolerant architectures.

REFERENCE STYLE

not published yet

KEYWORDS

QEC, silicon atom qubit, donor-cluster architecture

Most subradiant bound photon pairs from chirality-mediated dispersion softening

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ABSTRACT

In the two-excitation sector of waveguide QED, the collective emission from subwavelength atom arrays universally hosts two distinct classes of subradiant eigenstates: free-Fermion states (FSs) and bound photon pairs (bound states, BSs). FSs emerge from the quadratic band extrema of the single-excitation polaritonic dispersion, displaying a universal N^{-3} decay rate scaling with respect to the atom number N; BSs are subradiant bound atomic excitations that reside within the bandgaps of the scattering continuum. In conventional non-chiral systems, FSs are typically the longest-lived two-excitation states. However, the competition between FSs and BSs in dictating the most subradiant states in chiral waveguide QED, as well as a rigorous analytical derivation for the scaling of BS decay rates, remain largely unexplored.

We address this gap by investigating the subradiant decay rates of BSs in the presence of interaction chirality. We demonstrate that chiral interactions can drive BSs to become the most subradiant two-excitation states across a wide range of lattice spacings. This phenomenon is rooted in a mechanism we term *chirality-mediated dispersion softening*. Specifically, we rigorously prove that the BS decay rate follows the scaling $\Gamma \sim |\alpha_2|/N^3$ if the BS dispersion is $E_K \approx \alpha_2(K\text{-}K_{\mathrm{ex}})^2$ near a band extremum K_{ex}, revealing that by increasing chirality, the BS band curvature α_2 can be suppressed, which is the key to achieving extreme subradiance. Aided by an additional toy model, we clarify the general role of chirality for shaping polaritonic dispersion relations toward subradiance, and for engineering exotic photon-photon correlations in nanophotonic systems. Finally, we show that these subradiant chiral BSs can be prepared in a realistic optical nanofiber interface.

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KEYWORDS
Chiral waveguide QED, Bound photon pair, Subradiant emission, Decay rate scaling

On-chip valley-conserved dual-polarisation photonic crystal router

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ABSTRACT

Photonic crystals serve as a powerful platform for guiding light in ultra-compact geometries. However, in two-dimensional photonic crystals, overlapping transverse electric (TE) and transverse magnetic (TM) bandgaps cannot be realized with identical permittivities. Here, we achieve overlapping complete photonic bandgaps on a chip by exploiting the difference in 2D effective permittivities for TE and TM modes in lossless silicon photonic crystal slabs with hexagonal air holes arranged in a honeycomb lattice. Leveraging the valley degree of freedom, we design dual-polarization waveguide modes that exist below the light cone and achieve strong field confinement within the slab. This waveguide offers broadband transmission for both polarizations, unlike traditional narrowband TE-only valley photonic crystals with triangular air holes. We further utilize the valley-conserved properties of TE-polarized waveguide modes to design and fabricate an on-chip polarization router through interfacial engineering, employing a mirror-symmetric interface for TE routing and a glide-symmetric interface for exclusive TM propagation. Experimental results demonstrate a 7 GHz region of dual-mode operation within a combined 43 GHz bandwidth (24 GHz TE, 19 GHz TM), together with successful polarization splitting on the chip. Our work presents one of the first experimental realizations of a dual TE/TM polarized valley photonic crystal waveguide and router, enabling polarization-multiplexed functionality for integrated THz photonics. This platform paves the way for high-performance on-chip and inter-chip interconnects, supporting future AI systems, data centre scalability, and emerging 6G communication technologies.

REFERENCE STYLE

On-Chip Valley-Conserved Dual-Polarization Photonic Crystal Router, *APL Engineering Physics*, (in press), 2026, K.X.J. Ho, Y.J. Tan, R. Singh

KEYWORDS

Dual-polarization, valley photonic crystal, THz photonics, on-chip router, polarization multiplexing

Randomized quantum measurements in quantum information processing

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ABSTRACT
Quantum measurements are the key for extracting information from quantum systems and for connecting the quantum world with the classical world. For many applications in quantum information processing, randomized measurements have proved to be much more efficient in information extraction. In this talk I will discuss the applications of randomized measurements in various tasks, including verification of quantum states, gates, and computation, estimation of linear properties (say fidelity) and nonlinear properties (say purity), certification of (high-dimensional) entanglement, and the learning of unitary channels. In addition, I will explore the efficiency limits of these tasks and highlight the peculiar roles of quantum resources, such as entanglement and nonstabilizerness (magic).

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KEYWORDS
Randomized quantum measurements, Shadow estimation, Clifford Group, Magic, fidelity estimation

Transient entanglement generation in driven chiral networks beyond the secular approximation

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ABSTRACT

We study transient entanglement generation between two quantum nodes coupled through a chiral one-dimensional channel. In an emitter-only Born-Markov description, we show that continuous driving and an initial ground state can raise the maximum transient concurrence above the undriven 2/e benchmark associated with the effectively single-excitation model [1]. We then consider a more microscopic XX spin-chain channel with triangular plaquette couplings and compare a nonsecular time-convolutionless master equation (TCL-ME) with matrix-product-state (MPS) simulations. In the optimal driven regime, the nonsecular TCL-2 treatment reproduces the concurrence envelope and first transient peak qualitatively, while the remaining discrepancy is mainly attributable to beyond-Born system-bath correlations. The enhancement is traced to the failure of the secular approximation under strong driving, where nearby dressed transitions are not well separated on the dissipative timescale and nonsecular terms mix dressed-state coherences. Finally, we examine within TCL-2 the sensitivity of the protocol to positional disorder, imperfect chirality, and loss into nonguided modes. These results clarify when the familiar 2/e limitation ceases to apply and separate the roles of secular breakdown, Born-factorization error, and reduced-state memory in driven chiral entanglement generation.

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KEYWORDS

Waveguide QED, Open Quantum Systems, Entanglement Generation

Microscopic Dynamics in Simulating Lattice Gauge Theory with Ultracold Atoms

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ABSTRACT

Exploring the fundamental structure and basic laws of the universe constitutes an essential drive to physicists. The studies of ultracold atoms have built a bridge between the principles of microscopic world and the emergent macroscopic matter world. One can prepare and manipulate synthetic quantum material to simulate strongly correlated quantum many-body system with microscopic techniques to solve formidable tasks for the state-of-the-art supercomputers. I will introduce our recent research on one of such synthetic quantum material, the lattice gauge theory (LGT). We implemented a U(1) LGT Hamiltonian with ultracold atoms trapped in optical lattices and studied the relevant properties of gauge invariance, thermalization dynamics and quantum criticality.

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Hilbert Space Fragmentation in a Rydberg Atom Array

Hilbert space fragmentation, where the Hilbert space has been shattered into exponentially many disconnected subspaces, is a form of ergodicity breaking that can lead to rich dynamics in interacting quantum systems. In this talk, I will present our insights on realizing a broad class of Hamiltonians with Hilbert space fragmentation and discuss the implications of the Hilbert space structure on the quantum dynamics of Rydberg atom arrays. First, we uncover generalized quantum many-body scars arising from Z_{2k}-ordered initial states. In addition, we find that quantum thermalization proceeds in a way that is restricted to a particular Hilbert space fragment. Notably, thermalization between states belonging to different subspaces is precluded, even when these states have the same energy, defying expectations from the eigenstate thermalization hypothesis. Finally, we present the first experimental signatures of statistical localization in a constrained lattice gauge theory model, where expectation values of all conserved quantities remain locally distributed in typical quantum states, even though they are described by nonlocal string-like operators. Our work enables new capabilities on engineering far-from-equilibrium dynamics with control of the Hilbert space structure.

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A promising platform: from quantum advantage to universal fault-tolerant quantum computing

In recent years, several demonstrations of quantum advantage have drawn tremendous attention to its potential applications in specific areas. However, a critical leap in the quantum technology revolution—from the Noisy Intermediate-Scale Quantum (NISQ) era to universal fault-tolerant quantum computing remains the elephant in the room. This talk will focus on how the strengths of the neutral atom platform can break the "quantity-quality" paradox and our efforts to build a quantum machine with an exceptionally large scale of qubits and high-fidelity quantum gates. Several milestones have been established in our hardware development roadmap, including but not limited to scaling up the number of qubits, optimizing the fidelity of single-qubit and two-qubit gates, improving coherent transport, enabling parallel manipulation, and so on. Meanwhile, in collaboration with our partners, we have designed a blueprint for implementing efficient quantum error correction (QEC) codes (e.g., surface codes, color codes, qLDPC codes, etc.) on our quantum processor, whose layout is closely integrated with GPU-FPGA-QPU architecture.

We experimentally realized optical parametric down-conversion in the Langevin regime on a chip. By precisely controlling the loss inherently tied to fluctuation, we also observed the asymmetric Hong-Ou-Mandel dip—a hallmark of quantum fluctuation in the fluctuation-driven parametric down-conversion—and the fluctuation-induced compression of single photons. Our findings pave the way for manipulating quantum fluctuations, quantum states, and system-reservoir interactions.

Quantum computing platforms—including trapped ions, Rydberg atoms, superconducting circuits, and photonic systems—are rapidly advancing from physical to logical qubits with high-fidelity gates and versatile controllability. In this talk, I present our recent progress in quantum algorithm design for both combinatorial optimization and finite-temperature quantum simulation.In the first part, I address the challenge of encoding NP-hard optimization problems into atomic quantum systems. Using atom-cavity architectures with all-to-all connectivity, we show that the Number Partition Problem, vertex cover, 3-SAT, and general binary optimization (QUBO) can be efficiently mapped onto the cavity-mediated interactions with only linear overhead in atom number—a significant improvement over previous local architectures that require quadratic or cubic scaling. We classify a broad range of NP-complete problems by their encoding complexity into the atom-cavity Hamiltonian, identifying problems with linear, quadratic, and quartic scaling.
In the second part, I introduce the Quantum Kernel Function Expansion (QKFE), a method that converts quantum dynamics into quantum thermodynamics. By expanding the density of states in a Fourier series whose coefficients are efficiently measurable on a quantum computer, we obtain the free energy, thermal entropy, and heat capacity as analytic functions of temperature—without variational optimization. I present experimental realizations on the Zuchongzhi superconducting processor using both fully digital and hybrid digital-analogue protocols, demonstrating finite-temperature phase transitions in transverse-field Ising and XY models.

Fault-tolerant resource estimation must be driven by algorithms rather than hardware assumptions alone. In the fault-tolerant regime, different algorithms impose different requirements on logical operations, circuit depth, measurement schedules, magic-state consumption, code distances, runtime, and physical-qubit overhead. This work presents an algorithm-aware view of fault-tolerant resource estimation and organizes the current landscape into several key components: algorithmic workload characterization, logical-level compilation, error-correction overhead, architecture-dependent implementation, and end-to-end cost modeling. We review recent progress in these directions and emphasize that realistic resource estimates require a co-design perspective connecting algorithms, fault-tolerant protocols, and hardware architectures

Trapping over 10,000 individual atoms in a tweezer array by a single metasurface

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Tsinghua University

Abstract:

The scalability of physical qubit numbers is a central challenge toward a universal fault-tolerant quantum computer. Here, we robustly trap over 10, 000 individual atoms in a tweezer array, enabling the trapped qubit resource to enter the tens-of-thousands scale. This advance is enabled by a single metasurface, 1.98 cm in diameter, that generates the entire tweezer array from a Gaussian beam without the need for microscope objectives, maximizing laser power efficiency. The large aperture of the metasurface ensures a working distance of 1.5 cm, allowing the metasurface to be placed outside the vacuum cell and avoiding the technical complications of in-vacuum operation. We further characterize the randomly loaded atom array using the statistical theory of percolation phase transitions. This work takes an important first step toward a quantum computer at the 10,000-qubit scale.

In the second part, I will show our new setup integrating high-cooperativity cavity with atomic array. Our millimeter-scale Fabry–Pérot cavity reach the single-atom cooperativity of 125, with high resolution microscopes (NA=0.65) for addressing and imaging individual atoms in optical tweezers in the cavity mode. Atom-cavity transmission spectra of trapped atoms yield an effective spectroscopic cooperativity above 110, providing an in-situ verification of strong coupling in the integrated platform with up to 16 individually trapped atoms at the anti-node of the cavity mode. This setup enables us to investigate entanglement with programmable many-body interactions.