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P-001

Quantum Circuit Optimization with Hierarchical Reinforcement Learning

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The practical implementation of quantum algorithms on Noisy Intermediate-Scale Quantum devices encounters significant constraints due to hardware limitations [1]. These limitations necessitate the design of optimized quantum circuits with fewer gates and shallower depth for a given computational task. However, the optimization of quantum circuits presents major challenges due to the combinatorial nature of various circuit transformations and the exponential scaling of the search space faced by autonomous agents.

To address these challenges, we propose a scalable framework called Hierarchical Reinforcement Learning for Quantum Circuit Optimization (HRL-QCO), specifically designed to minimize gate count and circuit depth. HRL-QCO mitigates the curse of dimensionality by implementing a hierarchical policy that decouples rule selection from position selection. This decoupling greatly improves training efficiency.

To demonstrate how our methodology works, the HRL-QCO agent is applied to various random quantum circuits composed of either Pauli and CNOT gates or Clifford and T gates. We show that the agent achieves substantial optimization of the original quantum circuits while preserving the original functionality, yielding mathematically equivalent yet more efficient quantum circuits. This work provides a flexible and robust approach that can accelerate quantum circuit compilation and optimization, paving the way toward future fault-tolerant and utility-scale quantum systems.

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P-002

Quantum Parallelism in Random Number Generation via Quantum Circuits: Prospects for Quantum Heuristic Algorithms

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This work presents a comparative evaluation between quantum and classical random number generation, with a focus on quantum circuits implemented in Qiskit. By exploiting quantum parallelism, we demonstrate that quantum circuits yield fundamentally superior random number engines relative to classical approaches, measurable both in entropy quality and sampling efficiency. Quantum parallelism enables simultaneous evaluation of multiple bit states, thus offering unrivaled scalability for stochastic sampling tasks. Such quantum random engines are key for emerging quantum heuristic optimization techniques, including Quantum Genetic Algorithms (QGA) and Quantum Immune Algorithms (QIA). QGA integrates quantum bits and quantum gates to encode, evolve, and optimize populations in superposition, facilitating diverse solution exploration and rapid convergence for complex problems. QIA leverages quantum features to enrich the adaptive mechanisms of immune-inspired search, enhancing recognition and diversity retention. As quantum hardware advances, these quantum circuit-based engines are poised to serve as foundational modules for next-generation optimization, AI, and cryptography, providing practical quantum advantage wherever randomness and parallel solution search are critical.[1][2][3][4][5]

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P-003

Efficient Direct Quantum State Tomography Using Fan-out Gates

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Quantum State Tomography provides complete information about a quantum system but becomes impractical for large systems due to its exponential resource requirements [1]. Direct measurement offers an efficient alternative by extracting wavefunction information without extensive post-processing [2]. While early implementations relied on weak measurements, strong-measurement strategies have recently shown superior accuracy and scalability [3].

In this work, we introduce Direct Quantum State Tomography (DQST), a strong-measurement protocol that reconstructs the full density matrix through a single-depth fanout coupling between a meter qubit and system qubits, followed by measurements of the meter qubit in the X and Y basis. DQST requires only $2^{(n+1)}$-1 circuits to reconstruct an n-qubit state, achieving a substantial reduction compared to conventional QST. Experiments on IBM quantum hardware demonstrate reconstruction of four-qubit states with fidelities above 97%. Moreover, DQST enables single-circuit estimation of GHZ-state fidelity, allowing direct verification of genuine multipartite entanglement for up to 20 qubits.

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P-004

Entanglement-enabled advantage in distributed quantum machine learning

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Distributed quantum computing has emerged as a promising paradigm in the NISQ era, where multiple small processors cooperate to solve problems beyond the reach of individual devices. This approach relies on the quantum internet, which connects distant quantum nodes; however, communication latency poses a major obstacle. Pre-shared entanglement provides an efficient alternative, since it can be generated in advance and used without real-time signaling. Though entanglement alone cannot transmit information, it can reduce communication complexity in specific scenarios—known as communication complexity problems (CCPs)[1], such as the CHSH game—which are structurally similar to long-distance distributed quantum computation based on entanglement.

Here we implement distributed quantum machine learning (DQML) using two 4-qubit processors to classify 8-dimensional binary datasets with varying numbers of pre-shared Bell pairs. By analogy with the CHSH game, we show that entanglement enhances classification accuracy, with the gain depending on the embedding structure and loss function. In synthetic datasets, entanglement improves classification accuracy by up to 30%, with greater gains for complex data. Notably, we find that excessive entanglement could degrade accuracy, suggesting that an optimal level of entanglement is crucial. These findings highlight entanglement as a practical resource for distributed quantum machine learning beyond coherence-time limits.

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P-005

Bimodal switching current distributions in topological Josephson junctions

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Majorana zero modes (MZMs) in topological superconductors are promising for realizing fault-tolerant quantum computing, yet their conclusive detection remains elusive. Conventional experimental signatures such as zero-bias conductance peak and Shapiro-step doubling can arise from nontopological effects, leading to ongoing controversy over MZM confirmation. Although a bimodal switching current distribution (SCD) has been theoretically predicted in topological Josephson junction (JJ) [1], experimental evidence has been lacking. Here, we report the observation of bimodal SCDs in JJs based on Sb-doped Bi_2Se_3 topological insulator nanoribbons. The bimodal SCDs emerge at low temperatures below 0.5 K and are attributed to a double-well Josephson potential formed by the coexistence of 2π-periodic conventional and 4π-periodic topological supercurrents. Furthermore, microwave-irradiated measurements reveal the absence of the first (n = 1) Shapiro step, confirming the presence of a 4π-periodic supercurrent. The simultaneous observation of bimodal SCDs and missing Shapiro steps provides a more reliable route toward verifying MZMs in topological JJs.

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P-006

Unimodal switching current distributions of Al-InAs 2DEG-Al Josephson junctions

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Majorana zero modes (MZMs) are essential for realizing fault-tolerant quantum computing, yet their experimental verification remains challenging. Topological Josephson junctions (JJs) exhibiting a 4π-periodic current-phase relation are expected to show missing Shapiro steps, often regarded as a potential signature of MZMs. However, such behavior can also originate from non-topological Landau–Zener transitions (LZTs). Theoretically, a bimodal switching current distribution (SCD) has been proposed as an alternative indicator in topological JJs [1]. We fabricated highly transparent Al/InAs two-dimensional electron gas (2DEG) JJs operating in the ballistic regime and investigated their Shapiro steps, SCDs, and multiple Andreev reflections. While the first Shapiro step missing was observed at low temperatures, the SCD remained unimodal, implying a single-well Josephson potential. Subgap conductance analysis revealed a superconducting gap $\Delta = 156$ μeV and junction transparency $\tau = 0.8$. These results indicate that the missing Shapiro step in Al/InAs 2DEG JJ originates from LZTs rather than topological Josephson effect. Complementary measurements of Shapiro steps and SCDs provide a more reliable MZM verification in topological JJs.

Recent progress in superconducting quantum processors has accelerated the demand for

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P-007

Gate-tunable superconducting qubit based on Cd3As2 Dirac semimetal nanowires

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We demonstrate gate-tunable superconducting qubits based on Cd3As2 Dirac semimetal nanowires (NWs). The Cd3As2 NWs, contacted with Ti/Al superconducting electrodes to form Josephson junctions, are integrated with NbTi-based superconducting resonator circuits, while the Josephson junction properties are controlled electrostatically via side gate voltage. The qubit frequencies are adjustable from 1.5 to 4.3 GHz, attributed to gate-voltage-dependent modulation of the Josephson energy. Time-domain measurements demonstrated coherent Rabi oscillations with a decay time of approximately 8.8 ns, with the Rabi frequency scaling linearly with drive amplitude. These results represent the first demonstration of gate-tunable topological Dirac material-based gatemons, advancing the development of topological quantum computing architectures.

P-008

Magneto-optical properties of nitrogen vacancy centers in diamond upon different stress

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Recently, efforts have been made to utilize the NV^- center for probing the magnetic and superconducting properties of materials under extreme conditions. Doherty *et al.* observed greatly diminished spin readout contrast under hydrostatic pressure at 60 GPa [1]. To overcome this limitation, several studies have explored various types of stress and reported that uniaxial (111) stress applied along the N-V_C axis can preserve a reasonable spin-readout contrast even up to 100 GPa [2, 3]. It is also known that applying uniaxial (111) stress induces additional stress components perpendicular to the N-V_C axis. To shed light the comprehensive properties of the NV^- center under extreme conditions, it is therefore crucial to investigate the effect of each individual stress components. In this work, we perform first-principles density-functional theory calculations to investigate key quantities of the NV^- center such as the ionization potential, zero-field splitting, and zero-phonon line under different stress. Our findings offer valuable insights into the stress-induced properties of the NV^- center in diamond, with potential applications in quantum information science.

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P-009

Erbium and its Complexes in Rutile TiO_2: A First-Principles Study

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Erbium-doped TiO_2 is a promising candidate for solid-state quantum emitters [1-3]. Previous studies have shown that erbium doping in TiO_2 induces oxygen vacancies, which cause lattice distortions, leading to enhanced nonradiative decay and shortened photoluminescence lifetimes [4]. However, a comprehensive understanding of erbium dopants and its defect complexes, including native defects, remains limited. In this study, we investigated point defects such as native defects, erbium dopants, and erbium related complexes in rutile TiO_2 using first-principles calculations. Our results indicate that Er^{3+} preferentially occupies the Ti^{4+} substitutional site (Er_{Ti}), consistent with experimental observations [4]. Moreover, the Er_{Ti}-V_O complex, formed between Er_{Ti} and oxygen vacancies (V_O), is energetically favorable. Interestingly, we found that V_O tends to be slightly separated from Er_{Ti}, which is also consistent with experimental findings [4]. We suggest that this stability mainly arises from atomic relaxation effects. We believe that our results provide insights into the defect engineering of Er dopants in TiO_2.

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P-010

Error correction for Rydberg-blockade-based maximum weighted independent set embedding

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Recently, an optical tweezer-arranged Rydberg atom system demonstrated the solution of the unit ball maximum weighted independent set (MWIS) problem [1–3], a special type of graph-coloring problem in the NP-complete class, by exploiting the Rydberg blockade mechanism [4]. However, since the blockade acts only locally, it cannot directly impose arbitrary connectivity, such as that required to realize non-unit-ball graphs. To overcome this, an embedding strategy [5] introduces auxiliary atoms, or gadgets, to realize effective long-range interactions. Three major embedding schemes have been proposed so far: the parity architecture [6], the crossing lattice [7], and the quantum wire [3, 8]. While these gadgets preserve logical relations among atoms, a clear method for applying error correction has been lacking.

Here, we develop an error correction algorithm tailored for Rydberg-blockade-based embeddings. Our method utilizes blockade information within each superatom, an internally blockaded atomic cluster forming a gadget, by counting Rydberg excitations to efficiently detect errored clusters. When a unique correction exists, it is applied directly; otherwise, the cluster is expanded. We benchmark our approach on two planar embeddings, the parity architecture and the crossing lattice, with a focus on the all-to-all connected case. The proposed cluster-based algorithm shows a clear threshold behavior under the independent and identically distributed (i.i.d.) error model, with a threshold physical error rate of 0.32 and 0.23 for the minimum configurations of the parity architecture and the crossing lattice, respectively. Moreover, it outperforms the Ebadi22 greedy algorithm [2]. Our approach offers a new route toward hardware-motivated error correction in Rydberg-based quantum optimization.

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P-011

First Demonstration of Quantum Lattice Boltzmann Fluid Simulations on Noisy Quantum Hardware

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Quantum computing offers a promising framework for computational fluid dynamics (CFD) [1-6], with the quantum lattice Boltzmann method (QLBM) providing a natural mapping onto quantum circuits [4-6]. While most previous studies have been limited to noiseless simulators [4-6], this work demonstrates the feasibility of executing QLBM on real quantum hardware. We perform comparative simulations on IBM's 127-qubit superconducting processor and IonQ's 36-qubit trapped-ion device, solving a two-dimensional Gaussian hill governed by the advection–diffusion equation [4]. Accuracy is evaluated using the root mean square error (RMSE). Due to short coherence times, IBM hardware did not yield meaningful results, and noise-mitigation techniques showed no significant improvement. In contrast, IonQ achieved RMSE ≈ 0.11, further reduced to ≈ 0.07 with mitigation strategies such as Pauli twirling, and dynamic decoupling. These findings highlight the advantage of trapped-ion hardware for quantum CFD and demonstrate the effectiveness of practical noise suppression strategies. The value of this study lies in bridging the gap between simulator-based QLBM research and real-device implementation. By establishing a systematic framework to compare different hardware platforms and quantify the impact of noise mitigation, this work provides essential insight into how near-term quantum computers can contribute to the long-term goal of scalable quantum fluid dynamics.

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P-012

Decoherence dynamics of diamond NV spin ensembles in the presence of paramagnetic defects: a cluster-correlation expansion study

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Nitrogen-vacancy defects in diamond (DNV) have emerged as a promising platform for quantum sensing applications. One of the main challenges in their practical use is the rapid spin decoherence induced by electronic spin baths in diamond, including nitrogen (P1 centers), hydrogen, vacancies, and their complexes. In this study, we systematically investigate the DNV decoherence in the presence of paramagnetic (PM) defects from first-principles in which the spin decoherence dynamics are elucidated using the quantum many-body cluster-correlation expansion (CCE) method, and the electronic structures of PM defects are computed using density functional theory (DFT). First, we examine the contribution of P1 baths—the most common type of defect—under Hahn-echo [1] and dynamical-decoupling pulse sequences [2] for varying P1 concentrations and numbers of π pulses. Our quantum-mechanical simulations show better agreement with experimental T_2 behaviors as a function of P1 density and pulse number compared to predictions from a widely used semi-classical theory, thereby providing a more accurate microscopic understanding of P1-induced decoherence. Second, we analyze mixed spin baths composed of P1 and other PM defects, categorized into two groups: nitrogen-related defects (NV^-, NV^0, NVH^-, and N_2^+) and vacancy/hydrogen-related defects (VH^0, VH^-, V^0, V^-, and V^+) [3]. For nitrogen-related mixed baths, we find that bath inhomogeneity can enhance coherence times at low total PM defect concentrations. In contrast, the presence of vacancy/hydrogen-related defects leads to a further reduction in T_2 in P1-dominant environment. Finally, our theoretical predictions show excellent agreement with experimental measurements. This study provides an in-depth understanding of how electronic spin defects affect NV-center decoherence and offers essential insights for guiding future experiments and optimizing the performance of diamond-based quantum sensing devices.

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P-013

First-principles prediction of quantum defect candidate in zinc oxide

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Zinc oxide (ZnO) is an attractive platform for spin-based quantum technologies, combining a wide bandgap, low nuclear spin noise, and potential for ultra-high purity. Yet, its potential to host deep-level quantum defects has remained largely unexplored. Here, we use first-principles calculations to demonstrate that ZnO supports a defect family of spin-photon interface: a transition-metal vacancy complex, $(MoZn\text{-}vO)^{2+}$ [1]. $(MoZn\text{-}vO)^{2+}$ combines a spin-triplet ground state with strong spin–orbit coupling, which may enable a high-fidelity optical readout. Remarkably, $(MoZn\text{-}vO)^{2+}$ also achieves the lowest Huang–Rhys factor reported in ZnO (~5), ensuring high quantum yield. This quantum defect candidate is thermodynamically stable, charge-state robust under optical excitation, and exhibits visible-range zero-phonon line with high radiative efficiency. Our finding positions ZnO as a versatile host for quantum defects and establish a transferable framework for discovering new quantum defects across wide-bandgap oxides.

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P-014

Magnetic-field dependent V_B^- spin decoherence in hexagonal boron nitrides: a first-principles study

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The negatively charged boron vacancy (V_B^-) in h-BN is a spin-1 defect that serves as an optically addressable qubit in 2D materials.[1-3] Understanding its spin decoherence is crucial for advancing it into a robust qubit platform. In this work, we employ first-principles quantum many-body simulations to investigate the decoherence of V_B^- in dense nuclear spin baths of h-BN under magnetic fields from 0.01 to 3 T, considering isotopic variants h-$^{10}B^{14}N$, h-$^{11}B^{14}N$, h-$^{10}B^{15}N$, and h-$^{11}B^{15}N$.[4,5] We identify a transition boundary (TB) where the dominant decoherence mechanism changes. Below the TB, sub-microsecond decoherence arises from independent nuclear spin dynamics, whereas above it, pairwise flip-flops dominate, extending T_2 to tens of microseconds. Analytical predictions place the TB at 0.502 T for h-$^{10}B^{14}N$ and 0.205 T for h-$^{11}B^{14}N$. The larger TB in h-^{10}BN results from the larger nuclear spin of ^{10}B ($I = 3$), which produces stronger nuclear modulation over a wider field range. The analytical approach also explains the magnetic-field-insensitive fast modulation observed below the TB. These findings elucidate the role of dense high-spin nuclear environments ($I \geq 1$) in V_B^- decoherence and provide isotopic design principles for h-BN spin qubits.

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P-015

Coherence time of NV center under dynamical decoupling in a mixed electronic spin bath in diamond: a cluster-correlatiom-expansion study

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Diamond nitrogen-vacancy (NV) center is highly sensitive to changes in its surrounding environment, making it a promising candidate for quantum sensing applications. During the synthesis of NV centers, various defects such as nitrogen impurities (P1) have been experimentally introduced in diamond. These defects have been identified to contribute to the decoherence of NV centers [1]. Theoretical studies have primarily focused on P1, leaving a gap in the understanding of the role of other defects in the NV decoherence. Ref.[1] reported that, under the application of CPMG dynamical decoupling pulses to NV centers, the experimentally measured coherence time (T_2) as a function of the number of pulses shows a trend consistent with T_2 calculated using cluster-correlation expansion (CCE) simulations considering only P1 bath spins. However, discrepancies remain between the measured and computed T_2 values. To address this issue, we use CCE method to compute the CPMG T_2 of the NV center in the presence of not only P1 but also other defects and we compare the results with experimental data. We seek to characterize the effects of defects beyond P1 that contribute to NV center decoherence under dynamical decoupling pulse sequences, providing guidelines to optimize the performance of NV-based quantum sensors.

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P-016

Quadratically Shallow Quantum Circuits for Hamiltonian Functions

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Many quantum algorithms for ground-state preparation and energy estimation require the implementation of high-degree polynomials of a Hamiltonian to achieve better convergence rates. Their circuit implementation typically relies on quantum signal processing (QSP) [1], whose circuit depth is proportional to the degree of the polynomial. Previous studies exploit the Chebyshev polynomial approximation [2], which requires a Chebyshev series of degree $O(n \ln(1/\delta))$ for an n-degree polynomial, where δ is the approximation error. However, the approximation is limited to only a few functions, including monomials, truncated exponential, Gaussian, and error functions.

In this work, we present the most generalized function approximation methods [3] for δ-approximating linear combinations or products of polynomial-approximable functions with quadratically reduced-degree polynomials. We extend the list of polynomial-approximable functions by showing that the functions of cosine and sine can also be δ-approximated by quadratically reduced-degree Laurent polynomials. We demonstrate that various Hamiltonian functions for quantum ground-state preparation and energy estimation can be implemented with quadratically shallow circuits.

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P-017

Progress on Bosonic circuit QED experiments

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Superconducting resonators are one of the promising continuous-variable platforms for quantum information processing and offer a versatile medium for simulating bosonic phenomena arising from their intrinsic harmonic nature. The physical realization of such systems typically consists of high-Q superconducting 3D cavities coupled to nonlinear ancilla elements, enabling non-Gaussian operations and bosonic state readout. We report recent progress from our group in bosonic circuit-QED experiments, including system design, electromagnetic simulation, cryogenic characterization, and calibration approaches. Furthermore, we discuss our ongoing efforts toward the preparation, coherent control, and measurement of single bosonic states, as well as future system optimization and scale up of the system.

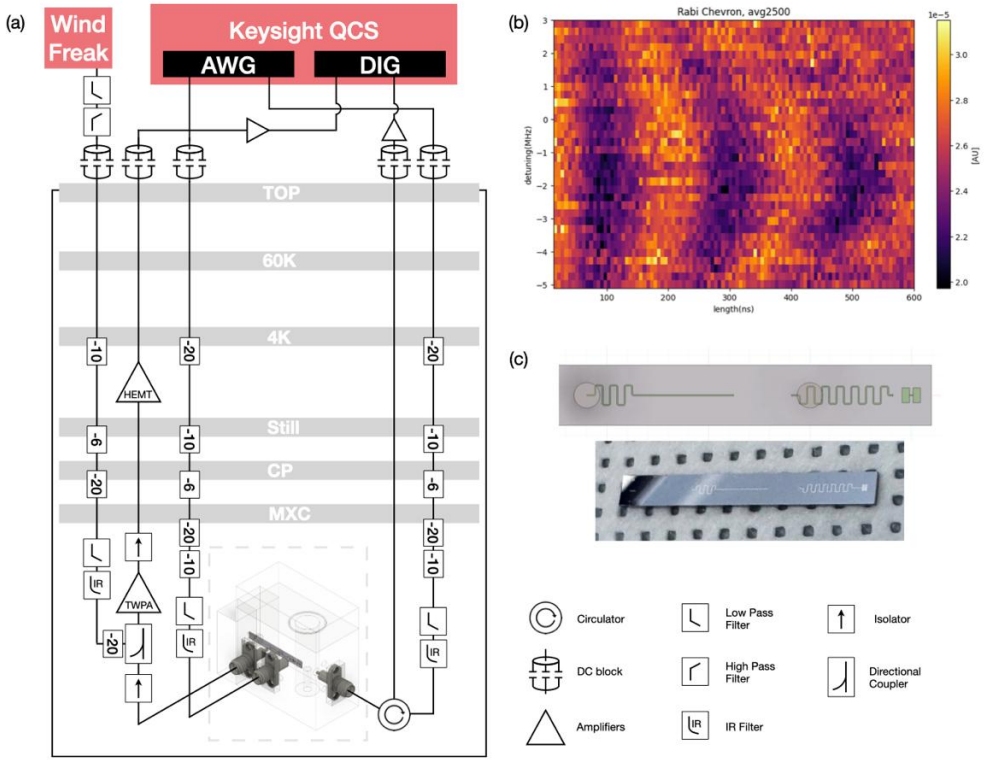

Fig.1. (a) Simplified schematic of the experiment setup. Device is cooled down to the around 10mK and manipulated using microwave pulses. The cavity body is machined from 99.999% pure Aluminum, while the transmon chip is fabricated on a high-resistivity silicon wafer. Micrometer scale structures are patterned with Nb and JJ is realized with Al (Manhattan style) (b) Rabi chevron data obtained from the experiment setup. (c) Design layout and optical image of the device chip. From right to left, the transmon qubit, readout resonator, and Purcell filter are shown. The transmission signal is used for measurement in the experiment.

P-018

Adaptive neural network holography with genetic algorithm for enhanced atom rearrangement in optical tweezer traps

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Constructing optical tweezer arrays with diverse geometries is a major strength of neutral-atom quantum platforms, particularly for quantum simulations and computations requiring flexible qubit connectivity. Since single-atoms are stochastically loaded into individual tweezer traps, rearranging traps to form defect-free arrays is a crucial experimental technique [1]. In that context, dynamic holographic optical tweezers, where all optical traps can be simultaneously moved by sequentially displaying holograms, offer a promising route toward large-scale atomic arrays. One key challenge, however, lies on rapidly retrieving the appropriate hologram during atom rearrangement. Recently, two neural-network-based approaches have been proposed to accelerate hologram generation. One employs a convolutional neural network (CNN) with residual blocks to estimate the target amplitude followed by inverse Fourier reconstruction [2], while the other augments the Gerchberg–Saxton (GS) algorithm by integrating a neural module into its iterative process [3]. Compared with these approaches, further improvement in both accuracy and computational efficiency remains desirable. We present a genetic-algorithm-driven neural-network model that embeds both Fourier and inverse Fourier transforms within the network. The neural layers are optimized using a genetic algorithm, enabling active control to find an optimal trade-off between hologram-generation speed and rearrangement fidelity. The neural-network is trained to directly optimize target parameters, offering greater flexibility. We have tested our approach to the rearrangement of 4x4 two-dimensional optical tweezer arrays, achieving a speed improvement by a factor of 30 in hologram inference compared with the GS-based approach.

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P-019

Adjusted Detuning for Ground-Energy Leakage Blockade in Maximum Independent Sets with Rydberg atoms

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Quantum computing using Rydberg neutral atoms has shown remarkable experimental progress in recent years. Among the potential applications, adiabatic quantum computation (AQC) provides a practical route to solving combinatorial optimization problems efficiently. Many such problems can be naturally mapped onto the Maximum Independent Set (MIS) problem, which Rydberg atom platforms can compile directly [1]. A major bottleneck in solving hard MIS instances, particularly those with a large degeneracy ratio between the ground and first-excited states, is the super-exponential decrease of the minimal spectral energy gap ($g_{\min}$) with system size. In these cases, the required adiabatic evolution time scales as $1/g_{\min}^3$ [2], making it difficult to reach the optimal MIS solutions within a limited coherence time. Consequently, population leakage from the ground-state to the first-excited state becomes inevitable. Here, we study the ground-to-excited state dynamics near the minimal spectral energy gap. For a fixed evolution time, we introduce the Adjusted Detuning for Ground-Energy Leakage Blockade (ADGLB) method, which optimizes the sweep of laser detuning in the vicinity of the energy gap to suppress population leakage from the ground state and thereby maximize the MIS population. We benchmarked this method using k-PXP chains [3], where the hardness parameter (HP) is large and the energy gap is small. Experiments on the QuEra Aquila machine via Amazon Bracket Service [4] demonstrated a performance improvement of approximately 50% in MIS accuracy for an $N = 13$ k-PXP chain ($\mathrm{HP} = 11.4$) (ADGLB 23.3%, Conventional scheme 15.4%).

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P-020

Spin Qubits in Strain-Engineered Graphene Quantum Dots

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Graphene provides an exceptional platform for quantum information technologies due to its high carrier mobility, long spin coherence. However, realizing qubits in pristine single-layer graphene is hindered by the absence of an intrinsic band gap, which complicates electrostatic confinement. To address this challenge, strain engineering has been proposed as a promising approach that induces robust quantum confinement by generating pseudo-magnetic fields and localized energy gaps, thereby forming well-defined quantum dot (QD) states without introducing chemical defects or stacking-induced disorder.

Recently, a systematic design framework for strain-induced graphene QDs has been established to realize charge qubits [1,2]. Building upon these developments, we incorporate spin degrees of freedom—specifically the Zeeman effect and Rashba spin–orbit coupling (SOC)—into the strain-induced QD platform to explore spin qubit behavior. Using tight-binding and quantum transport simulations, we investigate a double quantum dot (DQD) architecture and observe two distinct avoided level crossings corresponding to spin-conserving (at zero detuning) and spin-flip (at finite detuning) transitions. We further demonstrate coherent spin manipulation in this platform and characterize Rabi oscillation dynamics driven by the interplay of Rashba SOC, Zeeman fields, and gate-tunable electrostatic potentials.

These results establish strain-engineered graphene DQDs as a viable platform for a scalable spin qubit. By bridging materials physics and quantum device engineering, our study aligns with the broader goal of advancing quantum science and technology and identifying practical pathways toward next-generation quantum information processing.

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P-021

Native iSWAP entangling gates for Rydberg atoms

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Entangling gates are a fundamental resource for implementing most quantum algorithms. Here, we introduce iSWAP gates for neutral-atom platforms. While iSWAP gates in combination with CZ gates have shown advantages in reducing circuit depth, improving the speed-up [1–4] and providing novel ways of implementing Quantum Error Correction (QEC) codes [5, 6], their realisation within neutral-atom systems has not yet been systematically investigated.

We present a new family of fast, high-fidelity two-qubit iSWAP-like protocols obtained via GRAPE-like optimal control techniques [7]. By encoding the qubit states of each atom in two low energy states, laser coupled to two highly excited Rydberg states, we natively implement an XY-type exchange interaction mediated by the dipole-dipole coupling between the Rydberg states. We further analyse the performance of these protocols under realistic noise sources, including experimentally motivated laser noise models, and discuss their sensitivity and potential mitigation strategies. For a ^{88}Sr-based architecture, we demonstrate that gate fidelities below 10^{-3} are attainable, suggesting that Rydberg-mediated exchange interactions may provide a promising route towards a large-scale implementation of quantum algorithms, surpassing the surface-code threshold for error correction.

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P-022

Parabolic Mirror based Efficient Quantum Node with Neutral Atoms

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Building quantum networks that interconnect multiple quantum processors is a central goal in quantum information science, enabling capabilities such as remote entanglement, distributed quantum computing, and quantum sensing. Achieving this requires a robust and scalable platform that can serve as a building block of a quantum network.

In this work, we present a compact, plug-and-play quantum networking node where quantum information can be stored, processed, and distributed. The node is based on a parabolic mirror with a numerical aperture of 0.61, serving a dual purpose for atom trapping and efficient photon collection. It incorporates millimeter-scale, pre-aligned optical modules-including four out of six MOT beam modules, dipole trap module, and two GRIN modules for excitation and optical pumping- mounted on a Macor chip with fiber interfaces. The architecture provides a mechanically stable and optically efficient platform for quantum information processing while maintaining robustness against environmental drift.

Two parabolic mirror based nodes are currently operational. In one of them, we have demonstrated atom-photon entanglement with a fidelity exceeding 0.93 and a success probability of 3.6%, marking a key step toward realizing scalable, long-distance quantum networking.

P-023

Progress toward a high-fidelity quantum platform with ^{171}Yb neutral atoms

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Alkaline-earth-like atoms, especially ^{171}Yb, have attracted keen attention as promising candidates for second-generation quantum computing platforms. Owing to their rich electronic structure, including narrow-line singlet–triplet transitions, atoms trapped in magic-wavelength optical tweezers can encode nuclear-spin qubits that are intrinsically robust against magnetic-field fluctuations. This feature makes them highly suitable for realizing high-fidelity quantum gates with long coherence times. We present our experimental progress toward building a quantum computing platform based on ^{171}Yb atoms, to achieve high-fidelity two-qubit entanglement. A compact double magneto-optical trap (MOT) system has been constructed without a Zeeman slower. The blue (399 nm) and green (556 nm) MOT lasers are frequency-stabilized via modulation transfer spectroscopy (MTS) using a Yb hollow-cathode lamp and an iodine vapor cell, respectively. We have observed a 3D blue MOT for ^{171}Yb atoms, capturing up to 10^6 atoms with a peak density of $\sim 10^{11}$ cm^{-3}. This cold-atom ensemble serves as the source for the green MOT and for loading single-atom traps in our science chamber. Using a trapped single-atom array at either 532 nm or 486.78 nm, our future work will focus on developing techniques for high-fidelity and versatile quantum operations, including the realization of a triple-magic wavelength, active suppression of laser phase noise, Rydberg-state spectroscopy, and implementing resonant exchange interactions.

P-024

Quantum Teleportation Described in Visualized Concept

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Advances in quantum information science have increased interest in the limits of communication using quantum entanglement. Although entanglement creates nonclassical correlations between distant systems, it cannot be used to send information directly because of the no-communication theorem. To overcome this limitation, quantum teleportation was developed as a protocol that transfers an unknown quantum state by using shared entanglement together with classical communication.

In this work, the reason why immediate information transfer only by quantum entanglement is impossible will be explained based on no-communication theorem. As a alternative, we also explain the basic mechanism of teleportation using Bell-state measurements and describe how the protocol works without violating the no-communication theorem. It will start by describing the basis of quantum teleportation in mathematics such as how EPR pairs are described, how joint state is formed, what Hadamard gate and CNOT does in this mechanism, and finally how these concepts can be visualized in IBM Quantum Program.

This work is centered around fundamental concepts in quantum information science, primarily focusing how quantum teleportation can described and how these results are derived by visualization of quantum teleportation.

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P-025

Quantum simulation of the Hubbard model on a graphene hexagon: strengths of IQPE and noise constraints

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Quantum computing provides a powerful framework for simulating strongly correlated materials [1]. In this work, we leverage this capability to study the Hubbard model on a six-site graphene hexagon using Iterative Quantum Phase Estimation (IQPE) and adiabatic evolution. We show that, for small systems, a single Slater determinant is sufficient to initialize IQPE and recover ground-state energies (GSEs) with high accuracy. In noiseless simulations, IQPE converges rapidly to exact GSEs, while adiabatic evolution reproduces charge and spin densities and correlation functions in close agreement with exact diagonalization.

To examine realistic performance, we employ Qiskit Aer with a noise model reflecting IBM hardware, including depolarizing, relaxation, and readout errors. We further execute IQPE on IBM's ibm_strasbourg and ibm_fez devices for a reduced three-site system. Although ibm_fez yields results close to the exact values, residual deviations reveal the gap between simulated and physical noise. Extending our analysis up to six sites, we assess IQPE's scalability and highlight both its potential and its present limitations for simulating correlated electron systems on near-term quantum devices [2].

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P-026

Toward Quantum Advantage in Computational Chemistry: Hybrid Quantum Algorithms Applied to the Pyridine–Li^+ Complex

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Accurately describing electron correlation in large molecules is a central challenge in quantum chemistry and a driving force behind the development of novel quantum algorithms. Classical configuration–interaction methods, suffer from exponential scaling, preventing their application to large or strongly correlated molecular systems. Here, we apply VQE, SQD, and recently developed HI-VQE algorithms to the pyridine–Li^+ complex to discover how new generations of quantum algorithms effectively address the limitations of classical and earlier quantum approaches[1-3]. Although conventional VQE methods are constrained by limited scalability and noise sensitivity, the results obtained from SQD and HI-VQE demonstrate that hybrid quantum–classical frameworks can reach problem sizes inaccessible to classical computation. HI-VQE algorithm enables ground-state energy calculations for active spaces as large as (24e,22o), where classical, VQE and SQD become impractical. This capability is crucial because it offers a realistic pathway for quantum computers to evaluate exact molecular energies by systematically including more electrons within the quantum treatment. This method remains robust against hardware noise which represents a major improvement over VQE approaches. These results confirm HI-VQE as a scalable and robust framework that extends the current boundary of quantum algorithms, providing a viable pathway toward practical quantum advantage in computational chemistry.

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P-027

Quantum Monte Carlo Integration of Dose Distribution for Photon Radiation Therapy

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High-fidelity dose calculation is a still computationally intensive task in radiation therapy planning. While the Monte Carlo method is considered the gold standard, its clinical application is often hindered by long computation times. Quantum computing offers a potential pathway to accelerate these simulations. This work proposes and demonstrates a modular Quantum Monte Carlo Integration (QMCI) framework as a proof-of-concept for radiotherapy dose calculation. The framework consists of two main components: a Machine Learning method that learns and prepares the probability distribution of particle interactions, and a Quantum Amplitude Estimation (QAE) algorithm that evaluates the dose deposition integral with a theoretical quadratic speedup. We demonstrate the framework by calculating the depth-dose distribution for a 6 MeV photon beam, focusing on the dominant first-order Compton scattering events. On quantum emulator, our QMCI results closely reproduce the key features of the analytical and Geant4 reference depth-dose curves, validating the framework's potential as a scalable foundation for future, clinically relevant quantum applications in radiotherapy. In future work, our goal is to extend this framework from one-dimensional to higher-dimensional integrals in order to compute the final, clinically relevant dose distribution.

P-028

Flat Bands and Qubit-Tunable Edge States in a Hexagonal Circuit QED Lattice with Triple-Leg Stripline Resonators

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We theoretically investigate the quantum-geometric properties of a photonic hexagonal lattice built from triple-leg stripline resonators (TSRs) in a circuit QED system. Each TSR supports two-fold degenerate microwave modes that play the role of two orbitals per lattice site, leading to a four-band structure with Dirac cones and two flat bands at the top and bottom of the spectrum. Using a capacitance-based tight-binding model, we show that destructive interference stabilizes compact localized states (CLSs) which generate flat bands that touch neighboring dispersive bands quadratically, realizing singular flat bands. We further uncover the associated real-space topology by constructing appropriate non-contractible loop states (NLSs). For a zigzag ribbon geometry, we compute the Zak phase and demonstrate the emergence of topological zero-energy flat edge modes, as well as additional dispersive edge bands whose effective mass is dictated by the quantum distance around the singular band-touching point, thus establishing a geometric bulk–boundary correspondence. Finally, we propose to laterally couple superconducting qubits to the outer legs of edge TSRs, which enables qubit-tunable shifts of both flat and dispersive edge modes and makes them resolvable as pronounced reflection dips in microwave input-output spectroscopy. Our results provide a concrete route to probe and control quantum-geometric flat band edge physics in circuit QED photonic lattices.

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P-029

Investigation of the hyperfine structure and optical cycling scheme of fermionic ^{25}MgF molecules via LIF spectroscopy

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Magnesium monofluoride (MgF) molecules have emerged as promising candidates for laser cooling and trapping due to their light mass and ultraviolet optical transition in alkali-earth monofluoride diatomic molecules. Among the stable isotopologues, ^{25}MgF is of particular interest as a fermion, presenting distinct physical distinct from the bosonic ^{24}MgF and ^{26}MgF. However, unlike other bosonic MgF where the nuclear spin of Mg is zero, ^{25}Mg possesses a nuclear spin $I = 5/2$, which results in a much more complex hyperfine structure. Precise characterization of this energy scheme is a prequisite for implementing efficient laser cooling of ^{25}MgF.

In this work, we construct a rate equation-based simulation utilizing the effective Hamiltonian and dipole matrix elements of the $X^2\Sigma^+$ and $A^2\Pi_{1/2}$ state of ^{25}MgF to model the photon scattering rates in the Laser-Induced Flourescence (LIF) spectrum. Concurrently, we experimentally find the spectra of $\tilde{P}_{12}(N)$ and $\tilde{P}_{13}(N)$ transitions, where $N = 1, 2, 3$. By fitting the simulation to the experimental data, we estimate the hyperfine structure constants of $A^2\Pi_{1/2}$ state, reproducing the observed spectra with a reduced-chi squared(χ_r^2) 2.14. These results enable the effective design of the ^{25}MgF optical cycling scheme for laser cooling and trapping.

P-030

Assessing Two Quantum Algorithms for Molecular Energy Calculations

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For several decades, molecular energy calculation has attracted considerable interests among chemists. With advances in quantum technologies, research on quantum algorithms expected to outperform classical energy calculation methods especially for ground state has attracted increasing attention. However, in quantum algorithm research, multilevel system that characterize many photochemical and biochemical reactions have been insufficiently studied.

Here, we employ two quantum algorithms to compute multilevel system energies in conjugated molecules. Using exactly solvable Hamiltonian derive from the Hückel method, we verified that quantum algorithms successfully calculate molecular orbital energies. We further analyzed how circuit design affects the performance of these quantum algorithm and assessed the performance under noisy condition. The results demonstrated practically effective realizations in the noisy intermediate-scale quantum era for multilevel system.

P-031

Simulating Nonadiabatic Dynamics Using Variational Quantum Algorithms

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Nonadiabatic dynamics simulations are essential for understanding physicochemical phenomena such as photochemical reactions, excitation energy transfer, and charge separation [1]. When computed using classical approaches, the computational cost grows exponentially with system size. To overcome this challenge, researchers have been exploring strategies that leverage the computational advantages of quantum computing. Among these, variational quantum algorithms, which combine quantum circuits with classical computation to enhance efficiency, have recently emerged as one of the most actively studied topics [2].

In this study, we aim to perform Hamiltonian-based nonadiabatic dynamics within the variational quantum dynamics framework using parameterized quantum circuits (PQCs). Specifically, we investigate the multiset variational quantum dynamics algorithm (MS-VQD) [3], which has recently demonstrated significant accuracy even with shallow PQC depths by assigning distinct circuits to each electronic state in multi-electronic systems.

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P-032

Miniaturized NV-Diamond ensemble Magnetometer for Hidden Magnet Imaging and Meissner-Effect Visualization

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We present a miniaturized scanning magnetometer based on an ensemble of diamond nitrogen-vacancy (NV) centers, operated under ambient conditions and combined with a two-dimensional scanning setup to image static magnetic fields with millimeter-scale resolution. Using a lock-in detection scheme, we monitor shifts in the NV spin resonances induced by external magnetic fields and reconstruct magnetic-field maps above target samples. As a proof-of-principle demonstration for magnetic imaging of hidden objects, we employ a toy diorama containing concealed permanent magnets to emulate scenarios such as remote detection of buried landmines or locating embedded ferromagnetic structures at construction sites, focusing on image formation and analysis rather than optimizing sensitivity.

We show that the resulting magnetic images are strongly affected by the choice of detection frequency and by the magnitude and spatial distribution of the sample's magnetic field, and we find good agreement between measured images and magnetic simulations [1]. As a second application, we directly visualize the Meissner effect in a high-temperature superconductor (Yttrium Barium Copper Oxide, YBCO) by mapping the expulsion and distortion of static magnetic fields above the sample at temperatures above and below its critical temperature, in agreement with simulations and the expected behavior of superconductors. Furthermore, we propose an NV vector magnetometry–based approach to compensate for non-zero tilt angles of targets, enabling more accurate localization [2].

Our results establish room-temperature NV-based scanning magnetometry as a practical platform for visualizing superconducting phenomena and for detecting hidden magnetic objects with potential applications in military, industrial, and educational settings, and we are additionally preparing experiments to demonstrate a recently proposed NV-based thermometry scheme [3] on the same platform, highlighting its versatility for quantitative temperature sensing.

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P-033

Quantum metrology via quantum non-Gaussian states under noise

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Understanding how quantum principles govern the dynamics of quantum systems from microscopic to macroscopic scales is of foundational importance. It is equally important to identify how emerging quantum properties may be harnessed to achieve performance advantages beyond classical limits. Quantum metrology is one such pursuit, exploiting quantum resources to estimate unknown parameters with precision beyond classical limits [1,2].

One of the important tasks in quantum estimation is to measure an unknown phase shift in one arm of the Mach-Zehnder interferometer (MZI) [3]. This phase may arise from a difference in optical path length between the two arms, which forms the basis for measuring extremely weak signals, e.g. gravitational waves, using nonclassical states of light in interferometric experiments [4].

In this work, we investigate the enhancement and the robustness obtained by applying a non-Gaussian operation, specifically single-photon subtraction, to a Gaussian state under noisy conditions [5]. The resulting state is non-Gaussian, except when the input is a coherent state, and is experimentally feasible to prepare, making it a promising candidate for robust quantum metrology. Here, we investigate whether photon subtraction offers a quantum advantage under noise by comparing the performance of photon-subtracted Gaussian states with their original Gaussian counterparts.

We consider several relevant schemes for modeling a lossy and noisy environment in a MZI and for implementing single-photon subtraction. A two-mode squeezed vacuum (TMSV) state is used as input to the interferometer. To evaluate the effect of photon subtraction, we compare the performance of the photon-subtracted state with their original Gaussian counterpart by computing the quantum Fisher information [6].

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P-034

VUV-Free Laser Cooling of Neutral Carbon via Metastable State

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Laser cooling and trapping have become standard tools for preparing ultracold atomic samples used in quantum simulation, precision spectroscopy, and controlled collision studies. Despite its central role in chemistry, astrophysics, and atmospheric science, neutral carbon has not yet been brought into the laser-cooling regime. The main obstacle is that the relevant cycling transitions from the ground state lie in the vacuum ultraviolet (VUV), which makes a conventional cooling scheme technically demanding. To circumvent this, we propose an alternative route that operates entirely on long-lived excited states, specifically the metastable $^1D_2$ and $^1S_0$ levels, thereby avoiding any need for VUV light while still enabling an optical cycle.

In this study, we design a multi-stage protocol for laser cooling neutral carbon. A carbon vapor is first produced by laser ablation of a highly oriented pyrolytic graphite (HOPG) target and thermalized in a cryogenic helium buffer-gas cell, forming a cold, slow atomic beam. Under typical buffer-gas conditions, collisional quenching of the metastable manifold is expected to remain sufficiently weak so that a sizable fraction of atoms survives in the $^1D_2$ and $^1S_0$ states for subsequent optical manipulation. For the main cooling transition, we employ the strong electric-dipole line $^1S_0$ to $^1P^o_1$ 247.8 nm and use the metastable $^1D_2$ state as an intermediate reservoir that must be efficiently repumped.

A main difficulty is the extremely weak electric-quadrupole (E2) transition from $^1D_2$ to $^1S_0$. We demonstrate that by optimizing the polarization geometry under a bias magnetic field (e.g., ~0.5 G), the effective coupling strength can be maximized by avoiding dark states. Our calculations show that with attainable laser parameters, a scattering rate of ~30 kHz is achievable, enabling cooling without VUV sources.

P-035

Estimating the Trace Norm of Matrix Product Operators

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The trace norm is a widely used quantity in quantum information, crucial for diagnosing entanglement and quantifying distance between quantum states. We propose an efficient tensor-network method to estimate the trace norm ||A||_1 of matrix product operators (MPOs) A, which compactly represent physically relevant operators in quantum many-body settings, such as systems at thermal equilibrium or out of equilibrium. Using our tensor-network method based on rational approximation, we compute the entanglement negativity of various quantum many-body states, including cluster state under local decoherence. We further demonstrate that our method enables estimation of the quantum fidelity between MPOs.

P-036

Background free detection scheme for ^{24}MgF molecules

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Laser slowing of diatomic molecules is a starting point for cooling and controlling molecules. One way to slow down the diatomic molecules with complex internal structure is white-light slowing. While white-light slowing is frequently used to drive all necessary transitions, it inherently requires high-power lasers because the power is distributed across multiple frequency components. Furthermore, sharing the transition line between the laser slowing and the fluorescence detection severely degrades the signal-to-noise ratio (SNR).

Here, we present a background-free scheme to probe MgF molecules. We can achieve high SNR detection by utilizing the A^2\Pi \rightarrow C^2\Sigma^+ transition at a wavelength of 677 nm, and detecting C^2\Sigma^+ \rightarrow X^2\Sigma^+ decay, which is completely separated from the slowing transitions. This scheme will enable precise measurement of the laser slowing results, which facilitates easy optimization of the slowing parameters and ultimately contributes to the efficient production of ultracold molecules.

P-037

Scanning Gradiometry Using Diamond NV centers for AC Magnetic Field Detection

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Sensors offering nanoscale spatial resolution and high sensitivity are increasingly crucial for microscopic research and industrial applications. The nitrogen-vacancy (NV) center in diamond is a quantum sensor well-suited for highly sensitive magnetic field detection. Integrating this spin qubit with a scanning probe enables real-space, nanoscale imaging of both DC and AC magnetic fields. Here, we showcase DC and AC electrical current profiles measured using a novel technique that synchronizes dynamic-decoupling protocols with the driving signals of a single NV center integrated into an atomic force microscope (AFM) probe. This method is referred to as a gradiometry technique due to its capability to measure magnetic field gradients. The gradiometry technique for DC magnetic field signals was reproduced using current profile sample [1]. Furthermore, we demonstrated a novel gradiometry technique for detecting AC magnetic-field signals from the same current-profile sample, which enhances the phase accumulation of the electron spin in a single diamond NV center by down-converting the frequency of the target signals. A comparison between conventional magnetometry and this gradiometry method will also be provided. These results underscore the suitability of the single NV center magnetometry technique as a powerful tool for quantum magnetometry and gradiometry, highlighting its efficacy in high-performance nanoscale imaging.

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P-038

Magnetic Steganography Based on Wide-Field Diamond Quantum Microscopy

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Steganography, a technique for concealing information, has evolved from ancient practices to a vital tool for digital security and anti-counterfeiting [1]. While conventional optical methods are limited in revealing concealed features, quantum sensors offer new possibilities for secure imaging. In this work, we experimentally demonstrate magnetic steganography utilizing wide-field quantum microscopy based on diamond nitrogen-vacancy (NV) centers [2]. We fabricated microscopic structures, including pixel arts, barcodes, and QR codes, using a combination of magnetic (Ni) and non-magnetic (Au) materials. Although these structures appear identical under optical microscopy, the concealed magnetic information is clearly revealed through the high-sensitivity magnetic imaging provided by the NV centers. We compared three imaging modes—frequency shift, linewidth, and contrast—and found that the contrast mode offers the best quality for reconstructing hidden magnetic patterns. Furthermore, we implemented a dual driving method that simultaneously manipulates the NV's qutrit states, enhancing sensitivity and reducing the imaging time by a factor of three Our results suggest that wide-field quantum microscopy can serve as a powerful platform for advanced steganography applications.

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P-039

Enhanced Sub-MHz AC Magnetometry via Spin-Bath and Low-Frequency Noise Suppression in a Doubly Dressed Diamond Spin Qubit

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Pulsed dynamical decoupling (PDD) protocols are widely used in AC magnetometry, but they face significant challenges in the sub-MHz regime. Under typical low-frequency noise environments, the visibility of weak ac signals is strongly reduced. To overcome these issues, continuous dynamical decoupling (CDD) techniques have been explored. In this study [1], we carried out experiments using doubly dressed spin states, created through adiabatic transfer from the original bare qubit states. We show that this double-dressing scheme strongly suppresses both spin-bath and low-frequency noise, allowing stable detection of weak sub-MHz AC signals with a signal-to-noise ratio of about 17. This method also enhances coherence by a factor of 9.6. These results provide a viable pathway for detecting weakly coupled nuclear spins in low-field NMR and advancing sub-MHz AC magnetometry.

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P-040

A Hybrid Trusted/Untrusted Relay-Based Quantum Key Distribution Network Architecture for Military Communications Networks

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This paper proposes a Hybrid-Trusted and Untrusted Relay(HTUR)[1] QKD operational framework for the efficient and secure management of the Quantum Key Distribution Network(QKDN)[2,3] in heterogeneous military communication environments(wired, wireless, satellite). Conventional architectures, namely the high-efficiency Trusted Node(TN) method[4,5] and the high-security Measurement-Device-Independent(MDI) method[6,7], have distinct limitations, making a single solution inadequate for complex military networks. Based on the HTUR concept, the framework strategically deploys TN QKD in physically secured wired segments and MDI QKD in high-risk wireless/satellite links[8]. An AI-SDN-based[9] operational scenario is presented, enabling the control layer to dynamically analyze link quality and security levels to switch operational modes between TN and MDI in real-time. The HTUR-based military QKDN structure maintains a balance between security and efficiency, enhancing network resilience through flexible routing and rapid bypass capabilities. This paper provides unified structural guidance for continuous and secure quantum key distribution in multi-domain military networks, thereby contributing to the development of practical quantum-secure architectures for future military communication systems.

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P-041

Efficient Simulations of Fermionic Open Quantum Systems

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Fermions underlie the behavior of quantum materials, yet the standard model of quantum computation is qubit-based and must emulate fermionic statistics at a nontrivial overhead. This makes fermionic quantum computation models, where information is encoded directly in fermionic modes, highly relevant both for native fermionic hardware and for systematic mappings to qubit circuits. Within this context, fermionic Gaussian processes (generated by quadratic, possibly non-Hermitian Bogoliubov-de Gennes-type Hamiltonians and related channels) are especially important, since they admit efficient classical simulation and thus define a natural baseline for quantum advantage.

In this work, we develop a unified framework by reviewing existing classical simulation methods for fermionic Gaussian operations and introducing new techniques that fill the remaining gaps, building on Bravyi's fundamental framework [1] for classically simulating general fermionic Gaussian processes, including non-unitary evolution, measurements, dissipation, and random fermionic circuits acting on arbitrary "dressed" modes. We then apply these methods to two representative systems--the Kitaev Majorana chain and the non-Hermitian Hatano-Nelson model--to demonstrate how our approach can be used to study fermionic dynamics, decoherence, and measurement-induced phenomena in experimentally relevant settings.

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P-042

Symmetry and Liouville Space Formulation of Decoherence-Free Subsystems

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We propose a generic and systematic decoherence-free scheme to encode quantum information into an open quantum system by focusing on symmetry. Open-system dynamics are described either by completely positive trace-preserving maps or, in the Markovian regime, by the Lindblad master equation [1], which characterizes the noise by a set of Kraus or Lindblad operators, respectively. Under a given symmetry, the Liouville space is decomposed into invariant subspaces characterized by a tensor-product structure, and a decoherence-free subsystem is then identified as one factor of this tensor product. Unlike decoherence-free subspaces, which typically require "strong symmetries" imposing strict commutation conditions on each Kraus or Lindblad operator, decoherence-free systems are permitted under less restrictive "weak symmetries," where only the overall quantum channel or Lindbladian must be invariant.

Specifically, we primarily concern ourselves with the permutation symmetry in conjunction with the unitary symmetry and utilize the Schur-Weyl duality [2], which facilitates numerous efficient and systematic calculations based on the well-established group representation theory. Employing the isomorphism between the Liouville space and the fictitious Hilbert space, we construct a super-Schur basis that block-diagonalizes the super-operators describing noisy quantum channels, both in the Kraus representation and in terms of the quantum master equation.

Within each block of the super-Schur representation, the tensor-product structure becomes explicit, revealing the subsystem that remains unaffected by noise under the specified weak symmetry. This provides a unified, scalable framework for encoding quantum information into physically relevant decoherence-free subsystems without requiring strong commutation conditions among microscopic noise operators. Our approach, therefore, extends the applicability of symmetry-based noise mitigation to a broader class of quantum channels and offers a practical route to protecting quantum information in noisy multi-qudit systems.

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P-043

Combining PEC and Classical Shadows for Efficient Error Mitigation in NISQ Devices

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Quantum computers are inherently susceptible to noise and errors due to decoherence and imperfect gate operations. While Quantum Error Correction (QEC) provides a rigorous framework to achieve fault-tolerant quantum computation, its implementation requires a prohibitively large number of physical qubits and remains beyond current hardware capabilities [1,2]. As an alternative, Quantum Error Mitigation (QEM) has emerged as a practical approach to reduce the impact of noise without the full resource requirements of QEC, enabling near-term quantum devices to produce more reliable computational results[3].

In this work, we employ Probabilistic Error Cancellation (PEC) to suppress the effect of noise and improve the accuracy of expectation value estimation. PEC reconstructs the ideal noiseless statistics of observables by probabilistically sampling inverse noisy operations, thereby providing an unbiased estimator of the target quantity. Furthermore, we integrate Classical Shadow techniques to efficiently extract multiple observables from limited measurement data, effectively reducing the required number of shots. This combined approach provides a practical pathway to enhance the reliability and scalability of quantum computations on near-term noisy quantum devices.

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P-044

Performance Analysis of Advantage Distillation in Finite-Key effect Decoy State QKD

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QKD is a technology that utilizes the properties of quantum mechanics to allow two parties, Alice and Bob, to share a symmetric secret key while being able to detect the presence of eavesdropping. Since the first proposed QKD (BB84) in 1984[1], many research and implementations have been progressed to improve practical security and key rate performance [2,3]. However, these methods often are hard to implement or require high-cost hardware. Therefore, research is being conducted on how to increase the performance of QKD by improving post-processing protocols. Advantage Distillation (AD) is a technique used in the post-processing stage of QKD that utilizes two-way communication between Alice and Bob to distill valid bits, thereby enhancing the key rate[4].

In this work, we simulate the performance of AD in a practical weak+vacuum decoy-state QKD system. To reflect practical implementation environments, we consider finite-key effects rather than assuming the asymptotic limit. Our simulation results demonstrate that applying AD extends the maximum transmission distance by approximately 16.7% compared to the without AD.

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P-045

Analysis of rectangular surface code under the restricted number of CNOT gates

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Practical fault-tolerant quantum computers require high thresholds and low overheads. The surface code is the most promising candidate for quantum error correction code to be used in the fault-tolerant quantum computer [1].

In the superconducting qubit system, the CNOT gates cannot be implemented simultaneously because of the quantum crosstalk [2]. The max channels per pulse gate of ibm fez and ibm kyiv is nine, which means that up to nine CNOT gates can be implemented simultaneously [3]. It is also necessary to consider this situation in the implementation of the surface code [4]. Moreover, there is a problem where one type of Pauli error occurs more frequently than others. This type of error, known as biased noise, has recently become the focus of research on surface code structure [5,6].

In this study, We calculated effective physical error rate for the various relaxation (T1) and dephasing (T2) time in CNOT restricted surface code decoding. For this, we used the values of IBM's Heron r2(ibm fez, 156 qubit system) [3] and Google's Sycamore processor [7]. We analyzed the optimal rectangular surface code size and logical error rate under conditions where the number of available CNOT gates is limited and biased noise occurs.

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P-046

Continuous variable Quantum key distribution parameter estimation

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This paper aims to present an overview of the CV QKD protocols and estimation of parameters. We strive to derive the fundamental relationships, assuming minimal prior knowledge on this subject to make the content as accessible as possible.

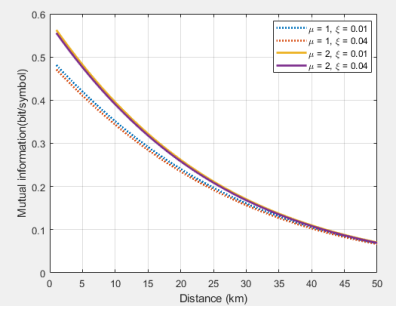
The Gaussian modulated signal light prepared by Alice is transmitted to Bob. [2] Afterwards, Bob performs X or P measurement according to the LO light to detect the bit value depending on where the signal is on the I/Q plane, and when X measure the key as a shared example, if the signal is located in the positive direction of the x axis, 0 bit value, 1 bit value is used to detect the signal if the signal is located in the negative direction of the X axis. When P measurement, signal detection is performed with 0 bit value if the signal is located in the positive direction of the y axis, signal detection is performed with 1 bit value if the signal is located in the negative direction of the y axis, and signal detection is performed with 1 bit value if the signal is located in the negative direction of the y axis.

The mutual information between Alice and Bob is defined by the formula below.[3]

$$I_{AB} = \frac{\mu}{2}\log_2\left(1 + \frac{\left(\frac{1}{\mu} * T * V_A\right)}{\left(1 + \left(\frac{1}{\mu}\right) * \xi\right)}\right) \quad (1)$$

μ is a factor that tells whether Bob performs a heterodyne or homodyne detection. If Bob performs homodyne detection, μ value is 1, and if Bob performs heterodyne detection, μ values is 2. T is the transmittance, V_A is the modulation variance and ξ is the excess noise. Using this formula, we will show how the mutual information between Alice Bob will change depending on μ and ξ.

Let's examine the change in mutual information as μ and ξ vary. When V_A is set to an experimentally predicted value, it can be observed that mutual information gradually decreases as the distance increases. When μ=1, that is, when Bob performs homodyne detection, the mutual information is relatively lower compared to when μ=2, where Bob performs heterodyne detection. The change in mutual information due to variations in ξ for the same μ value was within approximately 5%. Which means ξ does not give a big change in mutual information



P-047

Experimental Assessment of One-Way BB84 Quantum Key Distribution over Wavelength-Multiplexed Optical Channels

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As advances in quantum computing threaten the security of conventional RSA-based cryptography, quantum key distribution (QKD) has emerged as a promising method for information-theoretic secure communication. In this study, we experimentally evaluate the performance of a one-way BB84 QKD protocol coexisting with classical data channels in a wavelength-division multiplexing (WDM) system. A 1550-nm QKD channel is multiplexed with four on–off keying (OOK) data channels operating in the 1310–1430 nm band. To mitigate nonlinear noise such as Raman scattering generated during WDM transmission, a narrow 25-GHz bandpass filter is applied after demultiplexing. Under these conditions, the raw quantum bit error rate (QBER) increases from 17.28% (QKD-only transmission) to 19.59% when classical data traffic is simultaneously transmitted—an increase of approximately 2 percentage points. These results demonstrate both the feasibility and the practical limitations of WDM-based coexistence of QKD and classical communications. Future work will integrate improved encoding/decoding strategies as well as Cascade-based error correction and privacy amplification to generate secure keys and evaluate the achievable key rate.

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Coherent Control and Narrow-Linewidth Spectroscopy of a Four-Level Silicon Vacancy Spin in Silicon Carbide

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Spin-photon interfaces are key components for next-generation quantum technologies, including quantum communication and distributed quantum computing [1]. Among various platforms, point defects in silicon carbide (SiC) have emerged as promising candidates. They offer excellent spin coherence, bright photoluminescence, and compatibility with mature semiconductor fabrication technologies, making them well-suited for scalable quantum devices [2, 3]. In particular, silicon-vacancy-related defects in 4H-SiC, such as the V1 center, have attracted significant attention because of their robust spin and optical characteristics [3].

In this study, we report the construction of an experimental setup for demonstrating a spin-photon interface based on the V1 center in 4H-SiC. Our setup consists of a cryogenic confocal microscope operating at 5 K, equipped with a high-NA objective for efficient light collection. Resonant excitation is provided by a tunable narrow-linewidth laser, and spin manipulation is achieved with a broadband microwave antenna placed over the sample. Using our refined cryogenic confocal setup, we obtain high-contrast Ramsey interferometry at 5 K in isotopically purified 4H-^{28}Si^{12}C with $T_2^* > 22$ μs; leveraging spin-selective resonant transitions for coherent control, the spectra show the characteristic multi-component response of an $S = 3/2$ qudit arising from spectator (non-addressed) coherences. These results establish a stable, resonant spin–photon platform and core toolkit, which we will now extend through photonic integration toward spin–photon entanglement and network-level demonstrations.

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