Quantum Information Science on the Intersections of Nuclear and AMO Physics

Monday, January 13, 2025 - Wednesday, January 15, 2025

Book of Abstracts

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Session 2 / 14

Quantum Simulation with Rydberg-atom Synthetic Dimensions (25+5)

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A synthetic dimension, in which a discrete degree of freedom in a well-controlled quantum system can be mapped to the states of particles moving in a real-space lattice potential, is a powerful tool for quantum simulation because it provides control over the Hamiltonian and the ability to create configurations difficult to access in real space. I will describe the creation of a synthetic dimension from Rydberg levels in an 84-Sr atom, in which coupling between the states is induced with millimeter-waves. Tunneling amplitudes between synthetic lattice sites and on-site potentials are set by the millimeter-wave amplitudes and detunings respectively. The potential of this platform is demonstrated by realizing the single-particle Su-Schrieffer-Heeger Hamiltonian (SSH), a paradigmatic model of topological matter with alternating weak and strong tunneling in a one-dimensional configuration. Band structure is measured through the Rydberg photo-excitation rate into the manifold[1]. Using selective field-ionization of the Rydberg atoms, particle dynamics in the synthetic dimension are tracked with single-site resolution[2]. Bulk-states and topologically-protected edge states are clearly distinguished through their spectral and transport properties. (Funding has been provided by Rice University, NSF grants 1904294, 1848304, and 2110596, the AFOSR under Grant No. FA9550-17-1-0366, and the FWF (Austria) under Grant No. FWF-P35539-N and Doctoral College FWF W 1243 (Solids4Fun).)

[1] S. K. Kanungo, J. D. Whalen, Y. Lu, M. Yuan, S. Dasgupta, F. B. Dunning, K. R. A. Hazzard, and T. C. Killian, Realizing topological edge states with Rydberg-atom synthetic dimensions. Nat. Commun. 13, 972 (2022). https://doi.org/10.1038/s41467-022-28550-y

[2] Y. Lu, C. Wang, S. K. Kanungo, S. Yoshida, F. B. Dunning, and T. C. Killian, Wave packet dynamics and long-range tunneling within the SSH model using Rydberg-atom synthetic dimensions, Phys. Rev. A 109, 032801 (2024). https://doi.org/10.1103/PhysRevA.109.032801

Session 3 / 15

Probing and engineering nuclear spin ensembles in a central spin system (25+5)

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Central spin systems are ubiquitous, naturally occurring in a variety of physical systems, including rare-earth ions in nuclear spin-rich crystals and atomic-scale defects in two-dimensional materials. Here, we present novel quantum control methods for probing and manipulating a central spin system, where an optically addressable single electron spin is surrounded by an inaccessible dark nuclear spin

ensemble. Achieving effective and reliable control over these surrounding spin ensembles enables a wide range of quantum information science applications, including quantum memory for quantum networking, ancilla qubits in quantum computing, and ensemble-based quantum sensing.

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Making a solid-state nuclear optical clock (25+5)

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The first nuclear excited state or isomer of Th-229 has an extremely low energy (8.4 eV/148 nm) and long lived (~10^3 s) excited state, therefore termed an isomer (Th-229m). Owing to its narrow resonance, Th-229m is a platform for a future extremely precise nuclear optical clock. In a crystal such as CaF2 the ultimate precision is estimated to be on the 10^-17 level. Owing to its nuclear nature, it would be a new sensitive probe for fundamental physics. Recently, the very first laser spectroscopy of a nucleus, Th-229 doped in crystalline CaF2, has been achieved. Immediately the nuclear spectroscopy was reproduced for Th-229 doped in LiSAF. Afterwards, the first clock comparison was performed between the nuclear excited state of Th-229 in CaF2 and the electronic excited state in Sr-87 with a resolution of 300 kHz. This string of recent successes hinges on the development of a highly doped VUV transparent CaF2 crystal, doped with the radioactive Th-229. In previous attempts, the nuclear excitation seemed less efficient than is now known.

In this talk I will elaborate on the nuclear hyperfine spectroscopy measurements and how the crystal platform was originally developed and characterized: Crystal growth [12] and crystal healing [13]. More recently, an indication appeared why previous attempts of excitation in a crystal were unsuccessful: The nuclear excitation quenches through an interaction with the solid-state environment. I will further report a diverse array of new measurements and calculations characterizing the interaction and the solid-state environment of Th-229:CaF2 crystals. These measurements and calculations show we can control the interaction of the nucleus with its environment, shine light on its electronic environment and indicate exciting new ways to improve clock operation. With every characterization, and every simulation, the solid-state nuclear clock comes a step closer.

Session 4 / 17

Simulation of quantum models with physical and logical qubits (25+5)

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Progress in quantum computing with neutral atom qubits has advanced rapidly with the development of large 2D arrays and high fidelity entangling gates. We have used an array of Cs atom qubits to demonstrate a variational simulation of the Lipkin-Meshkov-Glick model incorporating noise mitigation techniques. In further work we have used a small error detecting code to implement a prototype Anderson Impurity Model ground state solver to demonstrate lower errors using encoded logical qubits.

Session 2 / 18

Analog quantum simulation of bosonic lattices and lattice gauge theories (25+5)

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Analog quantum simulators are purpose-built devices that imitate the behavior of complex quantum systems. Compared to universal error-corrected digital quantum computers, they are expected to have less stringent requirements, and are capable of natively representing the degrees of freedom and interactions in the target system with reduced overhead. In this talk, I will present our recent work on hardware-efficient analog quantum simulation using superconducting circuits in the Engineered Quantum Systems Lab. I will discuss our simulation of bosonic lattices in synthetic dimensions using multimode cavities, as well as our implementation of native three-qubit interactions for simulating lattice gauge theories.

Session 3 / 19

Building Solid-State Quantum Simulators for Applications in Lattice Gauge Theory (25+5)

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We are developing a new platform for atom-based solid-state analog quantum simulation with unique application in simulating lattice gauge theory. The method uses STM lithography to precisely locate individual atoms on a patterned silicon substrate. These atomic structures are then encased in epitaxial silicon, stable in ambient over long periods of time, and can be measured at low temperature in a dilution refrigerator. We have demonstrated atomically precise patterning and devices whose performance relies on atoms placed with one silicon lattice site resolution including a single atom transistor, single electron transistor (SET) sensors, and individual charge and spin measurements using transport and RF reflectometry. Recently we demonstrated the analog quantum simulation of an extended Hubbard model. In these results 3x3 arrays of dopant atoms were fabricated with varying degrees of tunnel coupling to enable quantum simulations of a Hubbard model from a weakly coupled regime to a strongly coupled array. Currently we are fabricating 2x2 plaquettes as building blocks for the proposed quantum simulation of a model of relevance to nuclear physics. Our proposal uses a dynamical lattice of coupled nuclear spins and conduction-band electrons to realize a quantum field theory: an extended Jackiw-Rebbi model involving coupled fermions and quantum rotors. Classical simulations of this platform show the feasibility of using precision placed nuclear spins hyperfine coupled to electrons to observe dynamical mass generation and a confinement-deconfinement quantum phase transition in 1+1 dimensions, even in the presence of strong long-range Coulomb interactions.

Session 5 / 20

Quantum sensing assisted by near-term quantum algorithms (25+5)

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In this presentation, we explore near-term quantum algorithms designed to prepare optimal quantum states for applications in quantum sensing and metrology. These algorithms can be tailored for implementation on noisy intermediate-scale quantum (NISQ) devices. Specifically, we examine the variational quantum algorithms to estimate the quantum Fisher information for this task and highlight their potential applications in atomic, molecular, and optical (AMO) physics, as well as nuclear physics. This talk is based on the following works: [1] Jacob L. Beckey, M. Cerezo, Akira Sone, and Patrick J. Coles, Phys. Rev. Research 4, 013083 (2022)
[2] M. Cerezo, Akira Sone, Jacob L. Beckey, and Patrick J. Coles, Quantum Sci. Technol. 6, 035008 (2021)
[3] Akira Sone, M. Cerezo, Jacob L. Beckey, and Patrick J. Coles, Phys. Rev. A 104, 062602 (2021)

Session 3 / 21

Where AMO meets Nuclear meets Particle: quantum state prep and read-out in molecules and the search for CP-violating physics (40+10)

Author: Eric Cornell[1]

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The many internal quantum states (vibrational, rotational, hyperfine, parity) of molecules add complexity to experiments but in exchange offer opportunity. Fr instance, the current best limit on the electron's electric dipole moment was set in a trapped-molecule experiment, and prospects for finding new CP-violating physics in radioactive molecules are excellent. I'll review some of this and also talk about an enabling technology: visions for reading out the internal state population in multiple quantum states in a single shot.

Session 2 / 22

Spin-Boson Simulations with Trapped Ions (25+5)

Author: Kenneth Brown[1]

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Spin-boson models are common throughout physics. Trapper ion quantum computers are built off internal degrees of freedom in the ions (qubits) and external degrees of freedom (phonons). For quantum computation, the phonons are used as an information bus for generating entanglement

between qubits, but are not used to store quantum information. We have recently used the spin and motional modes to perform quantum simulations of molecular dynamics of conical intersections [1] and vibrational energy transfer with structured baths [2]. After describing these results, we will explain how these methods can be applieed to the study of nuclear physics.

[1]J. Whitlow, Z. Jia, Y. Wang, C. Fang, J. Kim, and K.R. Brown, *Quantum simulation of conical intersections using trapped ions*, Nature Chemistry **15**, 1509 (2023)
[2] K. Sun, M. Kang, H. Nuomin, and G. Schwartz, D. N. Beratan, K. R. Brown, and J. Kim, *Quantum simulation of spin-boson models with structured bath*, arXiv:2405.14624

Session 1 / **23**

Towards simulating fundamental physics with near-term quantum computers (25+5)

Author: Jack Araz[1]

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A fundamental goal of strong interaction physics is to describe and interpret scattering experiments from first principles quantum chromodynamics (QCD) and to understand the internal structure of nuclei. However, the complexity of QCD, particularly in its non-perturbative regime, presents major challenges. Classical computing techniques, while driving substantial progress, have inherent limitations: perturbative QCD is only applicable in the weakly coupled regime, and Euclidean-time lattice QCD is constrained by the sign problem, making it difficult to simulate real-time dynamics. Combining Hamiltonian formulations for field theories with emerging quantum computing techniques could offer a promising way to overcome the limitations of current methods. In this talk, we'll delve into the application of quantum computing for quantum simulations, exploring its algorithmic and hardware constraints. We'll also discuss strategies to overcome these limitations and unlock the full potential of quantum computers in the near future.

Session 6 / **24**

Analog quantum simulation of meson scattering and string breaking (25+5)

Author: Elizabeth Bennewitz[1]

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Probing the non-equilibrium and real-time dynamics of composite particles, such as hadrons and nuclei, is an overarching goal for quantum simulators. Observations of confinement and composite excitations in spin systems have enabled the exploration of string-breaking and scattering dynamics with analog quantum simulators. In this talk, I will discuss our recent proposal for meson scattering [1] and our experimental demonstration of string-breaking [2] within a family of quantum Ising chains exhibiting domain-wall confinement. These works signify both the current advancements and the future potential of AMO-based quantum simulators in the field of nuclear physics. [1] https://arxiv.org/abs/2403.07061 [2] https://arxiv.org/abs/2411.10652

Session 6 / **25**

Intersections with Nuclear Physics, from the Trapped Ion QIP Perspective (25+5)

Author: Wes Campbell[1]

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I will present an overview of the ways that some AMO researchers working in quantum information find connections to nuclear physics, as well as a wish list from the AMO side.

Session 4 / 26

Quantum Computing Enhanced Sensing (25+5)

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Structured Light to Quantum Information Science (25+5)

Author: Andy Chong[1]

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The propagation of optical waves is traditionally understood as two distinct processes: beam (spatial) and pulse (temporal) propagation. However, spatiotemporal three-dimensional (3D) wave packets—featuring unique combinations of spatial and temporal wave characteristics—open the door to novel phenomena. In this seminar, we will explore the progress made in understanding these 3D optical wave packets, their distinctive behaviors, and their potential future applications in various fields especially in quantum information science.

Session 1 / 28

Radioactive Atoms and Molecules as Quantum Sensors for Nuclear Physics (25+5)

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Quantum Sensor Networks (25+5)

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Session 5 / 30

Quasiparton and quasifragmentation functions in the massive Schwinger model (25+5)

Author: Sebastian Grieninger[1]

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We analyze the quasiparton distributions of the lightest meson in massive QED2. For increasing rapidity, we compute the spatial quasiparton distribution functions and amplitude for the lowest excited state numerically both at strong and weak coupling and compare them to light front results in the lowest Fock space approximation. Moreover, we introduce the concept of the quark quasifragmentation function (qFF) using an equal-time and spatially boosted form of the Collins-Soper fragmentation function where the out-meson fragment is replaced by the current asymptotic condition. In the massive Schwinger model, we compute the qFF by exact diagonalization of the spin Hamiltonian. Finally, we compare the results to the qFF following from the Drell-Levy-Yan result for QED2 and to QCD2 in the lowest Fock approximation.

Session 5 / 31

A lattice field theory of quantum circuits (25+5)

Author: Neill Warrington[1]

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Session 6 / 32

Quantum Simulation of Deep Inelastic Scattering (25+5)

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I will present quantum simulation of Deep Inelastic Scattering in (1+1)-dimensional QED.

Session 2 / 33

Ising Superconductors in Quantum Sensing (25+5)

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TBA

Session 1 / 34

Entanglement and thermalization in high energy collisions (40+10)

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Session 1 / 35

Fundamental and Applied Science with Rare Isotope Doped Superconducting Sensors (25+5)

Author: Kyle Leach[1]

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By leveraging many years of development by the materials science, quantum computing, astronomy, and AMO communities, we have entered an era where practical precision experiments are possible (and already taking data) in subatomic physics with superconducting sensors. These devices are characterized by their exceptionally high energy resolution and low thresholds for the detection of various types of radiation from the eV to MeV scale – particularly nuclear beta and electron capture (EC) decay which serve as sensitive probes of the structure and symmetries at the microscopic scale of our Universe. For the past few years, we have taken the approach of embedding rare isotopes in thin-film superconducting tunnel junctions (STJs) to precisely measure the recoiling atom that gets an eV-scale "kick"from the neutrino, electron, or photon. These recoils are encoded with the fundamental quantum information of the decay process, and carry unique signatures of weakly coupled beyond standard model (BSM) physics; including neutrino mass, exotic weak currents, and

potential "dark"particles created within the energy-window of the decay. These measurements provide a complimentary and (crucially) model-independent portal to the dark sector with sensitivities that push towards synergy between laboratory and cosmological probes. In this talk, I will discuss the broad program we have developed to provide leading limits in these areas, the technological advances across several sub-disciplines of science required to enable this work, and future applications including biomedical sciences, nuclear safeguards, and computing.

Session 4 / 36

Ionizing Radiation and Superconducting Qubits (25+5)

Author: Ben Loer[1]

[1] *Pacific Northwest National Laboratory*

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Ionizing radiation has been shown to reduce the performance of superconducting quantum circuits. In this talk, I will first provide an overview of this rapidly evolving area of research, up to the implications of the latest demonstration of quantum error correction gains by Google. I will provide an overview of some of our recent work that identifies potentially problematic sources of radiation in a typical superconducting quantum computing system. I will conclude with our estimates for potential performance gains for devices operating in PNNL's new Low Background Cryogenic Facility operating in the 30 m.w.e Shallow Underground Laboratory.

Session 5 / 37

Detection of nuclear decays with levitated mechanical quantum sensors (40+10)

Author: David Moore[1]

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The development of optomechanical systems—in which the motion of a massive object is controlled and measured using light—has revolutionized the detection of tiny forces over the past few decades. As such technologies reach, and even surpass, quantum measurement limits, they can enable the detection of tiny forces relevant in nuclear physics. I will present results from a recent proof-of-principle measurement that demonstrate that the force imparted by a single nuclear decay occurring within an optically levitated, dust-sized particle can be detected. Future applications of this work to nuclear safeguards and reconstruction of neutrinos emitted in beta decays will be described.

Session 4 / 38

Superconducting Nanowires as High-Energy Particle Detectors (25+5)

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Toward quantum simulations for nuclear physics with qubits and qumodes (25+5)

Author: Felix Ringer[1]

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The strong force in nature, described by the theory of quantum chromodynamics (QCD), governs the interaction of quarks and gluons, which constitute the main building blocks of the visible universe. Since its development over five decades ago, various fundamental questions have remained unanswered despite significant theoretical and experimental efforts: How do the dynamics of quarks and gluons give rise to emergent structures such as nucleons and nuclei? What is the phase diagram of nuclear matter and what are the real-time and non-equilibrium dynamics at collider experiments and in the early universe? While significant progress has been made on the theory side using perturbative techniques and lattice QCD, the answers to some of the most challenging questions are beyond the capabilities of classical computing. Advances in quantum computing coupled with the development of innovative algorithms motivate the exploration of quantum simulations to address these questions. In this talk, I will discuss recent progress toward quantum simulations for fundamental particle and nuclear physics covering both discrete (qubit) and continuous variable (qumode) approaches.

Session 3 / 40

Towards quantum advantage in lattice gauge theory calculations (25+5)

Author: George Siopsis[1]

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Recent progress in quantum computing offers promising opportunities to address computational challenges in lattice gauge theories, particularly for real-time dynamics and scattering amplitudes that are inaccessible through classical methods like lattice QCD due to limitations such as the sign problem. This talk focuses on the use of measurement-based photonic quantum processors to calculate scattering observables in quantum field theories. The approach employs continuous-variable quantum information encoded in photonic qumodes, providing a scalable framework for simulating complex quantum systems with deterministic generation of exotic gates and fault-tolerant architectures. We will discuss methods for determining matrix elements of time-separated currents, which are essential for computing scattering amplitudes. By employing photonic quantum computing techniques, this work addresses critical challenges in simulating nonperturbative dynamics and real-time evolution of strongly interacting systems. These efforts represent an important step toward achieving quantum advantage in lattice gauge theory applied to nuclear and high-energy physics.

Session 4 / 41

Applications of quantum calorimetry in nuclear physics (25+5)

Author: Paul Szypryt[1]

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Our group at the University of Colorado Boulder (CU Boulder) and the National Institute of Standards and Technology (NIST) has over a decade of experience in developing quantum calorimeters based on the superconducting transition-edge sensor (TES). More recently, we have began exploring the calorimetric capabilities of the kinetic inductance detector (KID), a superconducting resonator technology that can be operated across a broad energy range and is more readily scalable than its TES counterpart. In order to make them suitable for nuclear physics applications, we have developed large-area thermal kinetic inductance detectors (TKIDs) optimized for charged-particle and gamma-ray detection, and we have begun applying these devices for practical measurements in nuclear physics. In particular, we have used our TKIDs to measure the ionizing radiation background inside a cryostat environment representative of that of superconducting qubits in an effort to understand how these radiation effects can impact qubit decoherence. We are also designing large-format TKID arrays to be used at the NIST Center for Neutron Research (NCNR) to improve studies of neutron beta decay, among other potential applications. In this presentation, we discuss both of these research thrusts as well as provide a more general overview of the quantum calorimetry program at CU Boulder/NIST as it relates to nuclear physics (and AMO) research.

Session 6 / 42

Many Body Physics in Superconducting Devices (25+5)

Author: Neill Warrington[1]

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How can quantum field theory advance superconducting device capabilities? How can superconducting devices probe quantum field theory? I will discuss these questions in the context of recent work on fluxonium, a superconducting quantum circuit used as a qubit. I will present a numerical framework for optimizing qubits, as well as a lattice field theory of physical devices. The discussion around these two applications identifies several compelling opportunities for quantum field theory to advance device physics.

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Solid-State 229Th Laser Based on the Optonuclear Quadrupolar Effect (25+5)

Author: Haowei Xu[1]

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The radiative excitation of the 8.3 eV isomeric state of 229Th is an outstanding challenge due to the lack of tunable far-ultraviolet sources. In this talk, I will first introduce an optonuclear quadrupolar (ONQ) effect, which facilitates efficient interactions between optical photons and nuclear degrees of freedom. Using the ONQ control over nuclear spins, we suggest several promising applications ranging from materials spectroscopy to quantum memory and quantum transduction. Leveraging the ONQ coupling to nuclear orbital excitations, we propose an efficient two-photon pumping scheme for the 229Th isomeric state, which only requires a 300 nm UV-B pumping laser. We further demonstrate that population inversion between the nuclear isomeric and ground states can be achieved at room temperature using a two-step pumping process. The nuclear laser, which has been pursued for decades, may be realized using a Watt-level UV-B pumping laser and ultrawide bandgap thorium compounds (e.g., ThF4, Na2ThF6, or K2ThF6) as the gain medium.

Session 1 / 44

Efficient Quantum Circuit for the Block Encoding of a Pairing Hamiltonian (25+5)

Author: Chao Yang[1]

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We present an efficient quantum circuit for block encoding a pairing Hamiltonian often studied in nuclear physics. Our block encoding scheme does not require mapping the creation and annihilation operators to the Pauli operators and representing the Hamiltonian as a linear combination of unitaries. Instead, we show how to encode the Hamiltonian directly using controlled swap operations. We analyze the gate complexity of the block encoding circuit and show that it scales polynomially with respect to the number of qubits required to represent a quantum state associated with the pairing Hamiltonian. The techniques presented can be extended to encode more general second-quantized Hamiltonians.

Session 2 / 45

Quantum Machine Learning for Particle Physics (25+5)

Author: Shinjae Yoo[1]

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We have pioneered quantum machine learning to make a breakthrough in quantum machine learning on the target of particle physics data challenges. We have investigated from quantum support vector machines of collision event classification to quantum anomaly detection on novel event discovery. We will share our success and failure and outlook of upcoming quantum centric supercomputing.

Session 5 / 46

Enhancing Quantum Utility: simulating large-scale quantum spin chains on superconducting quantum computers (25+5)

Author: Kwangmin Yu[1]

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We present the quantum simulation of the frustrated quantum spin-1/2 antiferromagnetic Heisenberg spin chain with competing nearest-neighbor (⊠1) and next-nearest-neighbor (⊠2) exchange interactions in the real superconducting quantum computer with qubits ranging up to 100. In particular, we implement the Hamiltonian with the next-nearest neighbor exchange interaction in conjunction with the nearest-neighbor interaction on IBM's superconducting quantum computer and carry out the time evolution of the spin chain by employing the first-order Trotterization. Furthermore, our implementation of the second-order Trotterization for the isotropic Heisenberg spin chain, involving only nearest-neighbor exchange interaction, enables precise measurement of the expectation values of staggered magnetization observable across a range of up to 100 qubits. Notably, in both cases, our approach results in a constant circuit depth in each Trotter step, independent of the number of qubits. Our demonstration of the accurate measurement of expectation values for the large-scale quantum system using superconducting quantum computers designates the quantum utility of these devices for investigating various properties of many-body quantum systems. This will be a stepping stone to achieving the quantum advantage over classical ones in simulating quantum systems before the fault tolerance quantum era.

Session 6 / 47

Thorium-229 nuclear clock: nuclear physics meets metrology (25+5)

Author: Chuankun Zhang[1]

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Laser-based measurement and control of atomic and molecular states form the foundation of modern quantum technology and provide deep insights into fundamental physics. In this talk, I'll present our work in JILA on quantum-state-resolved thorium-229 nuclear laser spectroscopy using a coherent frequency comb in the vacuum-ultraviolet. I will also discuss our recent effort producing thin-film thorium-229 fluoride targets, demonstrating a novel platform towards future nanophotonic integration of nuclear clocks. This unification of precision metrology and nuclear physics sparks new ideas for fundamental physics tests and promises robust nuclear-based timing applications.

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Registration Opens

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TBD

Session 1 / 51

Quantum Algorithms for Quantum Many-Body Systems (25+5)

Author: Dean Lee[1]

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N/A

Session 3 / 52

Laser-cooled alkaline-earth like molecules for quantum science (25+5)

Author: Daniel McCarron[1]

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N/A

Session 2 / 53

Engineering of Kerr-Hamiltonians in a cavity QED system

Author: Simone Colombo[1]

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We propose a protocol for the generation of effective universal nonlinear Kerr Hamiltonians in a collective-spin system coupled to bosonic modes of a cavity QED apparatus. We expand the effective collective spin Hamiltonian beyond the second-order term (the well-studied one-axis-twisting) and map it to an effective Kerr Hamiltonian using the Holstein-Primakoff transformation. We give examples of systems that can be simulated with this protocol.