QISENET

Quantum Information Science and Engineering: Building "Triplets" to Bridge Academia and Industry

Sponsored by the National Science Foundation within "Quantum Leap" and "Growing Convergent Research"

Chicago

November 2018

QISENET First Meeting of Triplets – November 9, 2018

Welcome to the QISENET Triplets Workshop:

Thank you for joining us at this inaugural meeting of the QISENET Triplets. We are confident the opportunity to meet your colleagues, share your research, and review how different teams are navigating common challenges will make for an exciting and valuable experience. The Quantum Leap Big Idea was formulated as a cross-NSF activity focused on advancing the development of quantum technologies. The "Triplets" approach is one of the activities funded under the NSF Quantum Leap umbrella. It aims to develop a cohort of triplets, with each trio, comprised of a University faculty member, an Industrial Partner or National Laboratory, and a Graduate Student, working together over a period of three years. There are twenty-one triplets that are currently funded to form the NSF Quantum Information Science and Engineering Network (QISENET). This unique mode of integrating research, education and technology transfer is highly convergent and cross-cutting in nature, and includes triplets in the areas of materials science, chemistry, device engineering, physics, computer science, and industrial technology.

We are happy you are able to join us.

David Awschalom and Evelyn Hu

QISENET Triplet Meeting Agenda

University of Chicago – Eckhardt Research Center (ERC) — Room 161
5640 South Ellis Ave, Chicago, IL 60637

8:15 – 9:00AM	Continental Breakfast	
9:00 – 9:15AM	Overview	**Evelyn Hu**, Tarr-Coyne Professor of Electrical Engineering and Applied Science, School of Engineering and Applied Science, Harvard University
9:15 – 10:15AM	Keynote	**Linda S. Sapochak**, Division Director, Division of Materials Research, NSF
10:15 – 10:30AM	Break	
10:30 – 11:30AM	Industry and National Labs Panel	**Lisa F. Edge**, Sr. Program Manager Epitaxial Materials, IR Program Office, HRL Laboratories, LLC; **Ben Lawrie**, Staff Scientist, Quantum Information Science Group, Oak Ridge National Laboratory; **Ryan Babbush**, Senior Research Scientist, Google Inc.; **Barbara Jones**, Almaden Research, IBM
11:30 AM – 12:30PM	Student Poster Session	
12:30 PM	Conference Concludes	

Probing and Controlling Quantum Coherence of Single Emitters in van der Waals Materials

Kevin Sampson with Elaine Ni
University of Texas

Quantum emitters in van der Waals (vdW) materials present a promising platform for non-classical light generation and integration into quantum networks. In particular, defects in hexagonal boron nitride (hBN) have been discovered to produce bright single-photon emission even at room temperature. Quantum emitters embedded in wide-gap vdW materials inherit other unique advantages associated with atomically thin materials: emitter locations may be controlled through strain engineering, and emitter properties are readily tuned via external fields and modifications of the surface dielectric environment. Emitters spanning a spectrum of several hundred nanometers may be incorporated into high-gap vdW materials, and van der Waals bonding allows transfer of active layers onto other structures, easing integration with silicon-based photonic devices. Improving the photon statistics of this class of emitters is an open problem, which we plan to address using two-dimensional coherent spectroscopy (2DCS) to investigate the intrinsic homogeneous linewidth and broadening mechanisms of the emitters (relating to decoherence), along with processes like cascaded biexciton emission. We will complement this work by fabricating vdW photonic devices which can be subjected to controlled strain through piezo-electric substrates and to electric and magnetic fields, with the aim of manipulating electronic wave functions to enhance emitter coherence times.

Quantum algorithms for convex optimization

Tongyang Li with Andrew Childes
University of Maryland

Convex optimization has been a central topic in the study of theoretical computer science, machine learning, and operations research in the last decades. However, compared to its significant developments in classical computing, little is known about whether quantum computers could provide speedups for convex optimization. We give two quantum algorithms for solving n-dimensional convex optimization problems. The first one optimizes a general convex function over a convex body using linear number of quantum queries (in n) to oracles that evaluate the objective function and determine membership in the convex body; this represents a quadratic improvement over the best-known classical algorithm. The second one solves a special class called semidefinite programs (SDPs), which extends the better-known linear programs (LPs) and becomes an important tool for designing efficient optimization and approximation algorithms. We show that there is a quantum algorithm that solves sparse SDPs in only square-root time in n, which gives a polynomial speedup compared to the state-of-the-art classical algorithm. For both general convex optimization and SDPs, we complement our quantum algorithms with quantum lower bounds which restrict the quantum speedups for both problems to be at most polynomial compared to the classical counterparts, and hence it is impossible to obtain exponential quantum speedups for both problems.

Nitrogen Vacancy Center Nanodiamond for Quantum Sensing in Environmentally Relevant Matrices

Zachary Jones with Robert Hamers
University of Wisconsin – Madison

As the use of nanomaterials in commercial products grows over time, so too does the need to understand the implications of nanomaterials being released into the environment. Nitrogen Vacancy nanodiamond (NVND) presents a powerful tool for the study of this nano-bio interface by overcoming many of the limitations of fluorescence imaging. Problems like chemical/photo-stability, biocompatibility, and limited chemical information from other fluorophores are addressed via the stability of NVND combined with the field sensitive fluorescence of the NV center. We are working to implement fluorescence imaging background subtraction in vivo by taking advantage of the spin dependent fluorescence of NV centers in nanodiamonds. Further, we aim to understand how biologically relevant surface modification impacts the charge state, spin relaxation, and coherence properties of NV centers, and how these effects can be leveraged for quantum sensing in vivo. By combining the expertise of Adamas Nanotechnologies in controlled production of NV nanodiamond with our functionalization and characterization expertise, we can work toward developing NV centers as a platform for quantum-based chemical sensing.

Implementing Quantum Principal Component Analysis on Small Superconducting Qubit Processors

Amy Greene with Will Oliver
Massachusetts Institute of Technology

Recent advances in theoretical and experimental work on realizing quantum processors have brought us to the current era of Noisy Intermediate-Scale Quantum (NISQ) computing. In this stage before error-correction, useful applications for quantum technology will involve algorithms that can outperform classical computers with a small number of qubits. Quantum principal component analysis has strong potential to be such an algorithm with application to machine learning, and is the focus of our work.

Quantum principal component analysis (qPCA) is a quantum counterpart to a classical machine-learning algorithm that, for certain problems, offers exponential speedup over the classical version, and which have strong potential to be useful when run on the small-scale quantum processors already available. The crux of the algorithm lies in the performance of a controlled density matrix exponentiation, an operation which has not previously been demonstrated. Here, we present progress towards demonstrating this operation using superconducting circuits of the so-called transmon type. Once this operation has been achieved, we will use it to implement qPCA first on a five-qubit testbed at MIT, and then on a larger device in collaboration with Google.

Simulating the t-J and Driven Dissipative Models on a Quantum Computer

Brian Rost with James Freericks
Georgetown University

Quantum computers are known to give an exponential speed-up over classical computers for the simulation of correlated quantum systems, therefore efficiently implementing these simulations is of great interest for many fields in the physical sciences. In conjunction with IBM Almaden, we are working on two projects for quantum simulation of physical systems through both classical and quantum computer simulations. Our first and smaller project relates on the t-J model, a prominent model for high temperature superconductivity. We investigate optimal algorithms for extracting the system's Green's function, self energy and magnetic susceptibility, from which a wide variety of interesting physical quantities can be computed. Our larger project will investigate the simulation of driven dissipative quantum systems e.g. Hubbard-Holstein in an electric field. Our hope is to characterize the steady states of these systems and use the characterizations to develop an approach which can mitigate the need for expensive state initialization.

Investigating Photon-Phonon Pair Correlations for Microscale Photonic Technology

Kai Shinbrough with Virginia Lorenz
University of Illinois--Urbana-Champaign

Raman scattering is an important and popular resource for quantum applications in communication, cryptography, and computation, yet the correlations of photon–excitation pairs derived therein have only been partially explored. We present a phenomenological model for the photon–excitation joint state in solid state media, including effects due to finite excitation linewidth and group velocity dispersion. We show that this model has implications for photon–phonon pairs produced in the novel photonic medium of single-crystal sapphire (α-Al_2O_3). We investigate the photon–phonon correlations through both simulation and experiment, finding quantitative agreement between the independent phenomenological predictions and experimental data. Application of these results to microscale Si_3N_4 waveguides is underway.

SuperVan Qubit

Abhinandan Antony with James Hong
Columbia University

We will use two-dimensional Van der Waals (VdW) materials to develop novel superconducting devices – SuperVan devices – for quantum information processing. By using defect and impurity free, single crystalline graphene, hexagonal boron nitride (hBN) and niobium diselenide (NbSe2), we aim to produce ultra-low noise, miniaturized superconducting qubits and two-qubit voltage controlled gates through fast, voltage tunable junctions.

These SuperVan devices can potentially shrink the size of the superconducting qubits and resonators by more than three orders of magnitude. The strength of Van der Waals materials liesin the ability to utilize highly crystalline materials with precisely controlled, ultra-clean interfaces, to eliminate the dielectric loss due to the two-level systems that couple to the qubits by electric fields. Specifically, parallel plate capacitors with single crystalline hBN could directly address the dominant two-level systems loss from impurities in the qubit capacitance, within a dramatically smaller footprint.

The use of graphene-based Josephson junctions, where the critical current can be controlled by a gate voltage, which in turn changes the inductance and thus resonator frequency, will allow high-bandwidth tuning. These couplers could potentially be driven in different regimes to produce two qubit controls such as parametric gate coupling. Our proposed electrical voltage controlled coupler departs from the common magnetic flux control, which could potentially simplify device complexity, as electric fields are easier to confine than magnetic fields. Moreover, these devices will increase the speed of control because of the high mobility and saturation velocity of electrons in graphene.

Optimized compilation of aggregated instructions for realistic quantum computers

Yunong Shi with Fred Chong
The University of Chicago

We proposed a new quantum compilation scheme for near-term quantum architectures utilizing quantum optimal control algorithms. By breaking down intermediate-scale quantum circuits into small subcircuits with size quantum optimal control algorithms can scale up to, we generate optimized pulse sequences for each subcircuits. We ensure the parallelism of the circuit is protected and commutative gates are scheduled in a way that maximize the speedup in each subcircuit. This compilation methodology essentially breaks the ISA abstraction of 1-qubit and 2-qubit gates. In this way, pulse time has shown to be improved by a considerable amount in most cases.
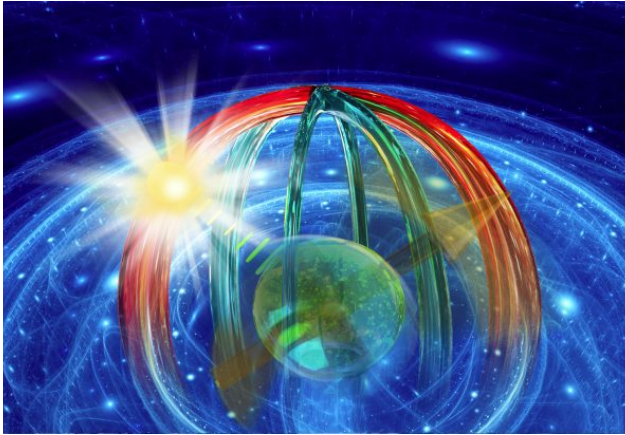
Building and Commercializing a Universal Reconfigurable Trapped Ion Quantum Computer

Laird Egan with Chris Monroe
University of Maryland

Trapped ions are leading contenders for quantum computing technology due to their long coherence times, indistinguishable properties, dense local qubit connectivity and remote optical networkability. The University of Maryland and IonQ, Inc. are collaborating to build a reconfigurable quantum processor using 171Yb+ ions that is capable of individual qubit addressing, ancilla readout, and parallel entangling gates. This unique academic-industrial partnership enables IonQ to focus on commercialization by maturing hardware, developing high-level software controller and cloud interfaces, while UMD investigates new physics in multi-species ion chains, phase-independent gates, and fault-tolerant logical qubits. This work presents the state-of-the-art system development underway at JQI/UMD with links to ongoing work at IonQ.

Two mode squeezed qubit readout and remote entanglement

Xi Cao with Michael Hatridge
University of Pittsburgh

Implementing quantum information processing on a large scale with flawed components requires highly efficient, quantum non-demolition qubit readout. The ability to remotely entangle distant quantum systems is also very desirable. Currently, a typical dispersive superconducting qubit measurement and remote entanglement are achieved using coherent light or Fock states. Here, we demonstrate a dispersive qubit readout which exploits the two-mode squeezed light generated from a Josephson Parametric Converter (JPC) and processed by a second JPC to form an amplified interferometer and compare its readout fidelity to coherent light. In future work, we also propose a remote entanglement protocol by adding a second qubit-cavity system to the other arm of the interferometer. This work is partially supported by Army research funding.

Computational Boundaries of Quantum Dynamics

Erika Ye with Austin Minnich and Ryan Babbush
### California Institute of Technology

Due to the potentially exponential growth in entanglement during time evolution, computing the dynamics of a system accurately is difficult for long simulation times. By solving the Nakajima-Zwanzig (NZ) equation, one is able to exactly calculate the dynamics of a system of interest, provided that one can knows the memory kernel, which contains all of the relevant dynamics of the surrounding environment. While computing the memory kernel is also computationally intensive, it goes to zero relatively quickly for most systems. The lifetime of the memory kernel can potentially be used as a metric to classify the simulation complexity of different kinds of Hamiltonians. Here, we write the NZ equation in the tensor network language, allowing one to efficiently calculate the memory kernel for arbitrary Hamiltonians and obtain approximate solutions for those that could not be solved for using previous methods.

Inherent quantum error correction in generalized superfast algorithm

Kanav Setia with James Whitfield
Dartmouth College

Quantum simulation is one of the most important applications of quantum computers. Efficient quantum simulation algorithms which are robust against noise are required for applications on near term quantum computers. Here, we generalize the superfast algorithm and prove its error correcting properties.

The cost of implementing physical fermionic operators in superfast algorithm goes as $O(d)$ where d is the degree of the interaction graph. In comparison, the cost of fermionic operators goes as $O(N)$ and $O(\log(N))$ for Jordan-Wigner and binary mapping. We show that for Hubbard model, not only superfast algorithm has error correcting properties but is also more efficient than Jordan-Wigner and Bravyi-Kitaev algorithm. This comes at the expense of using $O(N)$ extra qubits.
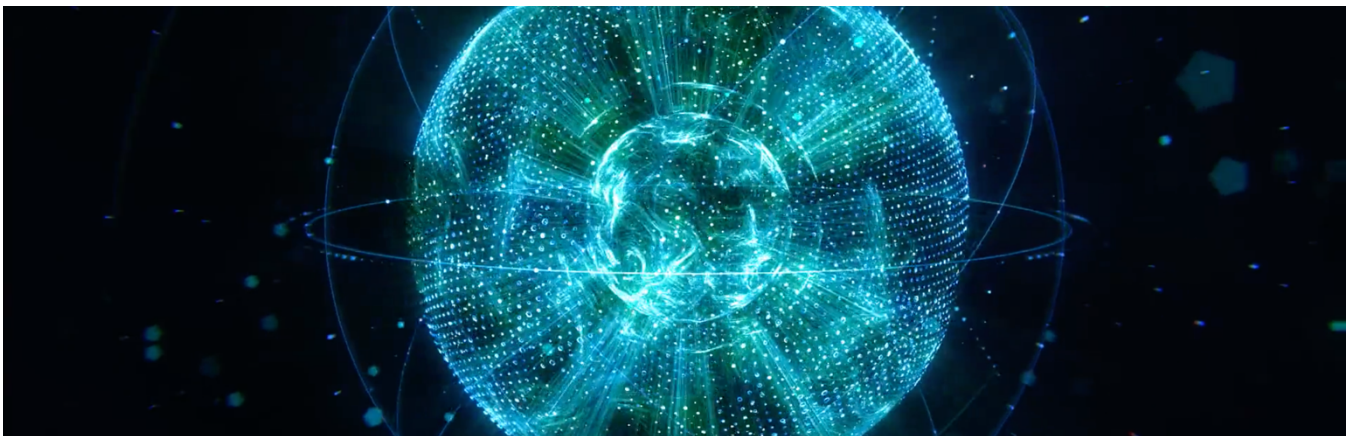
Plasmonic Control of Photon Indistiguishabiltity in Single Quantum Emitters

Matthew Feldman with Richard Haglund
Vanderbilt University

Problems intrinsic to all solid-state SQEs are their non-ideal antibunching and photon indistinguishability, due to background impurities, spectral diffusion, and electron-phonon coupling. To overcome these problems a common strategy is to couple SQEs to nanophotonic cavities (photonic or plasmonic) thereby enhancing the photonic density of states. This Purcell enhancement enables SQEs to emit indistinguishable photons by shortening the emission lifetime (T1) such that T1 << T2, where T2 is the coherence time of the SQE. This is necessary so that photons emitted fall within their coherence times to attain photon indistinguishability. Recently plasmonic cavities have been shown to offer high Purcell enhancements and deterministic coupling to SQEs in 2D materials, but require cryogenic operation to minimize phonon induced linebroadening. These difficulties motivate a concerted effort to explore the condensed matter physics and quantum information science aspects of controlling plasmon interactions with SQEs by investigating the fabrication, characterization, and modeling of SQEs and SQEs coupled to plasmonic cavities to attain photon indistinguishability. SQEs found in the two-dimensional van der Waals materials hexagonal boron nitride (hBN) and tungsten diselenide (WSe2) offer a unique opportunity to explore such interactions given the recent finding that they can be deterministically positioned and coupled to plasmonic cavities using localized strain potentials. In particular, WSe2 is a prime candidate for quantum information science given its valley pseudo-spin and and spin-orbit selection rules. I therefore propose to focus on the potential for SQEs in WSe2. My research will explore the limits of photon-indistinguishability in plasmonic/SQEs nanostructures due to spectral diffusion.

Quantum Photonics in Lithium Niobate

Ian Christen with Dirk Englund and Matt Eichenfeld
Massachusetts Institute of Technology

A robust and active photonics platform is essential for scalably-engineered photon-mediated quantum interactions. Such a platform must have sufficiently wide bandgap, as atom-like quantum systems emit dominantly into the visible spectrum. Lithium niobate is a compelling material platform satisfying these requirements: being transparent down to the UV and having a strong electrooptic nonlinearity. We examine the performance—in particular, the achievable propagation loss and the effect of photo refractive damage—of x-cut and magnesium-doped lithium niobate nanophotonic waveguides across and beyond the visible spectrum. Future work will involve the modulation of both excitation to and emission from leading quantum memories. These memories include optically-trapped rubidium atoms (420 nm), diamond color centers (532-737 nm), and quantum dots (940 nm).

Ionization energies and excited state lifetime of charged defects in Two-dimensional Materials

Tyler Smart with Yuan Ping and Marco Govoni
University of California, Santa Cruz

Defects in 2D materials such as ultrathin h-BN have been found to be promising single-photon emitters with stable polarized and ultrabright single-photon emission at room temperature. This opens up possibilities for emergent applications in nanophotonics and quantum information, with potentially much better scalability than the long-studied nitrogen vacancy (NV-) in diamond. However, first-principles prediction of accurate defect properties in 2D materials remains challenging, mainly because of the highly anisotropic dielectric screening in 2D materials and strong many body interactions. This work shows how we solve the numerical convergence issues for charged defect properties in 2D materials at both the DFT and MBPT levels, and how we tackle the complex many body interactions including electron-electron, electron-phonon and defect-excitons for the excited state properties of defective 2D materials and heterojunctions. Next, we compared different levels of theory and propose fundamental principles to obtain reliable ionization energies of charged defects in 2D materials. We also have preliminary results of phonon-assisted non-radiative recombination lifetime of defects in 2D materials, computing different recombination processes between defect-defect states and defect-band edge states for complex defects in monolayer BN. With our methods, we will design promising quantum defects that have deep defect levels, weak electron-phonon coupling and long excited state lifetime.

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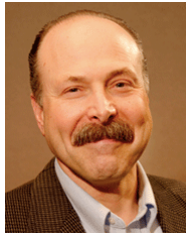
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QISENET is sponsored by the National Science Foundation (NSF), an independent federal agency that has helped fund cutting-edge science for over sixty years. By fostering a unique partnership between industry and academia, QISENET distinguishes itself as part of the "Quantum Leap" and "Growing Convergent Research" initiatives—two of the "Big Ideas" that make up NSF's long-term research agenda. Operating at the intersection of institutions, individuals, and ideas, QISENET aims to discover the underlying science that will unlock the next generation of quantum technologies.