# MQC Entanglement 2024

*The 3rd annual meeting of the Midwest Quantum Collaboratory (MQC)*

Facility for Rare Isotope Beams (FRIB)
Michigan State University
East Lansing, MI
August 5-6, 2024

MIDWEST QUANTUM COLLABORATORY

UNIVERSITY OF MICHIGAN  MICHIGAN STATE UNIVERSITY  PURDUE UNIVERSITY

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# About

The Midwest Quantum Collaboratory (MQC) is a consortium founded in 2021 by Michigan State University, University of Michigan, and Purdue University. The goal of the MQC is to promote research activity and collaboration for quantum computing (QC) and quantum information sciences and engineering (QISE) in the Midwest. In addition to virtual workshops and a biweekly seminar series, the MQC holds an annual in-person "Entanglement" conference, which draws ~200 quantum experts and stakeholders from academia, industry, and government. The meeting has two complementary themes: creating new frontiers for entanglement applications and fostering university-industry-funding “entanglement” needed to create next-generation QISE.

MQC Board:
Yong Chen (PU), Steve Cundiff (UM), Mack Kira (UM), Johannes Pollanen (MSU), David Stewart (PU), Angela Wilson (MSU)

## Conference History

2024: Michigan State University (East Lansing, MI)
2023: Purdue University (West Lafayette, IN)
2022: University of Michigan (Ann Arbor, MI)

## MQC Seminars

During the academic year, the MQC hosts a biweekly seminar series "Frontiers in Quantum Information and Technology". Recordings are available on the MQC Youtube channel:

or visit www.youtube.com/@MidwestQuantumCollaboratory

## Wi-Fi

Wi-Fi is available via Eduroam (with a university email) or MSUnet Guest 3.0.

# Program, Day 1

## Monday, August 5

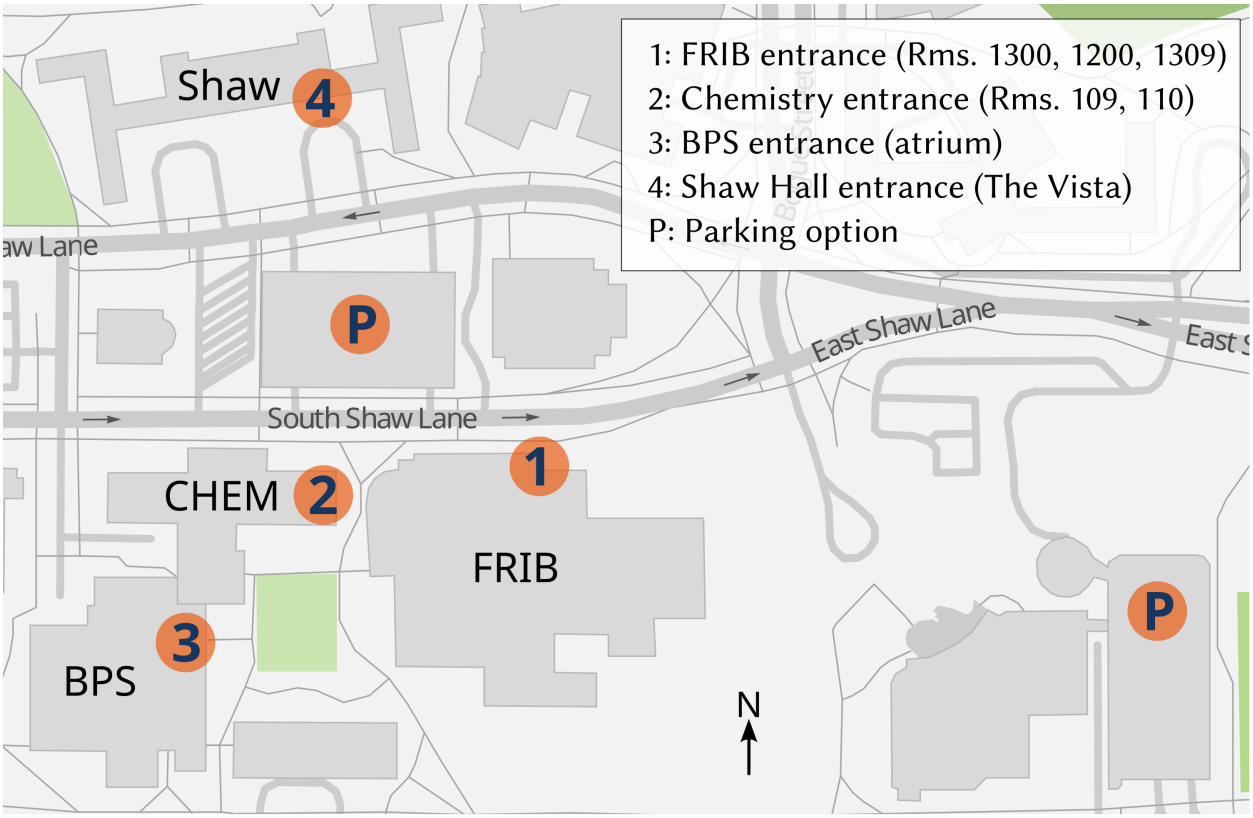
| | |
|---|---|
| 8:15–9:00 AM | **Registration, Networking, and Breakfast** |
| 9:00–9:10 AM | Angela Wilson, Michigan State University |
| 9:10–9:15 AM | Thomas Glasmacher, Michigan State University |
| 9:15–9:20 AM | Phil Duxbury, Michigan State University |
| 9:20–9:35 AM | Sebastian Wicklein, Fraunhofer USA |
| 9:35–9:50 AM | Mack Kira, University of Michigan |
| 9:50–10:05 AM | Yong Chen, Purdue University |
| 10:05–10:20 AM | Johannes Pollanen, Michigan State University |
| 10:20–10:35 AM | Mark Wolf, NVIDIA |
| 10:35–10:55 AM | **Coffee Break** |
| 10:55–11:10 AM | Zubin Jacob, Purdue University |
| 11:10–11:25 AM | Charles Cerny, AFRL |
| 11:25–11:40 AM | Dani Couger, Lockheed Martin |
| 11:40–12:25 PM | 1-slide introductions |
| 12:25–1:50 PM | **Lunch (boxed) & Breakout Sessions** |
| 1:50–2:30 PM | Breakout session summaries |
| 2:30–2:45 PM | Di Liang, University of Michigan |
| 2:45–3:00 PM | Kortny Rolston-Duce, Quantinuum |
| 3:00–3:15 PM | Christian Miller, Keysight |
| 3:15–3:30 PM | **Break** |
| 3:30–3:45 PM | Jonas Becker, Michigan State University |
| 3:45–4:00 PM | Roger Blake, Merit Network |
| 4:00–4:15 PM | Patrick Scully, Quantum Corridor |
| 4:15–6:00 PM | **Poster Session #1 (Odd Numbers)** |
| 4:15–5:15 PM | **Optional FRIB Tour** |
| 6:00–6:30 PM | **Transportation to Dinner** |
| 6:30–8:30 PM | **Dinner (Lansing Brewing Company)** |

# Program, Day 2

## Tuesday, August 6

| | |
|---|---|
| 8:15–9:00 AM | **Registration, Networking, and Breakfast** |
| 9:00–9:15 AM | Tiancong Zhu, Purdue University |
| 9:15–9:30 AM | Carl Dukatz, Accenture |
| 9:30–9:45 AM | Tim Rogers, IonQ |
| 9:45–10:00 AM | Shankari Rajagopal, Stanford University |
| 10:00–10:15 AM | Kyle Castoria, EeroQ |
| 10:15–10:30 AM | Paul Quayle, Great Lakes Crystal Technologies |
| 10:30–10:55 AM | **Coffee Break** |
| 10:55–11:40 AM | Industry panel discussion |
| 11:40–12:40 PM | **Lunch (The Vista at Shaw)** |
| 12:40–2:30 PM | **Poster Session #2 (Even Numbers)** |
| 12:40–1:40 PM | **Optional FRIB Tour** |
| 2:30–3:00 PM | MQC Town Hall |
| 3:00 PM | **Adjourn** |

# Map




Registration, breakfasts, and coffee breaks will take place in the lobby outside FRIB 1300 (**1**).

Lectures will take place in FRIB 1300 (**1**).

Lunch on Monday will be grab-and-go from the FRIB lobby (**1**), and breakout sessions will take place in FRIB (**1**) and Chemistry (**2**).

Poster sessions will be in the atrium of the Biomedical and Physical Sciences (BPS) Building (**3**).

Tuesday's lunch will be at The Vista at Shaw (**4**).

Dinner (Monday) will be at Lansing Brewing Company (518 E Shiawassee St, Lansing, MI 48912).

The conference hotel is The Graduate (133 Evergreen Ave, East Lansing, MI 48823).

# List of Abstracts – Talks

## Monday, August 5 – Morning

### Welcome, MQC Overview, and MSU QIS Overview

**Angela Wilson**
*John A. Hannah Distinguished Professor of Chemistry and Director of MSU Center for Quantum Computing, Science, and Engineering (MSU-Q), Michigan State University*

### Welcome to FRIB

**Thomas Glasmacher**
*FRIB Laboratory Director, Michigan State University*

### Remarks

**Phil Duxbury**
*Dean of College of Natural Science, Michigan State University*

### Fraunhofer and our Technology Transfer Activities of Quantum Technology to the Industry

**Sebastian Wicklein**
*Director, Business Development Coordination, Fraunhofer USA*

This presentation, shows the extensive role of Fraunhofer in advancing quantum technology through strategic technology development and transfer to the industry. We present an overview of the organization and its position as the world's largest applied R&D organization. Key activities include industrial-scale R&D, technology transfer, and collaboration with industry, academia, and government partners.

The presentation details Fraunhofer's approach to quantum technology development, emphasizing a holistic, multidisciplinary method that is repeatable, reliable, and scalable. Significant achievements include advancements in Extreme Ultraviolet Lithography and the development of quantum technologies such as quantum computing, quantum imaging, and quantum communication. The presentation also showcases Fraunhofer's state-of-the-art R&D facilities and its competence network in quantum computing and technology.

Additionally, the collaboration with Michigan State University on diamond technologies for quantum applications is highlighted, demonstrating the organization's commitment to leveraging strategic partnerships for technological advancements. The socio-economic benefits of Fraunhofer's initiatives are underscored, focusing on de-risking technology development projects and fostering technological sovereignty.

Overall, the presentation encapsulates Fraunhofer's mission to transform theoretical research into

practical, scalable solutions that meet the needs of various industries, thereby driving innovation and economic growth.

## University of Michigan QIS Overview

**Mack Kira**
*Professor of Electrical Engineering & Computer Science and Director of UM Quantum Research Institute (QRI), University of Michigan*

## Purdue University QIS Overview

**Yong Chen**
*Karl Lark-Horovitz Professor of Physics and Astronomy, Professor of Electrical and Computer Engineering, Director of Purdue Quantum Science and Engineering Institute, Purdue University*

## Hybrid quantum phononics with superconducting qubits*

**Johannes Pollanen**
*Cowen Distinguished Chair in Experimental Physics, Associate Professor of Physics, and Associate Director of MSU Center for Quantum Computing, Science, and Engineering (MSU-Q), Michigan State University*

Superconducting qubits, and the experimental architecture of circuit quantum electrodynamics (cQED), have emerged as not only a promising platform for quantum computation but also for investigating fundamental and applied aspects of synthetic/hybrid quantum systems composed of qubits coupled to other quantum systems or degrees of freedom. In particular, the ability to leverage the properties of superconducting qubits to investigate and manipulate phononic degrees of freedom opens the door to exploring new regimes of circuit quantum optics using high-frequency sound. Due to the intrinsically strong nonlinearity provided by the qubit, these types of hybrid "quantum acoustic" systems have the potential to access a broad class of quantum states of motion beyond what is achievable with effectively linear optomechanical or electromechanical interactions.

In this talk I will describe some of our recent experimental results investigating the fundamental physics of hybrid systems based on superconducting qubits coupled to piezoelectric surface and bulk acoustic wave devices and how these systems can be used to develop next-generation technologies for quantum sensing, computation, and communication. As I will describe, these engineered systems, in which quantum information stored in the qubit can be controllably coupled to the microscopic surface and bulk phonon modes of a piezoelectric crystal, are an ideal platform for investigating the exotic behavior of synthetic open quantum systems and phononic interference in the quantum regime. Additionally, I will describe how these devices pave the way to exciting new technologies ranging from quantum-limited surface sensing to phonon-based bosonic quantum memories.

*This work was supported by the National Science Foundation via Grant No. ECCS-2142846 (CAREER)

## Is NVIDIA Building a Quantum Computer?

**Mark Wolf**
*Technical Marketing Engineer, NVIDIA*

This talk will provide an overview of NVIDIA's recent efforts to enable the entire quantum computing ecosystem. Topics will range from the NVIDIA CUDA-Q platform for accelerating hybrid quantum-classical applications to research that leverages generative AI for novel quantum computing algorithms. And, most importantly, this talk will answer the question. "Is NVIDIA building a quantum computer?".

## Quantum optical detectors and sensors for information processing

**Zubin Jacob**
*Elmore Professor of Electrical and Computer Engineering, Purdue University*

In this talk, we will discuss next generation superconducting single photon detectors, remote/near-field sensing and structured light for quantum applications. More details can be found at www.electrodynamics.org.

## Rydberg Atom Photon Interleaver for Quantum Information Excision

**Charles Cerny**
*USAF Research Laboratory, Wright-Patterson AFB*

Under the Ohio Federal Research Network (OFRN) proposal, Team GhostWave will demonstrate a quantum sensing system, based on the integration of Rydberg atom quantum RF electric field sensors with telecommunications band wavelength converters and RF noise radar waveforms. We will quantitatively characterize the systems level of quantum advantage from the integration of state-of-the-art quantum technology with state-of-the-art-classical technology. We anticipate that the high sensitivity of the quantum sensor will reduce system noise, thereby providing system level enhancement in dynamic range and fidelity. Wavelength conversion and complex RF signal processing algorithms aid telecommunication bands providing increases stand-off distance capability. Our results have the potential to significantly impact future applications of interest to the DoD and other Government organizations.

## Transitioning quantum technology through the horizons of innovation

**Dani Couger** (she/her)
*Quantum Lead, Lockheed Martin*

The quantum landscape has dramatically evolved over the last 5-10 years, perhaps most on how we partner and select research avenues. Dani Couger will walk through Lockheed Martin's quantum strategy and how she sees Aerospace & Defense and large industries are reshaping, in-order to push through the horizons of quantum research and technology. Through the lens of balancing near-term realities with longer-term, higher risk investments, Dani will point to potential high impact areas in next-generation quantum-information science and engineering (QISE).

# Monday, August 5 – Afternoon

## Extending the heterogeneous integrated photonics from classical applications to quantum technology

**Di Liang**
*Professor of Electrical Engineering and Computer Science, University of Michigan*

Integrated quantum photonics is an emerging field focused on miniaturizing quantum optical systems onto chip-scale integrated photonic platforms. This approach aims for enhanced performance, large-volume manufacturing, and cost-effective convenient deployment. Drawing on my industrial and academic experience in classical photonic integration R&D for optical communication and computing applications, I will attempt to discuss how heterogeneous integration can provide a wider array of materials, additional building blocks, and diverse architectural options to drive innovations that benefit both classical and quantum domains synergistically.

## Scaling Trapped Ion Quantum Computers

**Kortny Rolston-Duce**
*Director of Ecosystem Development, Quantinuum*

In recent months, Quantinuum has made significant progress toward scaling its trapped ion quantum computing technologies and improving performance. In this talk, we will review some of that progress and discuss what's next.

## Supporting a maturing quantum market.

**Christian Miller**
*Global Strategic Business Development Director, Keysight*

As quantum start-ups begin growing past their seed stage and large quantum organizations are moving out of internal research and development stage (IRAD) they begin to value some level of standardization in their processes. At Keysight, our heritage of 80 years supporting emerging technology markets has informed how we look to support these market making enterprises.

## Spin Defects in Synthetic Diamond for Use in Quantum Technologies and Fundamental Physics

**Jonas Becker**
*Jerry Cowen Chair of Experimental Physics, Assistant Professor of Physics, Michigan State University*

Due to its wide bandgap and low nuclear spin background, diamond is an excellent host for thousands of crystal defects with interesting optical and spin properties, only a few of which have been studied in greater detail so far. While some of these so-called color centers, such as the nitrogen vacancy or group-IV vacancy centers, have already emerged as leading candidates for quantum computing, networking and sensing, diamond holds the potential to host novel defects with potential to improve upon existing systems or to enable novel applications. Here I will present a brief overview of our group's work on one such defect, the nickel vacancy, which shows excellent optical characteristics such as lifetime-limited linewidths in the near-infrared regime in initial experiments. Moreover, I will outline some of our plans to use some of the already established

as well as novel defects in diamond as a tool to study aspects of fundamental physics such as the search for permanent electric dipole moments in octupole-deformed nuclei as signatures for time-reversal violating forces or to study structure and dynamics of low-dimensional electron systems and their potentially non-trivial spin textures.

## Collaborating with Merit Network in Quantum Communications

**Roger Blake**

*President and CEO, Merit Network*

Founded by University of Michigan, Michigan State University, and Wayne State University in 1966, Merit Network will introduce the MQC to its research and education mission and extensive fiber optic network footprint in Michigan and the region. As one of the nation's foremost non-profit research and education networks, Merit Network is uniquely positioned to collaborate with MQC members to leverage its assets and relationships to support research interests, workforce development goals, and industry field trials in ways that advance knowledge of quantum communications.

## Quantum Corridor: Foundation for Quantum Networking and Research

**Patrick Scully**

*Chief Product Officer, Quantum Corridor*

This session will provide an overview of the activities at Quantum Corridor, and how the network architecture is laying the foundation for next generation quantum networking. We will also cover how the various industry and academia partnerships are working together on a network built for a combination of ultra-high capacity for classical traffic and a proving ground for evolving quantum communications technologies.

# Tuesday, August 6

## Exploring and manipulating engineered quantum states with scanning tunneling microscopy

**Tiancong Zhu**

*Assistant Professor of Physics and Astronomy, Purdue University*

In this talk, I will explore how a combination of functional devices with scanning tunneling microscopy (STM) can offer new insights into understanding and engineering novel quantum states of matter in two-dimensional materials. I will first demonstrate how STM can directly visualize the chiral edge states in a quantum anomalous Hall insulator, showcasing how the spatial location and chirality of these states can be precisely controlled using the STM tip. Next, I will discuss the creation of an atomic scale 1D quantum well within a monolayer transition metal dichalcogenide (TMD), where we can manipulate its spin state through electrostatic gating and investigate these states with STM. I will conclude by outlining how these techniques can be extended to other engineered quantum material systems and their implications for quantum information science.

## Experiences applying quantum technology in industry

**Carl Dukatz**

*Next Gen Compute Lead, Accenture*

The advancements of quantum technology promise significant progress for industrial applications, offering opportunities for innovation and efficiency. This talk explores the practical experiences and challenges of integrating quantum technologies within various industries. Drawing from real-world case studies, it highlights the transformative potential of quantum and will delve into specific industry use cases, such as optimizing insurance, enhancing cybersecurity, and improving global sustainability. Attendees will gain insights into how businesses perceive quantum technology today and consider the strategic next steps as breakthroughs emerge.

## Advancing Quantum Computing Towards Commercial Advantage

**Tim Rogers**

*Solutions Engineer, IonQ*

I will plan to present IonQ's current plan to progress our technology over the coming years and show some technical roadmap milestones.

## Dynamical engineering of Rydberg atom systems for quantum-enhanced sensing and simulation

**Shankari Rajagopal**

*Postdoctoral Scholar, Stanford University*

Quantum sensors hold promise for improved sensing of time, electromagnetic fields, and forces; however, the inherent probabilistic nature of quantum mechanics introduces uncertainty that can limit sensor precision. We can hope to overcome this uncertainty by engineering entanglement to create correlated behavior in atomic systems. Unfortunately, in practice, introducing and

controlling these correlations is limited by the local nature of interactions on many promising sensing platforms, including optical tweezer clocks and solid-state magnetometers. In this talk, I will discuss how we can use temporal control over local Rydberg interactions to extend interaction coherence times and minimize atomic loss in an array of atomic ensembles. With these improvements, we generate metrologically useful entanglement across several spatially separated ensembles in parallel. This work demonstrates the power of dynamical control to enhance and expand our understanding of entanglement in atomic systems; I will touch on future prospects in quantum sensing, simulation, and optimization on a new experiment utilizing a Rydberg atom array in an optical cavity.

## Quantum Computing With Electrons on Helium

**Kyle Castoria**
*Quantum Engineer, EeroQ*

Electrons on Helium offer a unique platform for quantum information. The isolation of the electrons in vacuum above the surface of superfluid helium offers a system robust from noise and predicted long coherence times. Further, electrostatic control of the mobile electrons allows for dynamic architectures which are highly scalable. In this talk, I will discuss the design and principle by which a quantum computer would function in this implementation and recent experimental advances to this end.

## Accelerating the Development of Quantum Diamond-based Technologies

**Paul Quayle**
*Chief Scientist and Vice President of R&D, Great Lakes Crystal Technologies*

Great Lakes Crystal Technologies is working to accelerate the advancement and maturation of Quantum Diamond technologies, and to further the United State's competitive advantage in the critical National Security technology space.

Diamond is a novel, high-performance material that is poised to transform critical technology areas, including microelectronics assurance, complementary position, navigation, and timing (PNT) systems, medical diagnostics, and will serve as a bedrock for scalable quantum technologies from sensing to networking and computing.

In this presentation, we report on the growth and characterization of high purity (Type IIa) diamond substrates and N-doped epitaxial layers for quantum applications. Free-standing substrates grown using microwave plasma-assisted chemical vapor deposition (CVD) technique are assessed using cross-polarized and quantitative birefringence, x-ray diffraction and x-ray topography. Increasingly, more sophisticated materials design and device configurations are required to enable quantum technologies. GLCT diamond will be discussed in light of the application specific requirements.

# Poster Numbers

Odd #: Monday, 4:15-6:00 PM
Even #: Tuesday, 12:40-2:30 PM

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# List of Abstracts – Posters

## 1: Phase Transition in Non-linear Dicke model with cavity loss

Aanal Jayesh Shah, Simone Felicetti, Peter Kirton, Hadiseh Alaeian
*Purdue University*

Our work is primarily focused on understanding the behavior of phase transition of two-photon/non-linear Dicke model with cavity loss. We find that the literature uses the standard mean field treatment but a fully quantum treatment shows drastically different results that are not captured using mean-field theory. We find that our modified mean-field shows good agreement with the full quantum model. The system is unstable with closed form and single photon loss beyond a critical point. Our work demonstrates for the first time how to stabilize the system for small number of spins to thermodynamic limit.

## 2: Quantum spectroscopy of biexcitons in atomically-thin quantum materials

Aaditya Hambarde [1], Jason Horng [2,3], Hui Deng [2], Mackillo Kira [1,2]
*1 Department of Electrical Engineering and Computer Science, University of Michigan*
*2 Department of Physics, University of Michigan*
*3 National Institute of Standards and Technology, Boulder, CO*

Quantum spectroscopy [1-3] offers a novel approach to directly probing correlations and tracking entanglement dynamics in two-dimensional quantum materials under strong light-matter coupling conditions. The resulting optical response becomes highly sensitive to chirp, driven by pronounced wave-mixing nonlinearities. We showcase the unique capability of quantum spectroscopy to distinguish biexcitonic nonlinearities from wave-mixing nonlinearities, achieving a level of precision unattainable by classical spectroscopy methods.

[1] M. Kira and S.W. Koch, Phys. Rev. A 73(1), 013813 (2006).
[2] M. Kira, S.W. Koch, R.P. Smith, A.E. Hunter, and S.T. Cundiff, Nat. Phys. 7(10), 799-804 (2011).
[3] A.E. Almand-Hunter, H. Li, S.T. Cundiff, M. Mootz, M. Kira, and S.W. Koch, Nature 506(7489), 471-475 (2014).

## 3: K-Commutativity to reduce VQE circuit depth

Andrew Koren, Ben Dalfavero, Ryan Larose
*Michigan State University*

We apply the notion of k-commutativity [https://arxiv.org/abs/2312.11840], which interpolates between qubit-wise commutativity and full commutativity, to reduce the depth of a recently-introduced ansatz for variational quantum algorithms. This ansastz, known as the Hamiltonian-based graph state ansatz (HGSA) [https://arxiv.org/abs/2312.17146], is formed by grouping operators into mutually commuting sets to construct diagonalization circuits which appear in the ansatz. We apply k-commutativity when grouping operators to reduce the overall depth of the HGSA, a crucial consideration for implementation on near-term quantum computers. We compare the performance of the new ansatz using k-commutativity (k-HGSA) to the original (HGSA) on various benchmark problems. Our results show that the k-HGSA can reduce variations quantum algorithm (VQA) depth by as much as half while still achieving accurate results on chemical benchmarks[, and significantly improves the performance of the HGSA in the presence of noise.]

## 4: Non-Markovian Collective Emitter Dynamics in a Nonlinear Dispersion

Ankit Kundu, Kanu Sinha, Hadiseh Alaeian
*Purdue University*

Waveguides enable efficient coupling between distant quantum emitters, with nanophotonic structures facilitating such engineerable photonic dispersion properties. Engineering the dispersion can decrease the speed of light by several orders of magnitude compared to free space, facilitating long-ranged interactions between quantum emitters and exotic many-body light-matter interactions. In such regimes, the dynamics of quantum emitters becomes non-Markovian owing to the memory effects of the slow electromagnetic fields mediating the interaction. We explore the collective dynamics of a system of N quantum emitters coupled to a dispersive waveguide. Considering the waveguide dispersion to be nonlinear, we analyze the resulting non-Markovian dynamics of the emitters, demonstrating the formation of atom-photon bound states. Such waveguide mediated non-Markovian collective atom-field interactions are relevant to distributed quantum sensing and metrology protocols and quantum networks.

## 5: Optimizing sensor placement in real water distribution networks using classical and quantum optimization algorithms

Anurag Ramesh, David E. Bernal Neira
*Purdue University*

Efficient placement of pressure sensors in Water Distribution Networks (WDNs) is crucial for timely fault detection and isolation. This research aims to solve the sensor placement problem by leveraging classical formulations, such as Mixed-Integer Programming (MIP) and Quadratic Unconstrained Binary Optimization (QUBO). These optimization problem formulations are tackled through classical optimization methods, such as GUROBI along with simulated annealing through the package neal (https://github.com/dwavesystems/dwave-neal). We also evaluate the use of quantum annealing to address this problem using D-Wave Advantage system 4.1.

The WDN's are represented as a graph G (V, E), where V represents the set of nodes for water consumption and E represents the set of pipes connecting the nodes from the set V. Seven different WDN's, each from a different city are considered for the optimal sensor placement problem. Edge betweenness and node degree centrality metrics have been used to quantify the nodes and edges of the WDN (Speziali et al., 2021), (Giustolisi et al., 2019).

By applying these methods to the WDN, we aim to evaluate and compare the performance of classical and quantum techniques in finding optimal sensor placements. The goal is to determine the most effective approach, enhancing the reliability and efficiency of WDN monitoring systems through optimal sensor deployment.

References:

S. Speziali et al., "Solving Sensor Placement Problems In Real Water Distribution Networks Using Adiabatic Quantum Computation," 2021 IEEE International Conference on Quantum Computing and Engineering (QCE), Broomfield, CO, USA, 2021, pp. 463-464, https://doi.org/10.1109/QCE52317.2021.00079.

Giustolisi, O., Ridolfi, L., & Simone, A. (2019). Tailoring centrality metrics for water distribution networks. Water Resources Research, 55, 2348–2369. https://doi.org/10.1029/2018WR023966

## 6: Excitonic Rydberg Quantum Materials : A Novel Platform for Scalable Quantum Technology

Kinjol Barua, Samuel Peana, Zachariah Martin, Arya Deepak Keni, Omer Yesilurt, Vahagn Mkhitaryan, Alex Senichev, Vladimir Shalaev, Yong P. Chen, Alexandra Boltasseva, Hadiseh Alaeian
*Purdue University*

The quest for strong photon-photon interactions represents a crucial objective in the realm of quantum optics, holding the potential to transform quantum information technologies. Nonetheless, the absence of substantial interaction between photons impedes the development of extensive optical quantum communication networks. Highly excited Rydberg excitons in cuprous oxide (Cu_2 O), characterized by large principal quantum numbers (n), enable the creation of significant optical nonlinearity at the level of single or few photons. This phenomenon arises from strong interactions attributable to dipole-dipole and van der Waals potentials. Although Rydberg exciton states up to n=30 have been observed in natural bulk cuprous oxide, these natural samples contain point defects that compromise exciton lifetimes. Moreover, integrating bulk natural samples with current nanofabrication methods for quantum photonics is labor-intensive. Additionally, bulk samples pose substantial challenges in offering the flexibility needed to control film thickness and observe the "Rydberg Blockade," which is fundamental for generating giant single-photon nonlinearity. This poster presents a robust, CMOS-compatible growth recipe for defect-free, highly crystalline 2D arrays of cuprous oxide (Cu_2 O) with site-controlled capabilities and their integration with nanophotonic structures to exploit single-photon nonlinearity. Utilizing a bottom-up approach, this growth recipe aligns with current nanofabrication techniques. We demonstrate the observation of Rydberg excitons up to n=5 within these 2D cuprous oxide arrays, discussing the spatial variation of their spectrum across arrays of different sizes and their integration with nanophotonic structures. Towards the end, we will present the first-ever measurements of the lifetimes of Rydberg excitons in Cu_2 O. By employing a time-resolved photoluminescence (TRPL) method, we measured the lifetimes of the first five Rydberg excitonic states and analyzed their temporal dynamics as a function of exciton densities. The results of this study will merge the controllability and strong interaction of Rydberg excitons with the scalability and integrability of nanophotonic circuits, enabling strong light-matter interactions on a solid-state platform. This advancement opens new frontiers in the development of scalable, on-chip, and highly tunable quantum devices.

## 7: Extreme lightwave-driven tunnel currents through atomic defect complexes in gallium arsenide

Vedran Jelic, Stefanie Adams, Mohamed Hassan, Kaedon Cleland-Host, Austin C. Hayes, Spencer E. Ammerman, Tyler L. Cocker

*Michigan State University*

Lightwave-driven terahertz scanning tunneling microscopy (THz-STM) utilizes the oscillating electric field of a THz light pulse to coherently control the tunnel current of electrons between the tip and sample of an STM in order to simultaneously provide atomic spatial resolution and ultrafast temporal resolution of material surfaces. A recent advance at MSU has added atomic-scale THz time-domain spectroscopy (THz-TDS) to the THz-STM toolkit as well. Here, we image silicon-doped gallium arsenide with THz-STM and observe unusually 'bright' silicon dopant atoms at the sample surface. When the tip is located over one of these defects, the THz field drives currents reaching over 100 electrons in less than a half a picosecond (10^12 s). However, when the tip is located over other nearby silicon dopants, the lightwave-driven currents are orders of magnitude smaller. The relative scarcity of the bright defects suggests they correspond to defect complexes rather than single atomic dopants or vacancies. In rare cases, bright defects can exhibit a strong resonance in THz-TDS measurements at 1 THz, which suggests a unique electronic structure that strongly resembles that of a 'DX center'. The technological relevance of these DX centers and other key observations related to their identification will be shown in this presentation, along with further characterization of other bright defects.

## 8: High Frequency Dynamics of the Liquid and Solid Phases of Electrons on Helium

A.J. Schleusner, N.R. Beysengulov, C.A. Mikolas, D.G. Rees, J. Pollanen

*Michigan State University*

The Coulomb liquid and solid states of electrons floating above the surface of superfluid helium exhibit non-trivial spatial structure and high-frequency temporal dynamics. This is particularly true of the collective interaction between the electronic Wigner solid state and the bosonic field of ripplons on the helium surface. Here we present high-frequency transport measurements of microchannel confined electrons on helium to probe the interaction between the electron system and the thermal ripplonic bath. Measurements were carried out over a wide range of frequency from 0.3-170 MHz via capacitively coupled lock-in techniques.

## 9: Selective Optically Driven Spin-Flip and Charge Transfer Dynamics in FeCO

Benjamin G. Peyton, Angela K. Wilson
*Michigan State University*

Controlling the ultrafast dynamics of spin-flip (intersystem crossing) mechanisms is crucial to the development of electronic spin qubits, a promising elementary unit for quantum computing. These qubits require controllable initialization of specific electronic spin states on an ultrafast timescale. Quantum dynamics simulations enable the theoretical prediction and tuning of these processes for potential qubit candidates. A prototype transition metal complex, FeCO, is studied following an electric field pulse using the time-dependent spin-orbit configuration interaction (TD-SOCI) formalism. The optimization of the electric field pulse is achieved via comparison to a two-state model as well as frequency chirping. It is shown that, through a series of precisely engineered pulses, selective spin-flip and charge transfer dynamics can be achieved on the femtosecond timescale.

## 10: Investigating Many-body States in Electrostatically Doped Monolayer MoSe2 with Polarization-dependent Multidimensional Coherent Spectroscopy

Blake T. Hipsley, Adam Alfrey, Chenxi Li, Hui Deng, Steven T. Cundiff
*University of Michigan*

Bound electron-hole pairs (excitons) dominate the optical properties of monolayer semiconducting transition metal dichalcogenides (TMDs). Higher-order many-body states and interactions can exist between multiple excitons, such as the biexciton state consisting of two bound excitons, but cannot be easily distinguished through linear spectroscopic techniques. Instead, we use polarization-dependent multidimensional coherent spectroscopy (MDCS) to identify and separate the presence of exciton states and various many-body interactions. Previous work has shown that many-body interactions are modified by cross-polarization excitations in GaAs quantum wells and monolayer MoSe2. Here, we present MDCS data collected on electrostatically doped MoSe2 and the influence of polarization on many-body interactions. Our results indicate the formation of a charged biexciton (neutral exciton bound to a charged exciton, also referred as a trion) is present from collinear polarization excitation, as verified by simulations using the optical Bloch equations.

## 11: The dipole moment of a super-atom

B. Yang, Y. Li, S. Nie, Y. Mei, H. Nguyen, P. R. Berman, and A. Kuzmich
*University of Michigan*

Homodyne detection is used to measure the (collective) atomic dipole moment for an atomic ensemble that is prepared in a superposition of spatially phased Dicke states having at most two excitations (a so-called "super-atom"). Homodyne detection allows one to isolate the contributions to the radiated intensity that depend linearly on the average value of the collective atomic dipole moment operator. Depending on whether the atom - reference field interference is constructive or destructive, either super-Poisson or sub-Poisson statistics for the combined field is observed.

## 12: Plasmon engineering and towards cQED with electrons on helium

Camille A. Mikolas, Niyaz R. Beysengulov, Austin J. Schleusner, David G. Rees, Johannes Pollanen
*Michigan State University*

An ensemble of electrons trapped above a superfluid helium surface (eHe) is a paradigm system for investigating and controlling the collective charge dynamics of low-dimensional electronic matter. Of particular interest is the ability to engineer the spatial and spectral structure of surface plasmon modes in this system for integration into hybrid quantum systems or circuit quantum electrodynamic device architectures. We present experiments on an eHe microchannel device designed to host microwave- frequency plasmon modes with a spatial structure dictated by the geometry of the channel confinement. Plasma oscillations are generated via local microwave frequency excitation of the microchannel confined electrons. When the plasmon mode is resonant with the excitation frequency, it produces non-equilibrium heating of the electrons, which we detect as changes in the device conductance via simultaneous transport measurements. We find the spatial structure of the surface plasmons is in good agreement with our model and device design parameters and the mode frequencies can be tuned over a broad range (several GHz) by precisely varying the electron areal density in the central channel. Furthermore, by measuring the plasmon mode lineshape and power dependence, we quantify the level of spatial homogeneity associated with each plasmon mode. The results highlight the versatility of electrons on helium as a model system for investigating, and engineering, the collective mode structure of low-dimensional Coulomb liquid and solid states. Lastly, we present a next generation device and initial results where microchannel confined collective excitations of eHe is coupled to a superconducting coplanar waveguide resonator.

## 13: Decoherence of surface phonons in the weak dispersive regime of circuit quantum acoustodynamics

Camryn Undershute, Joe M Kitzman, Pranaya Kishore Rath, Johannes Pollanen
*Michigan State University*

Circuit quantum acoustodynamic (cQAD) systems are ideal for investigating the quantum properties of mechanical resonators by leveraging the intrinsic nonlinearity of superconducting qubits. Here we describe an experiment in which the electro-mechanical response of a surface acoustic wave (SAW) device enables the realization of an open cQAD system. The hybrid system is implemented via capacitive coupling between a 3D transmon qubit and a custom-designed SAW device. This device architecture allows for the transmon to simultaneously couple strongly to a resonant SAW mode and also weakly with non-resonant, lossy surface phonon modes. By populating the SAW device with phonons and then dispersively reading out its state via the qubit, we are able to measure the dynamics and decoherence of the surface phonon states in the resonator. In this fashion, with a single device, we can measure the decoherence of phonons in the resonant mode, and use the broader SAW phonon spectrum to investigate the decoherence of the hybrid system.

## 14: Tweezer array of Rb atoms with state-insensitive trapping and Rydberg excitation

C. Jansohn, A. Londono, Y. Li, P. R. Berman, and A. Kuzmich
*University of Michigan*

By confining atoms in state-insensitive optical lattice at a so-called "magic" 1012 nm wavelength, the ground-state–Rydberg coherence lifetime for collective atomic qubits has been increased to tens of microseconds [1-3]. Here we realize an optical tweezer array of Rb atoms at this magic wavelength and confirm its state-insensitive character by ground-Rydberg excitation spectroscopy. Such arrays can be used for ground-Rydberg qubit manipulation without the need to switch off the trapping potentials.

[1] "Entanglement between light and an optical atomic excitation," L. Li, Y. O. Dudin and A. Kuzmich, Nature 498, 466 (2013).
[2] "Long-lived coherence between ground and Rydberg levels in a magic wavelength lattice," J. Lampen, H. Nguyen, L. Li, P. R. Berman, and A. Kuzmich, Physical Review A 98, 033411 (2018).
[3] "Trapped Alkali-Metal Rydberg Qubit," Y. Mei, Y. Li, H. Nguyen, P.R. Berman, and A. Kuzmich, Physical Review Letters 128, 123601 (2022).

## 15: Distinguishing many-body states with angle-resolved photoemission spectroscopy

Cody Patterson & Mack Kira
*University of Michigan*

We present self-consistent many-body computations to predict correlation-specific information from angle-resolved photoemission measurements in two-dimensional materials.

## 16: MCEND: quantum electro-nuclear dynamics simulation program package

Cong Wang, Inga S. Ulusoy, Lucas E. Aebersold, and Angela K. Wilson
*Michigan State University*

The software MCEND (Multi-Configuration Electron-Nuclear Dynamics) is to solve the time-dependent Schrödinger equation for electrons and nuclei simultaneously, without introducing potential energy surface nor diabatic couplings. The formulations, implementations, and capacities are described. It is planned to release as an open-source software.

## 17: Rydberg macrodimers : understanding the interaction and blockade

Dhiya Varghese, Rejish Nath , Valentin Walther
*Purdue University*

Rydberg macrodimers are unique molecules composed of two Rydberg atoms, bound by strong and long-range van der Waals forces. These macrodimers exhibit properties, including vibrational degrees of freedom, that can be precisely controlled using magnetic fields and the polarization of coupling light fields. A comprehensive understanding of the interactions between macrodimers is critical for applications in quantum entanglement and spin models. This research focuses on the interaction between a macrodimer and a Rydberg atom as a precursor to studying macrodimer-macrodimer interactions, which elucidates the blockade interaction between macrodimers. Such insights hold significant potential for advancing many-body models

## 18: Quantum Education: How Do We Discover the Mess to be Mapped?

Dongyang Li, Zeynep G. Akdemir, Muhsin Menekse, Mahdi Hosseini, Erica W. Carlson, Nicholas Dang
*Purdue University*

The research project investigates the engineering education pedagogy of solving a systems problem that involves multiple stakeholders and the problematic situation that the current physics education does not overlap with engineering education in such a way that it prepares the graduates for working with quantum technologies of the future.

The challenge is the intricate and often abstract domain of quantum mechanics. Due to their complexity, quantum concepts pose a unique challenge in educational settings, making hands-on demonstration and accessible understanding a formidable task.

For this project, the goal is to Research and adapt the application of soft systems approaches to ill-defined and complex problem situations to solve a quantum workforce problem. Applying multiple systems methodologies to gain a deeper understanding of the problem situation, identify potential solutions, and investigate the appropriateness of the project's efforts. Evaluate the potential impact of the IQ-PARC project and identify systemlevel approaches to achieving its goals. Identify promising options for the near-term and long-term that require additional R&D support. Address key challenges in the field, including the lack of workforce and the need for interdisciplinary talent.

The Soft Systems Methodology (SSM) can be used to understand the problem situation and investigate the appropriateness of the project's efforts. Key challenges, such as the lack of workforce, can be resolved through workforce development investment. A rich picture of the problem situation will be developed from stakeholder interviews, etc. The data gathered will be examined to pinpoint structural, procedural, and environmental factors within the scenario. Additionally, the intervention will be reviewed alongside the social and political dimensions of the situation.

The research will involve conducting interviews, literature review, and constructing a system model using Soft Systems Methodology to understand the problem situation and identify feasible changes before moving to action. Potential paths forward could include investing in workforce development.

## 19: Error Mitigation Using Logical Shadow Tomography

Yanis Le Fur, Ethan Egger, Hong-Ye Hu, Ryan LaRose
*Michigan State University*

We present results of performing error mitigation experiments on real and simulated quantum computers. In particular, we implement the logical shadow tomography error mitigation technique [https://arxiv.org/abs/2203.07263] on various benchmark problems, primarily calculating the potential energy surface of molecular hydrogen. For this benchmark, we use the [[5,1,3]] code to embed the computation in a logical subspace and then use shadow tomography to project the noisy state into the codespace via classical post processing. Benchmarks are performed with depolarizing noise as well as Google's Quantum Virtual Machine in addition to the IBM Sherbrooke quantum computer. Our results show improvement in the calculated potential energy surface compared to the raw (unmitigated) results, showing promise for our technique on larger quantum computations.

## 20: Information Storage and Quantum Computing with Single-Molecule Magnets

F. Benner, S. Demir
*Michigan State University*

Organic radicals bear immense potential for the generation of lanthanide single-molecule magnets (SMMs) that exhibit magnetic memory effect such as classical magnets. We prepared unprecedented molecular magnets through coupling of multiple paramagnetic lanthanide ions via the diffuse spin orbitals of organic radicals, paving the way to high-temperature SMMs.

## 21: Computational Approaches for Modeling Superconducting Circuit Quantum Devices

Ghazi Khan, Thomas E. Roth
*Purdue University*

Superconducting circuit quantum devices are one of the most mature platforms for quantum computing, but significant performance improvements are still needed. Most approaches towards modeling these devices rely on inefficient classical full-wave simulations which are cumbersome and lack robustness. To improve the characterization of these devices while circumventing such pitfalls, we provide two novel ways to analyze single and multi-qubit interactions. The first method uses full-wave eigenmode tools in conjunction with our field-based quantization routine to simulate the actual 3D structure of the quantum circuit and accurately predict quantities of interest like the AC-Stark shift and ZZ interaction rate. These quantities are essential for helping design better readout strategies and reducing quantum crosstalk. The second method analytically derives a formula for evaluating the multi-qubit exchange coupling rate using the impedance parameters of the 3D circuit. This method avoids computationally expensive eigenmode decompositions while providing an accurate estimate of the parameter that sets the entanglement rate of multi-qubit gates and also influences quantum crosstalk.

## 22: A Hybrid Quantum-Classical Computing Ecosystem for Practical Quantum Advantage

Gokul Ravi
*University of Michigan*

I will discuss recent work related to : a) classical simulation methods to bootstrap variational quantum algorithms, b) scalable error mitigation techniques to boost fidelity on NISQ devices, c) lightweight decoders for quantum error correction.

## 23: Entanglement-enhanced Quantum Sensing for the Laser Trap Ra Atomic EDM Search

Himanshi Himanshi, Yousuf Alishan, Gordon Arrowsmith-Kron, Kevin G. Bailey, Michael N. Bishof, Aiden R. Boyer, Peter Mueller, Thomas P. O'Connor, Jaideep Singh
*Michigan State University*

The search for a non-zero electric dipole moment (EDM) could lead to revealing new sources of charge parity (CP) and time (T)-reversal symmetry violations, potentially explaining the baryon asymmetry of the universe and signaling physics beyond the Standard Model. Radium-225 nuclei, with their distinctive pear-shaped structure and enhanced nuclear Schiff moment, are particularly promising for atomic EDM investigations. At the Facility for Rare Isotope Beams (FRIB), we are currently developing offline upgrades to the Ra EDM experiment at Argonne National Laboratory.

Our research focuses on the possibility of implementing two advanced quantum techniques to significantly improve the detection efficiency of the Ra EDM search protocol. Firstly, we explore the application of quantum non-demolition (QND) measurements, a technique successfully employed in a recent Yb-171 EDM search. QND measurements allow repeated observations of the system without disturbing its quantum state, thus enhancing the precision and reliability of the results.

Secondly, we investigate spin-squeezing entanglement, recently proposed for a Fr electron EDM search. Spin-squeezing techniques can reduce quantum noise and improve measurement sensitivity beyond the standard quantum limit, providing a substantial enhancement in statistical sensitivity of the EDM search.

In combination with other experimental upgrades, these quantum sensing techniques aim to improve the sensitivity of the Ra EDM experiment by at least three orders of magnitude, potentially opening new frontiers in our understanding of fundamental physics.

## 24: Charge state control of the negatively charged nickel vacancy defect in diamond

Ian Morris, Tobias Lühmann, Kai Klink, Logan Crooks, David Hardeman, Shannon S. Nicley, Sébastien Pezzagna, Jan Meijer, Jonas N. Becker

*Michigan State University*

Crystal defects in diamond, such as the nitrogen vacancy (NV) and group-IV vacancy (SiV, GeV, SnV) centers have emerged as leading qubit candidates and have been used in numerous proof-of-principle experiments. However, they face several orthogonal challenges, with the NV's lack of inversion symmetry affecting its spectral properties and the group-IV vacancy's electronic structure resulting in short electron spin coherence times above mK temperatures. Recently, the negatively charged nickel vacancy (NiV-) was identified as a promising inversion-symmetric defect with a favorable electronic and spin structure and the potential to overcome some of these remaining limitations. Similar to the heavier group-IV centers, the NiV- has an orbital and spin doublet ground state featuring large spin-orbit splitting on the order of 700 GHz, reducing phonon-induced spin decoherence. However, unlike the group-IV centers, the NiV- features an excited state orbital singlet and spin doublet, enabling efficient optical control of the ground state spin requiring only small transverse magnetic fields. Despite this, like with other diamond defects, charge state stability remains an issue of paramount importance. Here, we use all-diamond p-i-p junctions made by ion-implantation to gain control over the Fermi level and study the charge state stability of the NiV-. We demonstrate charge state control at resonant excitation by applying bias voltages across the junctions. Further, we identify second-order Stark shifts by exploring the bias-dependence of resonant transitions and use this to confirm the inversion symmetry of the defect. Overall, this work contributes to a more general understanding of the charge state dynamics within diamond and provides a pathway for all-optical control of the NiV- for quantum network and computation applications.

## 25: Next Steps in the Rare Isotope-Containing Diamond Color Centers for Fundamental Symmetry Tests

Ismail A. Buliyaminu, Jose L. Mendoza-Cortes
*Michigan State University*

The measurement of a non-zero permanent electric dipole moment (EDM) within atomic nuclei, induced by the nuclear Schiff moment, is crucial for addressing some of the universe's most fundamental questions. The discovery of an EDM would imply the violation of both time reversal (T) and parity (P) symmetries, and consequently, CP symmetry as preserved by the CPT theorem. This study primarily focuses on designing materials with high sensitivity to EDM measurements. Certain pear-shaped nuclei, particularly 229Pa, have been predicted as good candidates for EDM sensitivity. Embedding these nuclei in synthetic diamond optical crystals can create defects with well-defined, molecule-like structures and isolated electronic states within the diamond band gap.

We employed spin-polarized density functional theory to investigate the structure and electronic properties of crystal defects in diamond containing 229Pa, a rare isotope predicted to exhibit exceptionally strong nuclear octupole deformation [1]. We calculated formation and cohesive energies for different defect configurations to determine the most stable one. Additionally, we identified and examined stable lanthanide-containing defects, specifically 141Pr defects in diamond, with similar electronic structures as nonradioactive proxies to facilitate experimental methods.

Future work will focus on extending our investigations to other rare isotopes and elements, examining the effects of applied electric fields or strain on the EDM, and optimizing the defect-engineering process to enhance sensitivity. Our continued research aims to further explore the potential of these diamond color centers in fundamental symmetry tests and develop new methodologies for EDM measurements across various elements.

References:
[1] Morris IM, Klink K, Singh JT, Mendoza-Cortes JL, Nicley SS, Becker JN. 2023 Rare isotope-containing diamond colour centres for fundamental symmetry tests. Phil. Trans. R. Soc. A 382: 20230169. https://doi.org/10.1098/rsta.2023.0169

## 26: Strong Light-Matter Interactions of Nanophotonics and Ytterbium Atom Arrays for Quantum Information Science

Jacob Barnhart
*University of Michigan*

## 27: Measurement Reduction for Quantum Error Correction Methods via K-Commutativity

Jeremiah Rowland, Ryan LaRose
*Michigan State University*

Robust error mitigation schemes suffer from poor scaling in the number of measurements as a function of system size as a result of exponential growth in the number of stabilizer group elements [1,2,3]. Leveraging the idea of k-commutativity [4] in certain error correcting codes, we show that we can reduce the depth of measurement circuits for simultaneous diagonalization by diagonalizing over subsystems of physical qubits. By implementing simultaneous diagonalization, we show that we can significantly reduce the measurement complexity which results from the exponential growth of the stabilizer group. By identifying k-commutativity properties for group elements of stabilizer codes, we can reasonably implement simultaneous diagonalization, reducing the effect of poor scaling with respect to the number of physical qubits, thereby enabling more robust error mitigation.

Citations:
[1] D. Bacon, "Operator quantum error-correcting subsystems for self-correcting quantum memories", Physical Review A 73, 10.1103/physreva.73.012340 (2006).
[2] P. W. Shor, "Scheme for reducing decoherence in quantum computer memory", Physical Review A 52, R2493–R2496 (1995).
[3] A. Y. Kitaev, "Quantum computations: algorithms and error correction", Russian Mathematical Surveys 52, 1191 (1997)
[4] B. DalFavero, R. Sarkar, D. Camps, N. Sawaya, and R. LaRose, k-Commutativity and Measurement Reduction for Expectation Values, 2023.

## 28: Hybrid Si3N4/ScAlN platform for enhanced quantum photonics

Jiangnan Liu, Shuai Liu, Abdur-Raheem Al-Hallak, Pierre-Luc Thériault, You Wu, Stéphane Kéna-Cohen, Mack Kira, Moe Soltani, Zheshen Zhang, Zetian Mi
*University of Michigan*

Scandium-doped aluminum nitride (ScAlN) has demonstrated strong optical nonlinearity that is possibly surpassing LiNbO3. Here, we present a microring resonator device with Q-factor of 140,000 based on a hybrid structure to harness the strong nonlinearity in ScAlN by integrating it with the ultralow-loss Si3N4 platform for quantum photonics.

## 29: Innovation at Zero Point Cryogenics

Dr. John P. Davis
*Zero Point Cryogenics Inc.*

At Zero Point Cryogenics, our mission is to make the world's best cryogenic systems, ensuring that your quantum experiments run smoothly for years. We strive to stay at the cutting edge of cryogenic technology, constantly improving our systems in terms of performance, longevity, and ease of use, while also developing new product lines to meet the ever changing demands of quantum experiments. Here, we will describe some our most recent innovations and highlight the benefits of our various systems.

## 30: Atomistic polarization waves in silicon carbide

Jungho Mun, Sathwik Bharadwaj, Zubin Jacob
*Purdue University*

Refractive index quantifies the light-matter interaction inside a matter and describes the behavior of light in the medium, but this description is valid for macroscopic planewaves where classical homogenization has been taken. A more general description of light in solids should consider the nonlocal, inhomogeneous, and multiple-scattering nature of the optical responses in the atomic lattices. In this Poster, we examine the atomistic optical lattice eigenwaves of a silicon carbide, an important semiconducting material for single-photon quantum sources. This description unveils that multiple optical eigenmodes exist in crystalline solids. Also, we utilize these optical eigenmodes to analyze the effective screening strength experienced by a macroscopic planewave to obtain the nonlocal macroscopic dielectric constant. Our work predicts the existence of hidden or dark eigenwaves inside crystalline solids and presents a general theoretical framework for picoscale electrodynamics.

## 31: Quantum Microwave's role in Quantum Computing

Justin Cobin, Andy Cobin
*Quantum Microwave Components LLC.*

Andy and I will be presenting our product portfolio and how our company operates within the Quantum market

## 32: Quantum effects in semi-conductor materials

Yuki Kobayashi, Katherine B. Lawrence, Kanchan Shaikh, Taejun Yoo, Zeyuan Zhu
*University of Michigan*

Investigating how the quantum-mechanical nature of electrons contribute to chemistry, such as reactivity, optical and electric responses, light harvesting, and signaling using different spectroscopic techniques.

## 33: Controlled Analytic Continuation of Matsubara Response Functions

Lei Zhang, Emanuel Gull
*University of Michigan*

Analytical continuation is a central step in the simulation of finite-temperature field theories in which numerically obtained Matsubara data is continued to the real frequency axis for physical interpretation. Numerical analytic continuation is considered to be an ill-posed problem where uncertainties on the Matsubara axis are aplified exponentially. Here, we present a systematic and controlled procedure that approximates any Matsubara function by a minimal pole representation to within a predefined precision. We then show systematic convergence to the exact spectral function on the real axis as a function of our control parameter for a range of physically relevant setups. Our methodology is robust to noise and paves the way towards reliable analytic continuation in many-body theory and, by providing access to the analytic structure of the functions, direct theoretical interpretation of physical properties.

## 34: Control of Electrons on Helium using NV Centers in Diamond

Logan Crooks, Shannon S. Nicley, Jonas N. Becker
*Michigan State University*

Electrons trapped at the surface of superfluid helium (eLHe) are a highly promising quantum system for quantum information processing applications, due to their expected long spin coherence times of >100s [1]. However, due to weak interactions with their environment and lack of optically addressable transitions, access to their spin degree of freedom has yet to be demonstrated. Our goal is to create a hybrid system combining eLHe with nitrogen-vacancy (NV) defects in single-crystal diamond, acting as optically accessible atom-sized quantum magnetometers and coherent spin interfaces. This will enable us to leverage the so far inaccessible (dark) spins of eLHe as a resource for quantum computation as well as to image the large scale structure and exotic spin textures of this two-dimensional electron system. Control nearby dark spins in diamond itself (such as substitutional nitrogen centers) via optically-controlled NV centers has been demonstrated previously, e.g. via Hartmann-Hahn coupling in a single- or double-rotating frame. [2,3,4]. Our approach uses similar techniques to couple to electrons trapped above an approx. 30nm thick noble gas layer on top of an engineered diamond substrate. We here present preliminary system and device designs as well as first proof-of-principle NV control, including antenna construction for RF control of the NV, and the custom construction of a scanning confocal microscope within a dilution refrigerator.

References:
[1] Lyon, S. A. (2006). Physical Review A, 74(5), 052338.
[2] Belthangady, C. et al. (2013). Physical Review Letters, 110(15), 157601.
[3] Degen, M. J. et al. (2021). Nature Communications, 12(1), 3470.
[4] Bartling, H. P. et al. (2023). arXiv:2311.10110.

## 35: Driving a Parametrically Modulated Spin Chain into a Topologically Nontrivial Regime

Mahmoud T. Elewa, Mark Dykman
*Michigan State University*

We study a resonantly modulated spin chain in a strong magnetic field. The spin dynamics in the rotating frame maps on the Kitaev chain. By varying the modulation frequency, the chain can be bought into a topologically nontrivial regime. We show that in this regime, the response to slow turning on the drive becomes nonadiabatic. The system displays a history-dependent behavior. It depends on how the drive parameters are changed so the system enters the topological regime, given that initially the spin system is in its ground state.

## 36: SALSA: How to Screen Earth-Abundant Semiconductors for Artificial Photosynthesis

Marcus Djokic, Sean M. Stafford, Alexander Aduenko, Yu-Hsiu Lin, Jose L Mendoza-Cortes
*Michigan State University*

We present a highly efficient workflow for designing semiconductor structures with specific physical properties, which can be utilized for a range of applications, including photocatalytic water splitting. Our algorithm generates candidate structures composed of earth-abundant elements that exhibit optimal light-trapping, high efficiency in H2 and/or O2 production, and resistance to reduction and oxidation in aqueous media. To achieve this, we use an ionic translation model trained on the Inorganic Crystal Structure Database to predict over 30000 undiscovered semiconductor compositions. These predictions are then screened for redox stability under hydrogen evolution reaction or oxygen evolution reaction conditions before generating thermodynamically stable crystal structures and calculating accurate bandgap values for the compounds. Our approach results in the identification of dozens of promising semiconductor candidates with ideal properties for artificial photosynthesis, offering significant advancement toward the conversion of sunlight into chemical fuels.

## 37: Quantum-state tomography of electric fields using valleytronics

Markus Borsch, Zetian Mi, Rupert Huber, Mackillo Kira
*University of Michigan*

Lightwave electronics [1] leverages optical-carrier waves as fast biasing fields to coherently drive electronic quantum states much faster than detrimental scattering processes. In earlier studies [2], we demonstrated that lightwave electronics can switch the valley pseudospin of coherent excitons in valleytronic materials faster than 5 fs using strong THz lightwaves. Here, we discuss how lightwave valleytronic switching can be functionalized to measure electric fields with extreme sensitivity and perform quantum-state tomography on lightwaves.

[1] M. Borsch, M. Meierhofer, R. Huber, and M. Kira. Lightwave electronics in condensed matter. Nat Rev Mater 8, 668–687 (2023).
[2] F. Langer et al. Lightwave valleytronics in a monolayer of tungsten diselenide. Nature 557, 76–80 (2018).

## 38: Adiabatic Quantum Computing for State Preparation of Ising Model Hamiltonian

Matthew Patkowski, Dean Lee, Katharine Hunt
*Michigan State University*

Adiabatic Quantum Computing offers a possibly efficient means of preparing ground states of a desired Hamiltonian by beginning with the ground state of a simple Hamiltonian and slowly changing it to the desired one. Ideally, evolving at an infinitely slow pace, this procedure will yield the exact ground state of the desired Hamiltonian. At finite evolution times, adiabatic time evolution can still generate a final state with a large overlap with the actual ground state, which can then be evolved into the exact ground state through other algorithms such as the Rodeo Algorithm. We test the efficacy of this procedure through an Ising Model Hamiltonian, constructing a larger chain by adiabatically coupling smaller disconnected blocks of the Hamiltonian. Additionally, we use the band theory of solid-state physics to predict the energy gap between the ground state and the first excited state, a parameter for determining the success probability of the adiabatic evolution.

## 39: Enhanced exciton transport in 1D guides

Matthias Florian, Zhaohan Jiang, Zidong Li, Kanak Datta, Markus Borsch, Qiannan Wen, Mackillo Kira, Parag B. Deotare
*University of Michigan*

Exciton transport dynamics is investigated in a one-dimensional (1D) exciton guide at room temperature. Spatial engineering of the exciton energy in a WSe2 monolayer is achieved using local strain and coupling to photonic modes in order to confine as well as direct exciton transport. In a joined theory-experiment afford we show that the exciton drift velocity monotonically increases at elevated exciton densities due to contributions from non-equilibrium many-body effects [1]. We also demonstrate how spatial modulations of the photonic environment can be utilized to control the exciton lifetime and accelerate the transport dynamics.

[1] Z. Li et al. ACS Nano 17, 22410 (2023)

## 40: Optimization of substitutional phosphorus in n-type diamond

Milos Sretenovic, Sarah P. Frechette Roberts, Alex J. Loomis, Luke Suter, Aaron Hardy, Matthias Muehle, Timothy P. Hogan, Jonas N. Becker, Shannon S. Nicley
*Michigan State University*

n-type diamond holds great potential for a wide array of technological applications, including quantum computing and sensing. Phosphorus is currently the most promising n-type dopant and has high potential for quantum devices. For example, long spin-coherence times in phosphorus-doped diamond has led to increased sensitivities of nitrogen-vacancy (NV) sensors, improved quantum fidelity, and longer quantum-memory times [1]. In addition, its inclusion in p-i-n junctions has been used to create single-photon sources which have applications in quantum communication, computing, and metrology [2]. Yet major challenges still exist such as phosphorus's low incorporation rate and a tendency to form phosphorus-vacancy complexes that compensate substitutional phosphorus atoms and reduce overall conductivity [3]. Achieving controllable levels of P is an area of significant interest [4-6] and so controlled parameter studies of the growth of P-doped diamond are needed.

To observe the substitutional behavior of phosphorus-doped diamond, we plan to grow two series of single-crystal P-doped diamond samples, one isothermal series and another isobaric series by Microwave-Plasma Assisted Chemical Vapor Deposition (MPACVD) using phosphine feed gas on (111) oriented single-crystal diamond substrates. Our eventual goal will be to determine the optimized growth conditions for substitutional phosphorus and n-type conductivity.

References

1. N. Mizuochi, "Control of Spin Coherence and Quantum Sensing in Diamond" in Hybrid Quantum Systems, Y. Hirayama, K. Ishibashi, K. Nemoto, Eds., (Springer, Singapore 2021), 1-11.
2. N. Mizuochi, et al., Nat. Photonics. 6, (2012) 299.
3. R. Jones, et al., Appl. Phys. Lett. 69, (1996) 2489.
4. R. Ohtani, et al., Appl. Phys. Lett. 105, (2014) 232106.
5. H. Kato, et al., Appl. Phys. Lett. 109, (2016) 142102.
6. T. A. Grotjohn, et al., Diamond Relat. Mater. 44, (2014) 129.

## 41: Collective decay of atoms in 1D waveguides

M. Eltohfa, F. Robicheaux
*Purdue University*

When atoms are placed near each other, they show collective behavior different from that of an individual atom. In the Dicke model, a system of atoms is characterized by the fast decay of the electronic excited state, or superradiance of the photons emitted. The atoms can also exhibit slow decay, or subradiance, in some configurations. We study how the motion of atoms in a 1D waveguide affects their collective decay rates. We also investigate the kicks imparted on the atoms during the decay process. We find a lower limit of the decay rate for a two atom system. Additionally, we investigate the entanglement between the electronic, motional, and photon degrees of freedom during the emission process. This sheds light on the purity of the states of atoms or photons used for quantum information or quantum computing.

## 42: Quantum Natural Stochastic Pairwise Coordinate Descent

Mohammad Aamir Sohail, Mohsen Heidari, Sandeep Pradhan
*University of Michigan*

Quantum machine learning through variational quantum algorithms (VQAs) has gained substantial attention in recent years. VQAs employ parameterized quantum circuits, which are typically optimized using gradient-based methods. However, these methods often exhibit sub-optimal convergence performance due to their dependence on Euclidean geometry. The quantum natural gradient descent (QNGD) optimization method, which considers the geometry of the quantum state space via a quantum information (Riemannian) metric tensor, provides a more effective optimization strategy. Despite its advantages, QNGD encounters notable challenges for learning from quantum data, including the no-cloning principle, which prohibits the replication of quantum data, state collapse, and the measurement postulate, which leads to the stochastic loss function. This paper introduces the quantum natural stochastic pairwise coordinate descent (2-QNSCD) optimization method. This method leverages the curved geometry of the quantum state space through a novel ensemble-based quantum information metric tensor, offering a more physically realizable optimization strategy for learning from quantum data. To improve computational efficiency and reduce sample complexity, we develop a highly sparse unbiased estimator of the novel metric tensor using a quantum circuit with gate complexity (1) times that of the parameterized quantum circuit and single-shot quantum measurements. Our approach avoids the need for multiple copies of quantum data, thus adhering to the no-cloning principle. We provide a detailed theoretical foundation for our optimization method, along with an exponential convergence analysis. Additionally, we validate the utility of our method through a series of numerical experiments.

## 44: Cyclic Time Evolution as a Benchmark of Digitized Adiabatic Evolution

Nathan Jansen, KLC Hunt
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In applications of adiabatic quantum computing, the quantum system is initialized in the known ground state of a simple Hamiltonian H, and then evolved under a slowly varying perturbation to obtain the ground state of a more complex problem Hamiltonian H'. By the adiabatic theorem of Born and Fock, if the variation of H to H' is carried out sufficiently slowly, assuming a non-zero gap between the ground and first excited state of the time dependent Hamiltonian, the system will remain in the instantaneous ground state throughout the evolution. In this study, we have drawn inspiration from Randomized Benchmarking by performing a forward and then backward time evolution with the adiabatic quantum computing algorithm. Schrödinger's cat states were prepared by starting in an eigenstate for noninteracting spins in a magnetic field in the x direction, and then converting the Hamiltonian to an Ising-model Hamiltonian with nearest neighbor coupling of the z components of the spins, additional "non-stoquastic" Hamiltonians were investigated with additional random fields and Jxx coupling strengths. By examining the differences between the paths forward and back, we have a potential benchmark for the "adiabaticity" of the algorithm, as well as a possible way to confirm that the evolution ended in the correct final state.

## 46: Application of the Rodeo Algorithm to Complex Systems Using Trotter Decomposition

Onat Ayyildiz
*Michigan State University*

Quantum computing has the potential to address many of the unsolved problems of quantum many-body physics. By allowing for arbitrary linear combinations of tensor products of qubits, one can store exponentially more information than classical bits. This research explores the quantum simulation of a 2D Heisenberg lattice of spin-1/2 particles, represented by qubits. We employ the Rodeo Algorithm to iteratively isolate the desired target eigenstate. The Rodeo Algorithm, which was developed by the Lee Research Group, can compute the full energy spectrum and prepare any energy eigenstate. It has been successfully applied to less complex systems.

The goal of this research is to extend its application to more complex Hamiltonians by utilizing Trotter decomposition for time evolution and incorporating controlled reversal gates to improve accuracy of our numerical computation of the time evolved Hamiltonian. Our approach aims to demonstrate the feasibility and effectiveness of these techniques in simulating complex quantum systems, paving the way for advancements in quantum many-body physics.

## 47: Quantum Evaporative Cooling: Algorithm for Low-Energy State Preparation of Many-Body Systems

Paul-Aymeric McRae, Dean Lee, Morten Hjorth-Jensen
*Michigan State University*

The problem of finding eigenstates of a Hamiltonian is well-studied in the field of quantum computing. However, the convergence of many state-of-the-art eigensolver methods (e.g. Rodeo Algorithm, Quantum Phase Estimation) depends on the overlap between the ansatz state and the target eigenvector. In view of this, we introduce Quantum Evaporative Cooling, an iterative and stochastic quantum computing algorithm which constructs the ground state (or a mixture of low-energy eigenstates) of a Hamiltonian with a localized potential well within some larger volume. The outcome of this algorithm can then be kept as a desired result or used as an ansatz for a second quantum process. In an analogue to classical evaporative cooling, we drive particles far away from our local potential towards the boundaries of our volume. We then eliminate "hot" particles near the boundary and, if no such particles are measured, suppress contributions to the wavefunction located in this boundary region. This method allows us to treat a variety of many-body Hamiltonians and sweep through multiple fixed-particle-number subspaces of such Hamiltonians. Owing to the connection between a chain of qubits and the Fock space of a second-quantized wavefunction, the qubit cost scales linearly with the number of discrete lattice sites in our volume.

## 48

Pranaya Rath
*Michigan State University*

## 49: Quantum Theory of OAM in Spatiotemporal Optical Vortices

Pronoy Das, Sathwik Bharadwaj, Zubin Jacob
*Purdue University*

Spatiotemporal Optical Vortices (STOVs) are structured electromagnetic fields propagating in free space with phase singularities in the space-time domain. Depending on the tilt of the helical phase front, STOVs can carry both longitudinal and transverse orbital angular momentum (OAM). Although STOVs have gained significant interest in the recent years, the current understanding is limited to the semi-classical picture. Here, we develop a quantum theory for STOVs with an arbitrary tilt, extending beyond the paraxial limit. We demonstrate that quantum STOV states, such as Fock and coherent twisted photon pulses, display non-vanishing longitudinal OAM fluctuations that are absent in conventional monochromatic twisted pulses. We show that these quantum fluctuations exhibit a unique texture, i.e. a spatial distribution which can be used to experimentally isolate these quantum effects. Our findings represent a step towards the exploitation of quantum effects of structured light for various applications such as OAM-based encoding protocols and platforms to explore novel light-matter interaction in 2D material systems.

## 50: Cavity- and Twist-Engineering of 2D Magnets

Qiuyang Li, Xin Xie, Adam Alfrey, Wyatt Alpers, Yujie Yang, Liuyan Zhao, Kai Sun, Hui Deng
*University of Michigan*

2D van der Waals (vdW) magnets possess numerous magnetic orders and spin structures and allow the study of magnetism in the 2D limit. Among 2D magnets, CrSBr is an anisotropic 2D semiconducting antiferromagnet, providing a unique platform for manipulating and coupling anisotropy, exciton, and magnetic orders. In this talk, I will discuss exciton and exciton-polariton properties of CrSBr. We form anisotropic, two-dimensional magnetic exciton polaritons by integrating a thin CrSBr with an anisotropic photonic crystal (PC) cavity. In this system, the spin, atomic lattice, and photonic lattices anisotropies are strongly correlated, giving rise to unusual properties of the hybrid system and new possibilities of tuning. We show exceptionally strong coupling between engineered anisotropic optical modes and anisotropic excitons in CrSBr and a highly tunable polariton polarization by tens of degrees by controlling the matter-light coupling via, for instance, spatial alignment between the material and photonic lattices, magnetic field, temperature, cavity detuning and cavity quality-factors. Interestingly, twist-engineering of two CrSBr monolayers also leads to new exciton states, as a result of the interplay between anisotropy and magnetic interactions. The cavity- and twist-engineering on 2D magnets open opportunities for both fundamental studies of low-dimensional systems and photonic technology.

## 51: Adapting structure factor twist averaging for low-dimensional materials

Ryan A. Baker, William Z. Van Benschoten, James J. Shepherd
*Michigan State University*

Wavefunction-based methods allow for highly accurate electronic structure calculations, which can be critical for detailing unique properties of materials from bulk solids to low-dimensional surfaces. Work from our group utilizing the transition structure factor (TSF), which relates a solid's correlation energy contribution to the corresponding many-body wavefunction, has been used to achieve twist-averaged (TA) CCSD level accuracy at a reduced cost (roughly a single calculation) [https://doi.org/10.1038/s43588-021-00165-1]. Normally twist-averaging requires tens to hundreds (or more) of calculations to be repeated, scaling the cost proportionally. Here, we adopt that structure factor twist averaging (sfTA) method for 2D systems, and develop it to reduce the cost for estimating twist-averaged interlayer binding energies between real monolayer- and bi-layer systems of various chemical and structural compositions. We Our development is to define a binding TSF analogous to the original TSF, which relates the interlayer binding energy to a difference between the mono-layer TSF and bi-layer TSF. We compare our sfTA calculation results with another common single calculation, -point, using the TA-CCSD energy. We observe that our method generally outperforms the -point calculation as indicated by better agreement with the TA-CCSD interlayer binding energy. These results are consistent with the observations for bulk solids made in the original sfTA method.

## 52: Apparent statistical transmutation of bosons and fermions in an extended collider

Sai Satyam Samal, Smitha Vishweshwara, Yuval Gefen and Jukka Vayrynen
*Purdue University*

Collision of quantum particles remains an effective way of probing their mutual statistics. Colliders based on quantum point contacts in quantum Hall edge states have been successfully used to probe the underlying statistics of quantum particles. Although an extensive amount of research has been done with point-like colliders, it is worth noting that these colliders might have a resonant level or multiple tunneling points and may not be truly point-like. Here we study bosonic and fermionic colliders with an extended, non-point-like geometry. Comparing the zero-frequency cross current correlations at the detectors with the classical benchmark shows an apparent statistical transmutation of bosons and fermions. Notwithstanding this apparent statistical transmutation (or observation), we define an irreducible cross current correlator which reveals the true statistical nature of fermions and bosons. We also show that the density-density correlations at the detectors also captures the exclusion property of the colliding particles.

## 53: Superradiantly coupled trapped atomic ensemble on an integrated photonic circuit

Xinchao Zhou, Hikaru Tamara, Tzuhan Chang, Saivirinchi, Dipanjan Das, Chen-lung Hung
*Purdue University*

Interfacing cold atoms with integrated nanophotonic devices could offer new paradigms for engineering atom-light interactions and provide a potentially scalable route for quantum sensing, metrol- ogy, and quantum information processing. However, it remains a challenging task to efficiently trap a large ensemble of cold atoms on an integrated nanophotonic circuit. Here, we demonstrate direct loading of an ensemble of up to 70 atoms into an optical microtrap on a nanophotonic microring circuit. Efficient trap loading is achieved by employing degenerate Raman-sideband cooling in the microtrap, where a built-in spin-motion coupling arises directly from the vector light shift of the evanescent field potential on a microring. Atoms are cooled into the trap via optical pumping with a single free space beam. We have achieved a trap lifetime approaching 700ms under continuous cooling. We show that the trapped atoms display large cooperative coupling and superradiant decay into a whispering-gallery mode of the microring resonator, holding promise for explorations of new collective effects.

## 54: Collective Effect in Yb Atom Arrays for Quantum Science

Saiwei Nie, Alex Burgers
*University of Michigan*

Neutral atoms trapped in arrays of optical tweezers is a cutting-edge platform for quantum information science. These tweezers offer precise spatial control over atoms, enabling arbitrary system geometries and coherent transport of atoms. Such programmable setups facilitate the investigation of collective dynamics within ordered atomic arrays. The interaction between atoms in these arrays gives rise to collective phenomena that significantly influence the system's optical properties. Specifically, the scattering behavior of atoms at the same optical transition wavelength is perturbed by neighboring atoms, leading to cooperative interference effects—either enhancing (super-radiance) or suppressing (sub-radiance) the emitted radiation. This poster explores the controlled manipulation of collective responses in such systems, with applications spanning quantum memories, precision sensors, and the generation of non-classical states of light using atomic photonic elements. Leveraging long-wavelength transitions within the telecom band (1.4 um to 1.9 um) connected to coherent metastable states in ytterbium (Yb), we investigate how these transitions interact with shorter tweezer trapping distances. Our work presents advancements toward probing and harnessing collective effects in atom arrays, paving the way for enhanced quantum technologies and fundamental quantum science exploration.

## 55: Multiphysics Numerical Methods for Designing Superconducting Quantum Computers

Samuel T. Elkin, Thomas E. Roth
*Purdue University*

Superconducting qubits are one of the leading architectures for producing commercially-viable quantum computers. However, reaching this milestone requires substantial improvement in the fidelity of qubit control and readout. Existing techniques for modeling these operations do not possess the accuracy, efficiency, and robustness necessary to form effective design aids. Here, we introduce a set of multiphysics numerical methods intended to bridge the gap between the capabilities of available tools and the modern needs of device designers. First, a Maxwell-Schrödinger method is presented as a high-fidelity approach to model the interaction between superconducting qubits and microwave circuitry. Additionally, a method for modeling Josephson traveling-wave parametric amplifiers, a core component of the readout circuitry, is introduced to enable analysis of non-ideal effects in these devices. These methods are combined to form the first-ever co-simulation method for multiplexed qubit readout. In the future, the numerical methods will be expanded to incorporate qubit-qubit interactions, integrate quantum noise sources, and enable direct estimation of readout fidelity.

## 56: Quench dynamics of attractive Bose gases in an optical box

Sambit Banerjee, Hikaru Tamura, Kai Zhou, Shiva Kant Tiwari, Rongjie Li, and Chen-Lung Hung
*Purdue University*

Atomic quantum gases confined in a box potential offer a versatile platform for studying non-equilibrium dynamics induced by interaction effects, vorticity, as well as effects of the box or an addressing potential. In this poster, we present our investigations of different quench-induced dynamics under two scenarios: multi-mode breathing dynamics in a quasi-one-dimensional (1D) Bose gas under attractive interactions, as well as collapse to a "vortex soliton" state in a rotating 2D gas. In the first case, we prepare a quasi-1D gas, and monitor evolutions of both local density and phase fluctuations after a quench from repulsive to attractive interaction. We observe recurring gain and loss of phase coherence, and periodic density modulation, resulting from the nonlinear stage of modulational instability. In the second case, we create a quantum vortex in a homogeneous 2D superfluid and observe that for a certain interaction strength, a 2D gas can evolve into a self-trapped state with a donut-shaped profile during a 2D time-of-flight (TOF), forming a vortex soliton carrying one unit of angular momentum. We also study the eventual fragmentation of such a rotating gas at different interactions. At more attractive interactions, instead of converging radially, the gas forms a necklace of Townes solitons. We observe a surprising universal scaling in the evolution of the density power spectrum during fragmentation as well as universal timescales for the azimuthal collapse dynamics.

## 57: The Effects of Low Methane Concentrations Chemical Vapor Deposition of High-Quality Single Crystal Diamond

Sarah P. Frechette Roberts, Alex J. Loomis, Aaron Hardy, Jonas N. Becker, and Shannon S. Nicley
*Michigan State University*

Previous work on the chemical vapor deposition (CVD) of single crystal diamond demonstrated the operation of a high power density and high pressure microwave plasma assisted chemical vapor deposition (MPACVD) reactor and studied operation conditions such as pressure, substrate temperature, and methane (CH4) composition [1]. Because this reactor was designed to increase growth rate, higher gas phase methane concentrations were explored, from 3 percent to 9 percent. However, the effects on single crystal diamond growth quality due to methane concentrations below 3 percent were not explored. Here, low methane concentrations, 3 percent and below, in the gas phase were studied. Three (100) CVD diamond substrates (MTI) were used for three depositions at various low methane percentages. All depositions were performed at 320 mbar (240 torr), 2000-2100 W, and a total gas flow rate of 400 SCCM. The methane percentages used were 3 percent, 2 per-cent, and 1 percent of the total gas phase gas composition. Each sample was characterized using differential interference contrast microscopy (DICM), birefringence imaging, Fourier Transform Infrared (FTIR) spectroscopy, ultra-violet and visible spectroscopy (UV-Vis), and Raman spectroscopy to determine the quality of the growth. Vertical growth rate was deter-mined by thickness measurements taken before and after deposition on a linear encoder. Growth rate decreased as methane concentration in the gas phase decreased. All samples exhibited step flow growth, indicative of good quality growth. Spectroscopic results showed an increase in nitrogen vacancy defects as methane concentrations decreased.

References

[1] Y. Gu, et al., Diam. Relat. Mater., 24, (2012). 210-214

## 58: Rare-Earth Metal Complexes in Molecular Qubit Design

Saroshan Deshapriya, Selvan Demir
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Molecular spin qubit systems allow higher tunability and customization over conventional solid-state qubits. Unique electronic structures possessed by rare-earth metals can be tailored to address problems in quantum information science through the utilization of appropriate ligand systems and metal oxidation states to mitigate spin decoherence and improve qubit performance.

## 59: Towards a magnetic centrifuge decelerator of polar molecules for testing fundamental symmetries of the universe

Sebastian Miki-Silva, Nicholas Emtage, Monika Fouad, Kyle Taft, Bjorn Vetne, Xing Wu
*Michigan State University*

Searching for a non-zero permanent electric dipole moment (EDM) of fundamental particles sheds light on physics beyond the Standard Model. Particularly, a non-zero EDM is a signature of additional CP violating interactions which are required to explain the observed asymmetry between matter and anti-matter in our Universe. Polar molecules containing 225Ra offer a quantum metrology platform with enhanced EDM interactions due to the molecules large internal electric field and parity doublet from the heavily deformed 225Ra nuclei. To make a precision measurement on their energy spectrum that can resolve the CP-violating interactions, these molecules need to be slowed down and cooled to the ultracold regime (1 mKelvin). Here we present a method for slowing molecules to a standstill using a centrifuge decelerator. The decelerator guides the molecules through a centrifugal potential hill that removes kinetic energy as the molecules move from the periphery to the center of the rotating frame. The method is shown to have higher yield, density, and efficiency than current molecular slowing schemes. Additionally, we present progress towards designing and constructing a second decelerator using a magnetic molecular guide.

## 60: Resolving a THz-induced phase transition in WTe2 on the sub-atomic scale with THz-STM

Vedran Jelic, Stefanie Adams, Daniel Maldonado-Lopez, Ismail Buliyaminu, Mohamed Hassan, Trevor Hickle, Jose L. Mendoza-Cortes and Tyler L. Cocker

*Michigan State University*

The discovery of topologically protected states has had a lasting impact on condensed matter research, leading to countless theoretical and experimental discoveries of new topological phases in materials. Amongst these, the transition metal dichalcogenide WTe2 has been proposed as a candidate type-II Weyl semimetal that hosts Weyl points at the contact points of electron and hole pockets. More recently, an experimental THz pump / ultrafast electron diffraction probe study of WTe2 has indicated that strong THz fields can drive a structural phase transition from the Weyl semimetal ground state into a trivial semimetal phase through an interlayer shear motion that restores lattice inversion symmetry. However, this study primarily relied on measurements of the lattice symmetry to deduce the topological transition and did not have access to the electronic properties of either phase. Here, we show that terahertz scanning tunneling microscopy (THz-STM) can both drive the phase transition of WTe2 via the enhanced THz fields at the STM tip apex and distinguish the electronic phases. We find evidence for the phase transition through THz-induced changes to the local density of states and real-space imaging, both supported by DFT calculations. The spatial contrast between the phases enables us to perform THz-STM imaging with unprecedented spatial resolution – down to the 10 picometer scale – revealing subtle differences in the surface electronic wavefunctions as the atomic positions distort and the lattice planes shift across the transition. The possibility of finely adjusting the density of states of a material with an ultrafast light field and simultaneously resolving the spatial dependence of the transition on the sub-atomic scale presents a novel way of studying topological phase transitions. Overall, our finding that THz-STM is extremely sensitive to differences between electronic phases is an exciting prospect for further studies of topological materials with THz-driven transitions.

## 61: Ultrafast Photocarrier Dynamics in CsPbBr3 Perovskite Microcrystals

Sheng Lee, Kyeongdeuk Moon, Muhammad Shoaib, Charles N. B. Pedorella, Kellen O'Brien, Meng-Ju Sher, Seokhyoung Kim, Tyler L. Cocker

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We study the ultrafast dynamics of photoexcited charge carriers in micron-scale crystals composed of the inorganic perovskite CsPbBr3 with time-resolved terahertz (THz) spectroscopy. Exciting with photon energy close to the band edge, we find that a fast (< 10 ps) decay emerges in the THz photoconductivity with increasing pump fluence and decreasing temperature, dominating the dynamics at 4 K. The fluence-dependent dynamics can be globally fit by a nonlinear recombination model, which reveals that the primary nonlinear recombination mechanism depends on temperature, with Auger scattering determining the fast decay at 77 K but radiative recombination responsible for the fast decay at 4 K. Spectroscopically, the THz photoconductivity resembles a Drude response at all delays, yet an additional Lorentz component due to an above-bandwidth exciton resonance is needed to fully reproduce the data. The coexistence of excitons with free charge carriers impacts the scale of the recombination coefficients, as the absorbed photon density significantly exceeds the free charge carrier density.

## 62: The Singlet–Triplet Gap of Cyclobutadiene: The CIPSI-Driven CC(P;Q) Study

Swati S. Priyadarsini, Karthik Gururangan, Jun Shen, and Piotr Piecuch
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Determination of the singlet–triplet gap in cyclobutadiene remains a challenging test for modern ab initio methods of quantum chemistry because one has to balance substantial nondynamical correlation effects needed for an accurate description of the low-spin singlet state, which has a multireference character, with the dynamical correlations of the high-spin triplet state, which is predominantly single-reference in nature [1-6]. It is well established that the high-level coupled-cluster (CC) approaches, such as the CC method with a full treatment of singly, doubly, and triply excited clusters (CCSDT), are capable of providing an accurate description of the singlet–triplet gap in cyclobutadiene, but the routine application of such methods is hindered by their high computational costs. Our group has recently developed [7] a practical alternative to converging the high-level CCSDT energetics at a small fraction of the computational cost in a user-friendly black-box manner by merging the CC(P;Q) moment expansions [8-10] with the selected configuration interaction methodology abbreviated as CIPSI [11-13]. By tailoring the expansion of the cluster operator used in CCSDT and using the relatively small CIPSI Hamiltonian diagonalizations to identify the leading triply excited determinants, while incorporating the remaining correlation effects with the help of noniterative CC(P;Q) corrections, we demonstrate that one can converge the CCSDT potential energy curves (PECs) characterizing the lowest singlet and triplet states of cyclobutadiene along the automerization coordinate and the gap between them using a tiny fraction of triply excited cluster amplitudes in the iterative part of the CIPSI-driven CC(P;Q) algorithm [14].

References:

[1] M. Eckert-Maksić, M. Vazdar, M. Barbatti, H. Lischka, and Z. B. Maksić, J. Chem. Phys. 125, 064310 (2006).
[2] T. Saito, S. Nishihara, S. Yamanaka, Y. Kitagawa, T. Kawakami, S. Yamada, H. Isobe, M. Okumura, and K. Yamaguchi, Theor. Chem. Acc. 130, 749 (2011).
[3] A. O. Ajala, J. Shen, and P. Piecuch, J. Phys. Chem. A 121, 3469 (2017).
[4] S. J. Stoneburner, J. Shen, A. O. Ajala, P. Piecuch, D. G. Truhlar, and L. Gagliardi, J. Chem. Phys. 147, 164120 (2017).
[5] A. Chakraborty, S. H. Yuwono, J. E. Deustua, J. Shen, and P. Piecuch, J. Chem. Phys. 157, 134101 (2022).
[6] E. Monino, M. Boggio-Pasqua, A. Scemama, D. Jacquemin, and P.-F. Loos, J. Phys. Chem. A 126, 4664 (2022).
[7] K. Gururangan, J. E. Deustua, J. Shen, and P. Piecuch, J. Chem. Phys. 155, 174114 (2021).
[8] J. Shen and P. Piecuch, J. Chem. Phys. 401, 180 (2012).
[9] J. Shen and P. Piecuch, J. Chem. Phys. 136, 144104 (2012).
[10] N. P. Bauman, J. Shen, and P. Piecuch, Mol. Phys. 115, 2860 (2017).
[11] B. Huron, J. P. Malrieu, and P. Rancurel, J. Chem. Phys. 58, 5745 (1973).
[12] Y. Garniron, A. Scemama, P.-F. Loos, and M. Caffarel, J. Chem. Phys. 147, 034101 (2017).
[13] Y. Garniron, T. Applencourt, K. Gasperich, A. Benali, A. Ferté, J. Paquier, B. Pradines, R. Assaraf, P. Reinhardt, J. Toulouse, P. Barbaresco, N. Renon, G. David, J.-P. Malrieu, M. Véril, M. Caffarel, P.-F. Loos, E. Giner, and A. Scemama, J. Chem. Theory Comput. 15, 3591 (2019).
[14] S. S. Priyadarsini, K. Gururangan, J. Shen, and P. Piecuch, arXiv preprint arXiv:2405.15864

(2024).

## 63: Benchmarking Approximate Coupled-Pair, Completely Renormalized, Active-Space, and CC(P;Q) Coupled-Cluster Methods against DMRG for Singlet–Triplet Gaps in Polyacenes

Tiange Deng, Jun Shen, and Piotr Piecuch
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Encouraged by the excellent performance of the approximate coupled-pair (ACP) methods in a recent investigation of the one-dimensional strongly correlated hydrogen clusters [1] and similarly successful past ACP studies of cyclic polyene model systems [2-7], we present a comprehensive investigation of the adiabatic singlet–triplet gaps in polyacenes composed of two to twelve linearly fused benzene rings. In addition to the ACP method with singles and doubles, abbreviated as ACCSD, and the ACP approaches with connected triply excited clusters, treated using active orbitals (ACCSDt) and noniterative corrections to ACCSD [ACC(2,3)] and ACCSDt [ACC(t;3)], we present the results of the conventional CCSD and CCSD(T) computations, completely renormalized CC calculations using the CR-CC(2,3) approach, and calculations using the active-space CCSDt method without and with the a posteriori triples corrections [CC(t;3)]. The singlet–triplet gaps obtained with all of the above approaches have been benchmarked against the highly accurate density matrix renormalization group (DMRG) computations reported in Ref. [8]. In agreement with DMRG and the majority of ab initio studies to date, our calculations show that the ground states of polyacenes are singlets and that the singlet–triplet gaps remain finite, at least up to twelve benzene rings. Generally, the inclusion of the connected triply excited clusters and the use of (T2)2 diagram selections defining the ACP approaches improve the results, with the ACC(t;3) approach, in which the ACCSDt energies are corrected for the remaining triples not captured with active orbitals, being most accurate and offering  1 kcal/mol or better accuracies relative to the DMRG reference data. Comparisons between the ACP [ACCSD, ACC(2,3), ACCSDt, and ACC(t;3)] and the analogous CC [CCSD, CR-CC(2,3), CCSDt, and CC(t;3)] results suggest that polyacenes are not as strongly correlated as stated in some previous studies, although the strength of the many-electron correlation effects in these systems depends on the number of rings and the number of correlated electrons included in post-Hartree-Fock calculations.

[1] I. Magoulas, J. Shen, and P. Piecuch, Mol. Phys. 120, e2057365 (2022).
[2] J. Paldus, J. Čížek, and M. Takahashi, Phys. Rev. A 30, 2193 (1984).
[3] J. Paldus, M. Takahashi, and R. W. H. Cho, Phys. Rev. B 30, 4267 (1984).
[4] P. Piecuch, S. Zarrabian, J. Paldus, and J. Čížek, Phys. Rev. B 42, 3351 (1990).
[5] P. Piecuch and J. Paldus, Int. J. Quantum Chem. Symp. 25, 9 (1991).
[6] J. Paldus and P. Piecuch, Int. J. Quantum Chem. 42, 135 (1992).
[7] P. Piecuch, J. Cizek, and J. Paldus, Int. J. Quantum Chem. 42, 165 (1992).
[8] J. Hachmann, J. J. Dorando, M. Avilés, and G. K.–L. Chan, J. Chem. Phys. 127, 134309 (2007).

## 64: Ultrafast Switching of Quantum-material States

Weiwei Jiang, Mack Kira
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Sufficiently nonresonant optical excitations in quantum matter can switch multi-electrons states extremely fast and most of all coherently. Here, we explain how ultrafast excitations further reduce dephasing as the light driven correlations avoid scattering through quantum-memory effects. We demonstrate how this fundamental feature can be leveraged to reach terahertz-rate photonic quantum-logic operations in quantum materials.

## 65: Nano-Electromagnetic Super-dephasing in Collective Atom-Atom Interactions

Wenbo Sun, Adrian E. Rubio López, Zubin Jacob
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Pure dephasing and spontaneous emission are two non-unitary processes of atoms or spins interacting with fluctuating electromagnetic (EM) modes. Collective spontaneous emission (e.g., superradiance) originates from interactions with EM modes in resonance with atoms and has received considerable attention. Meanwhile, the analogous collective dephasing phenomena remain poorly understood. Here, we introduce the nano-EM super-dephasing phenomenon arising in the photonic environment near lossy material interfaces. We show that this effect is enhanced by over 10 orders of magnitude compared to free space or photonic cavities due to the presence of long-range correlations in low-frequency evanescent EM fluctuations. We unravel the universality of nano-EM super-dephasing behaviors near ferrimagnets, metals, and superconductors and their dependence on low-frequency material properties. We demonstrate that the scaling of nano-EM super-dephasing is independent of EM modes' wavelengths and differs from the conventional $\hat{N2}$ scaling of superradiance by analyzing the decoherence of entangled states, including GHZ states. Finally, we show how to experimentally isolate and control super-dephasing to open interesting frontiers for scalable quantum systems.

## 66: First-principles calculations for the Jellium

William Z. Van Benschoten and James J. Shepherd
*Michigan State University*

We investigate the three-dimensional Jellium using full configuration interaction (FCI) and quantum Monte Carlo FCI (FCIQMC) calculations at two different electron numbers (N). The electron numbers are $2\hat{3}$ and $3\hat{3}$, which are reported to correspond with Wigner crystal formation at low electronic density. We make observations for the momentum distribution and static structure factor across a range of electronic densities. A higher density corresponds to a more gas/fluid like system, while a lower density corresponds towards a more solid like electronic system e.g. the Wigner crystal. We observe several interesting behaviors across the electronic density. Across electronic density, the lowest energy momentum symmetry is found to be dependent on the lattice symmetry. Additionally, we make observations on differences in the ground state momentum distribution and static structure factors.

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## 67: Towards quantum-enhanced test of fundamental symmetries using ultracold radioactive molecules at FRIB

Xing Wu
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Precision measurement of electric dipole moment (EDM) of fundamental particles sets stringent constraints on T-violating new physics beyond the Standard Model. The most sensitive electron EDM and many ongoing nuclear EDM searches are performed with molecules, benefiting from the substantial intra-molecular electric field. At the Facility for Rare Isotope Beams (FRIB), we are building a new generation of EDM searches using ultracold radioactive molecules. This project will leverage the unique opportunity to access pear-shaped nuclei (e.g. 225Ra) at FRIB, and the state-of-the-art technology in precision measurement using polar molecules. The former amplifies the Nuclear Schiff Moment and hence the sensitivity to hadronic CP-violation, thanks to the nuclear octupole deformation. The latter, built upon recent advances in atomic and optical physics, aims to bring the 225Ra-containing molecules into the ultracold regime, where both high phase-space density and seconds-long spin precession time have been demonstrated. With the nuclear enhancement and the quantum upgrades combined, this new project envisions to enhance the EDM sensitivity by orders of magnitude from the current best effort.

## 68: Quantum Soft Covering and Decoupling with Relative Entropy Criterion

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*University of Michigan*

We propose quantum soft covering problems for fully quantum channels and classical-quantum (CQ) channels using relative entropy as a criterion of operator closeness. We prove covering lemmas by deriving one-shot bounds on the rates in terms of smooth min-entropies and smooth max-divergences, respectively. In the asymptotic regime, we show that for quantum channels, the rate infimum defined as the logarithm of the minimum rank of the input state is the coherent information between the reference and output state; for CQ channels, the rate infimum defined as the logarithm of the minimum number of input codewords is the Helovo information between the input and output state. Furthermore, we present a one-shot quantum decoupling theorem with relative entropy criterion. Our results based on the relative-entropy criterion are tighter than the corresponding results based on the trace norm considered in the literature due to the Pinsker inequality.

## 69: Flowsheet Optimization of Pharmaceutical Manufacturing Process using Quantum Annealing

Yirang Park, David E. Bernal Neira
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Pharmaceutical industry has had its unique challenges in improving and effecting changes to the manufacturing practices due to the process complexity, logistical burden from regulatory oversight and procedures, and outdated product-centric operating strategy. With the global push for sustainability and the rising cost of research and development, the industry is motivated to adopt more efficient manufacturing practices, and one venture is adaption of continuous manufacturing for its potential benefits of robustness, easier control, and less waste. There is a need for quantitative and systematic approach to compare different modes of operations and process configurations in this transition. Flowsheet optimization is well-suited for this purpose, especially in a highly regulated environment like the pharmaceutical manufacturing sector, as it is a powerful tool to perform quantitative tech-economical analyses and comparisons of multiple process configurations without excessive capital investment.

In literature, there has been similar efforts using a simulation-based optimization where initial decision variable values are used to simulate the process, and the simulation output values are used to evaluate the objective function. This value is used to tune the decision variables in the next iteration, and this iterative cycle continues until the objection function value is not improved within the desired tolerance. While this approach enables optimization of a complex, nonlinear process, simulations are computationally expensive, and only select number of different configurations can be evaluated as a result to compensate for the cost. In this work, we propose to formulate the configuration design or decision as a quadratic unconstrainted binary optimization problem to accelerate the overall optimization and solve it using quantum computing.

In a case study of drug substance manufacturing process of a small molecule, various flowsheet configurations are examined for the purpose of minimizing the overall cost of production. The drug production process involves two reactions, solvent switch, crystallization, and filtration. The disjunctive choices involve batch or continuous unit operations; in total, three operational modes are explored: continuous, batch, and hybrid configurations. A superstructure is developed to encapsulate all configurations or combinations of unit operations w¬ith three decision variables (batch or continuous): reactor type, crystallizer type and number of units, and vaporizer operating mode. The flowsheet structure decisions are posed as a Quadratic Unconstrained Binary Optimization (QUBO) problem and solved through simulated annealing, and the process feasibility and economic analysis of each chosen process configuration are evaluated via flowsheet simulations using a python package, PharmaPy (https://github.com/CryPTSys/PharmaPy/tree/master).

## 70: Towards Entanglement Detector

You (Wade) Wu, Mack Kira
*University of Michigan*

We show that multi-photon processes in semiconductor quantum materials can be massively enhanced by a combination of Coulombic many-body effects and cavity effects to reach extremely efficient entanglement detection and quantum transduction.

## 71: Relativistic Laser-Driven Dynamics Control with Time-Dependent Spin-Orbit Configuration Interaction

Zachary J. Stewart, and Angela K. Wilson
*Michigan State University*

Advances in ultrafast spectroscopy have increased the viability of finely controlling electron dynamics such as electronic density and spin behaviors through the use of external perturbations such as laser pulses. The use and development of time-dependent methodologies for modelling the dynamics of electronic systems computationally is an active field. Progress on the use of Time-Dependent Spin-Orbit Configuration Interaction (TD-SOCI) for the analysis and modelling of an iron bipyridine complex interacting with applied laser pulses will be highlighted. Induced metal-to-ligand charge transfers and spin-flip can be demonstrated and visualized through the use of one-body operators applied to the TD-SOCI wavefunction, such as electronic density, spin density, and electronic current density.

## 72: Hybrid Quantum Branch-and-Bound Method for Quadratic Unconstrained Binary Optimization

Zedong Peng, Pedro Maciel Xavier, David E. Bernal Neira
*Purdue University*

With the advancement of quantum hardware and theory, quantum algorithms have demonstrated their effectiveness in finding high-quality solutions for Quadratic Unconstrained Binary Optimization (QUBO) problems. Moreover, there exists a myriad of novel methods aimed at finding reasonable solutions to QUBO problems efficiently, named Ising solvers, given the equivalence of QUBO to the transverse field Ising problem in statistical physics. However, optimization problems of interest to process system engineering are more general than QUBOs, usually involving discrete non-binary and continuous variables and constraints. Although it is possible to map such problems onto QUBOs, the size of solvable QUBOs is inherently limited by the number of qubits in available quantum computers. Moreover, the global optimality of the solution cannot be guaranteed due to the thermal noise and the nature of the algorithms implementable for this problem class in quantum devices. Guaranteeing global optimality has been recently addressed using hybrid quantum-classical algorithms. This work presents a hybrid quantum branch-and-bound method to address these challenges. This method utilizes the computational strengths of quantum hardware alongside the global search capabilities of the branch-and-bound method. The strategy of breaking the problem into smaller subproblems aligns well with the capabilities of quantum hardware. Contrary to previous work on characterizing the hardness of a branch-and-bound enhanced with quantum algorithms for exploring the nodes, this work provides a practical implementation of the method relying on a classical branch-and-bound enhanced with Ising solvers, potentially leveraging quantum mechanics, in an open-access repository (https://github.com/SECQUOIA/QuantumBranchAndBound). The Ising solver serves as a heuristic method, and we further explore the strategy of when and where to apply it within the branch and bound framework. Particularly, limitations in quantum annealers related to the embedding problem set such limitations. Additionally, a customized branching rule and an optimized embedding of QUBO problems are applied to accelerate the convergence of the algorithm, where even without enhancing the commercial solver Gurobi 11 with the solutions coming from Ising solvers, we can achieve a speedup of 20% with respect to the default branching rule in Gurobi. The performance of the proposed method is evaluated on hundreds of QUBO instances from QUBOLib.jl (https://github.com/SECQUOIA/QUBOLib.jl), using Gurobi as the branch-and-bound solver, several physics-inspired classical heuristics and the D-Wave quantum annealer as the quantum solver. Detailed computational results are presented, and the proposed method, Gurobi, and the hybrid B&B method are compared with classical heuristic approaches. Improvements in the solution time go up to 14%, and the reduction of the number of nodes explored to prove optimality reaches 16% using Ising solvers with respect to default Gurobi when solving QUBO problems to 0.01% of optimality, highlighting the value of this hybrid approach.

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