I-01

Unveiling quantum dynamics with lossy and dipolar atoms

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Synthetic quantum systems, consisting of atoms and light, provide a distinct platform for simulating unprecedented phenomena in condensed matter, high energy physics, and quantum information. One exciting frontier is the study of open quantum systems and a novel phase of matter influenced by long-range interactions. Here, I will present a few examples that showcase the quantum simulation of such quantum phenomena through engineered dissipation and dipolar interactions with neutral atoms.
First, dissipation plays a crucial role in open quantum systems and significantly influences the physical properties of atomic topological matter. I will discuss recent advancements in generalizing synthetic spin-orbit coupling to the non-Hermitian regime, which allows us to investigate exotic phenomena, including the non-Hermitian skin effect and high-order exceptional points. Secondly, I will highlight the rapid progress in dipolar atomic systems and address an outstanding open question regarding the impact of anisotropic dipolar interactions on Berezinskii-Kosterlitz-Thouless superfluidity in two dimensions. The study of this new phase of dipolar matter is now within our reach and holds the potential for revealing complex order. Towards the end of the talk, I will touch upon other exotic regimes that can be simulated with neutral atoms in a SU(N)-symmetric Fermi gas and tweezer atom array.

I-02

Microwave control of interactions between ultracold polar molecules

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In this presentation, I will discuss our recent findings on mitigating the two-body loss of ground-state NaRb molecules. To achieve this, we employ a blue-detuned microwave to create a long-range potential barrier, which significantly decreases the formation of the two-molecule complex, thereby reducing short-range loss by two orders of magnitude. Conversely, we observe a significant increase in elastic collisions, allowing the elastic collision rate to reach the hydrodynamic limit even at relatively low number densities. Additionally, we demonstrate efficient evaporative cooling, but only within a specific density range.

I-03

Observation of universal dissipative dynamics in strongly correlated quantum gas

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Dissipation is unavoidable in quantum systems. It usually induces decoher- ences and changes quantum correlations. To access the information of strongly correlated quantum matters, one has to overcome or suppress dissipation to extract out the underlying quantum phenomena. However, here we find an opposite effect that dissipation can be utilized as a powerful tool to probe the intrinsic correlations of quantum many-body systems. Applying highly-controllable dissipation in ultracold atomic systems, we observe a universal dissipative dynamics in strongly correlated one-dimensional quantum gases. The total particle number of this system follows a universal stretched-exponential decay, and the stretched exponent measures the anomalous dimension of the spectral function, a critical parameter characterizing strong quantum fluctuations of this system. This method could have broad applications in detecting strongly correlated features, including spin-charge separations and Fermi arcs in quantum materials.

I-04

Quantum simulation of few-body and many-body systems with optical and synthetic lattices

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A system of ultracold atoms is an ideal experimental platform for quantum simulation of quantum few- and many-body physics. In this talk, I will report our recent experiments using ultracold ytterbium (Yb) or rubidium (Rb) atoms loaded into an optical lattice or a synthetic dimensional lattice. First, few-body systems of ultracold bosons of Yb realized in an optical lattice is studied by high-resolution spectroscopy combined with a Feshbach resonance, revealing the evidence of a four-body force, which has never been observed in any few-body systems so far. Ultracold Yb atoms in an optical lattice are also utilized for the study of novel quantum thermalization for a strongly interacting system. Furthermore, a system of a synthetic dimensional lattice of Rb hyperfine states is used to realize a gain-engineering of ultracold atoms, demonstrating a novel phenomenon of topological atom lasing.

I-05

Synthetic tensor gauge fields

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Synthetic gauge fields have provided physicists with a unique tool to explore a wide range of fundamentally important phenomena. However, most experiments have been focusing on synthetic vector gauge fields. The very rich physics brought by coupling tensor gauge fields to fracton phase of matter remains unexplored in laboratories. In this talk, I will discuss schemes to realize synthetic tensor gauge fields and the novel phenomena induced by the couplings between tensor gauge fields and multipoles.

I-06

Microscopic study of strongly correlated synthetic quantum material

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Exploring the fundamental structure and basic laws of the universe constitutes an essential drive to physicists. Along with the achievements in laser cooling and implementation of Bose-Einstein condensate and quantum phase transitions in optical lattices, ultracold atoms become a unique system for quantum computation/simulation and precision measurement. We study strongly correlated synthetic quantum material with microscopic techniques for solving formidable tasks to the state-of-the-art supercomputers. Such tasks include quantum phase transition of strongly correlated quantum systems, the topological structure of multipartite entangled state [1-3] and lattice gauge theories [4-7].

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I-07

Simulating waveguide quantum electrodynamics with ultracold atoms

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Understanding and harnessing light-matter interactions in novel contexts is central to the development of modern quantum technologies. One example is the emerging field of waveguide quantum electrodynamics (wQED) which investigates the coherent coupling between one or more quantum emitters and an engineered low-dimensional photonic bath. While recent wQED experiments have observed effects such as modified spontaneous emission, bound-state mediated interactions, and superradiance, a clean access to the underlying mechanisms often remains challenging. We approach wQED physics with an unconventional platform in which artificial quantum emitters, realized with ultracold atoms in an optical lattice, undergo radiative decay by emitting single atoms rather than single photons. I will discuss the unique aspects of our platform and present some recent work on simulating radiative many-body effects at the boundary between quantum optics and condensed-matter physics. * work supported by NSF PHY-1912546 and 2208050

I-08

Quantum gas microscopy of a frustrated XY model in shaken triangular lattices

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Magnetic frustration is an intriguing issue in condensed matter physics. Even in the case of the simplest geometrical spin frustration that occurs in the triangular structure with antiferromagnetic interactions, competition between the interactions and the lattice geometry brings about various phases. We have developed an experimental apparatus of an Rb-87 Bose gas in an optical triangular lattice combined with a quantum gas microscope [1], which provides high spatial resolution and high sensitivity. By using a Bose-Einstein condensate in a shaken optical lattice, we investigated the relaxation and excitation in a frustrated XY model. We revealed that the two spiral phases with chiral modes show significant differences in relaxation time from the initial ferromagnetic phase. With a fast ramp, simultaneous occupation of two ground states often occurs, which can be attributed to the domain formation of the chiral modes. We have detected the interference of the spatially separated chiral modes (chiral-mode domains), using the quantum gas microscope [2].

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I-09

Dynamics of quantum correlations in Rydberg-atom arrays

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The ability of quantum simulators to control the non-equilibrium dynamics of quantum many-body systems opens the door to a plethora of fundamental phenomena. A particularly fruitful playground for non-equilibrium physics is offered by Rydberg-atom arrays: their many-body properties can be monitored for individual atoms in real time; and their qubit-qubit interactions can be either ferromagnetic dipolar ones, leading to rather long-ranged correlations, as well as frustrated anti-ferromagnetic dipolar ones, with a much reduced effective range. In this talk I will focus on two main aspects, namely: 1) how non-equilibrium dynamics can realize massive many-body entanglement, which cannot be otherwise achieved at thermal equilibrium; and 2) how the study of correlation dynamics in Fourier space allows one to unveil the nature and dispersion relation of the elementary excitations in the system, providing a most convenient form of spectroscopy for quantum simulators at large. The work is based on a collaboration with the experimental team of Antoine Browaeys and Thierry Lahaye at Institut d'Optique, Palaiseau, France.

I-10

Krylov-restricted thermalization in a Rydberg atom array

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In most cases, the long-time dynamics of an isolated, non-integrable quantum many-body system follow the eigenstate thermalization hypothesis (ETH), where states within a narrow energy window are predicted to thermalize with each other. On the contrary, systems with a fragmented Hilbert space may allow thermalization to proceed only within but not between disconnected Krylov subspaces. In this talk, I will present our results on observing Krylov-restricted thermalization in a Rydberg atom array, where we realize a broad class of Hamiltonians with Hilbert space fragmentation. Our results show that thermalization between states belonging to different Krylov subspaces is forbidden, even when these states have the same energy, defying expectations from the ETH.

I-11

Ultrafast quantum simulation and quantum computing with ultracold atom arrays at quantum speed limit

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Many-body correlations drive a variety of important quantum phenomena and quantum machines including superconductivity and magnetism in condensed matter as well as quantum computers. Understanding and controlling quantum many-body correlations is thus one of the central goals of modern science and technology. My research group has recently pioneered a novel pathway towards this goal with nearby ultracold atoms excited with an ultrashort laser pulse to a Rydberg state far beyond the Rydberg blockade regime [1-7]. We first applied our ultrafast coherent control with attosecond precision [2,3] to a random ensemble of those Rydberg atoms in an optical dipole trap, and successfully observed and controlled their strongly correlated electron dynamics on a sub-nanosecond timescale [1]. This new approach is now applied to arbitrary atom arrays assembled with optical lattices or optical tweezers that develop into a pathbreaking platform for quantum simulation and quantum computing on an ultrafast timescale [4-7]. In this ultrafast quantum computing, as schematically shown in Fig. 1, we have recently succeeded in executing a controlled-Z gate, a conditional two-qubit gate essential for quantum computing, in only 6.5 nanoseconds at quantum speed limit, where the gate speed is solely determined by the interaction strength between two qubits [5]. This is faster than any other two-qubit gates with cold-atom hardware by two orders of magnitude. It is also two orders of magnitude faster than the noise from the external environment and operating lasers, whose timescale is in general 1 microsecond or slower, and thus can be safely isolated from the noise. Moreover, this two-qubit gate is faster than the fast two-qubit gate demonstrated recently by “Google AI Quantum” with superconducting qubits [8].

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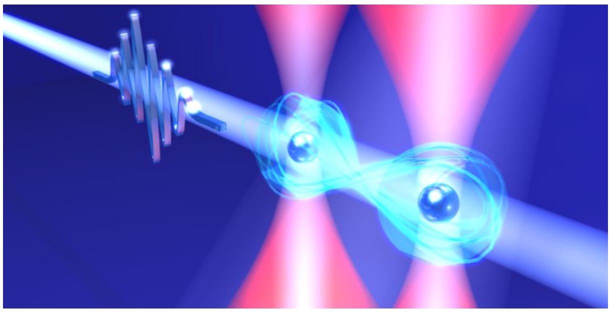

Figure 1: Conceptual diagram of the ultrafast two-qubit gate for quantum computing with cold atoms. Two single atoms captured in optical tweezers (red light) with a separation of a micrometer are entangled with an ultrafast laser pulse (blue light) shone for only 10 picoseconds [5]. Image source: Dr. Takafumi Tomita (IMS).

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I-12

Emergent Gauge Theory in Rydberg Atom Arrays

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Rydberg atom arrays have emerged as a novel platform exhibiting rich quantum many-body physics and offering promise for universal quantum computation. The Rydberg blockade effect plays an essential role in establishing many-body correlations in this system. In this review, we will highlight that the lattice gauge theory is an efficient description of the Rydberg blockade effect and overview recent exciting developments in this system from equilibrium phases to quantum dynamics. These developments include realizing exotic ground states such as spin liquids, discovering quantum many-body scar states violating quantum thermalization, and observing confinement-deconfinement transition through quantum dynamics. We emphasize that the gauge theory description offers a universal theoretical framework to capture all these phenomena. This perspective of Rydberg atom arrays will inspire further the future development of quantum simulation and quantum computation in this platform.

I-13

Quantum critical states in quasiperiodic lattices: from non-interacting to correlated

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The disordered quantum systems host three types of fundamental quantum states, the extended, localized, and critical states, of which the multifractal critical states are much less understood compared with the former two. Conventionally the characterization of the quantum critical states relies on arduous numerical verification. In this talk, I will present a systematic analytic and numerical study of the critical states in quasiperiodic systems, with or without particle-particle interactions. Through the Avila global theory, a Fields Medal work which we introduce for the first time to cold atoms, we propose a class of exactly solvable models, dubbed mosaic lattice models, hosting novel types of exact mobility edges separating localized from quantum critical or extended states [1], With these exactly solvable models, we discover a universal mechanism for the critical states that the such states are due to the vanishing Lyapunov exponent and the incommensurately distributed hopping zeros in the thermodynamic limit, which also serve as a rigorous characterization of the critical states. We further show that in the presence of interactions, the critical states turn into the many-body counterparts upon the finite-size scaling analysis, giving a many-body critical phase, which is an exotic phase in-between the thermal phase and many-body localization [2]. Thanks to the considerable progresses in spin-orbit coupled optical Raman lattices [3], the realizations of our predictions are proposed [4] and succeeded in experiment [5]. Future important issues will be commented.

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I-14

Stationary turbulence in spinor Bose-Einstein condensates

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Spinor Bose-Einstein condensates (BECs) of atomic gases represent a quantum fluid characterized by multiple symmetry breaking, providing an interesting platform for the exploration of quantum turbulence. In this talk, I will report our observation of a stationary turbulent state in a spin-1 atomic BEC driven by a radio-frequency magnetic field. The magnetic driving injects energy into the system through spin rotation, leading to the emergence of an irregular spin texture in the condensate. As the driving persists, the spinor condensate evolves into a nonequilibrium steady state marked by distinctive spin turbulence. Remarkably, under specific driving conditions, the turbulence attains its maximum intensity, accompanied by an isotropic spin composition. Through numerical simulations and experimental validation, we find that the turbulence in the BEC is sustained by a mechanism rooted in the chaotic nature of internal spin dynamics induced by the magnetic driving.

I-15

Quench dynamics and Higgs oscillations in a strongly interacting Fermi gas

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Ultracold atomic gases with tunable interactions offer a versatile environment for studying quantum systems out of equilibrium. In this study, we examine Fermi gases following a rapid interaction quench and investigate the ensuing many-body dynamics. Initially, we present measurements after a quench from the normal to the superfluid phase, where we observe the time-dependent formation of a pair condensate as the gas moves toward equilibrium. We find that short-range correlations develop significantly more rapidly than the long-range correlations required to form a Bose-Einstein Condensate (BEC). In a more recent study, we performed small quenches within the superfluid phase to excite Higgs amplitude oscillations, which we directly observed using Bragg spectroscopy. These oscillations provide a measure of the pairing gap across the BCS-BEC crossover and decay according to a power law with a damping exponent that varies with the interaction strength. We will also provide a brief update on the construction progress of the Dysprosium Quantum Gas Microscope and outline our plans.

I-16

Mesoscopic transport with ultracold atomic gases

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Ultracold atomic gases enable the simulation of fundamental aspects of complex nonequilibrium quantum many-body phenomena. Recently, atomtronics, serving as the cold-atom counterpart to electronics, has garnered attention due to experimental realizations of mesoscopic and circuit systems with ultracold atomic gases. In this talk, I will concentrate on mesoscopic phenomena realized by transport experiments with ultracold atomic gases. I will demonstrate that novel transport phenomena including mesoscopic transport with Bose systems, with synthetic dimensions, and in the presence of atom loss can be investigated through cold-atom setups.