Neutral Atom Quantum Simulators for HEP

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Ultracold atoms offer a wide arena to simulate quantum many-body systems, quantum field theories, quantum entanglement and models of critical importance to the research missions of HEP and condensed matter physics. These models cover a large range of length scales, from fundamental non-Abelian gauge fields that govern the microscopic interactions between quarks and gluons, to macroscopic effective theories of non-equilibrium phenomena, such as hydrodynamics of quantum fluids that play critical roles in the structure and dynamics of neutron stars. Analog quantum simulations using cold atom platforms have already had impact in nuclear physics. Moreover, they allow for unique opportunities for quantum simulation of Lattice Gauge Theories (LGT) and of quantum scrambling in quantum gravity models that are computationally challenging for the most advanced classical machines. We outline a number of immediate opportunities to make significant progress toward addressing these HEP grand challenges using atomic quantum simulators.

1 Quantum simulations of models for nuclear matter

Quantum gases of bosonic and fermionic atoms with tunable contact and long-range interactions serve as paradigmatic model systems for nuclear matter. Unitary atomic Fermi gases realize a pristine model for dilute neutron matter that have, e.g., enabled the experimental measurement of the Bertsch parameter - the ground state energy of a resonant Fermi gas in units of the energy of a non-interacting one. Using a puff of gas a million times thinner than air, these systems teach us the equation of state, the transport properties (particle, momentum, spin and heat) and the high-momentum behavior of neutron matter at 25 orders of magnitude higher densities. Already above the superfluid critical temperature, these unitary Fermi gases are seen as "perfect liquids", featuring kinematic viscosities and spin diffusivities as low as allowed by quantum mechanics – on the order of Planck's constant divided by the particle mass. This low-viscosity transport at ultralow energies in the Nanokelvin-range stands in direct correspondence to that measured for the quark-gluon plasma at 10^{12} Kelvin, the only other known "perfect liquid". We aim at the use of strongly interacting quantum gases to study quantum-limited hydrodynamics in comparison with predictions for nuclear matter. Further, the study of spin-imbalanced Fermi gases – extremely challenging theoretically due to the fermion sign problem – allows to constrain the equation of state of nuclear matter with imbalanced neutron-proton ratios. The short-range correlations between atomic fermions feature universal behavior (the "contact") that has recently been sought and found in experiments at Jefferson lab in nuclear matter as well. We will tailor cold atom simulators to closely match the parameters of nuclear matter to determine its short-range behavior. We will also set out to compare the dynamics found in unitary atomic gases with calculations of the dynamics of e.g. nuclear fission, as a way to validate the theoretical approach.Another outstanding question involves the existence of the so-called Fulde-Ferrell-Larkin-Ovchinnikov (FFLO-)state in imbalanced Fermi systems, proposed in quark matter in the core of dense neutron stars (color-flavor-locked phase).

2 Lattice gauge theory simulators

Simulating LGTs, which originate from HEP models such as Quantum Chromodynamics (QCD), is well known to be a computationally challenging task. Apart from their high energy physics significance, these models also play an important role in strongly correlated many-body systems, related to the so-called spin liquid (SL) states as well as in quantum information science (QIS). For these reasons, solving strongly coupled gauge theories, especially in two or three spatial dimensions, is of fundamental importance. However, on a lattice, gauge invariance and gauge invariant (plaquette) interactions typically involve (at least) four-body interactions that are challenging to realize experimentally. Cold-atom systems have advanced to the point where simulations of gauge theories and nuclear effective field theories can be addressed. Synthesized gauge fields within cold-atom systems using rapidly rotating gases, Raman spin-orbit coupling, laser-assisted tunneling, lattice shaking, of excitations to the Rydberg states are opening the door to investigations of quantum matter associated with charged particles in a gauge field, addressing systems such as quantum Hall effects, topological matter, or anyonic excitations. For U(1) theories, charged particles generate electro-magnetic fields, and complete simulations of the particle-field system includes feedback of the matter to the gauge fields. Systems capable of describing dynamical gauge fields can now begin to address non-linear theories, such as Yang-Mills and chiral effective theories, with an eye toward QCD and low-energy nuclear physics effective theories. Quantum dynamics in one-dimensional quantum link models have been recently studied in Rydberg atom arrays, and is currently being extended to two-dimensional systems. We intend to introduce and explore dynamical non-Abelian gauge fields in cold atom systems, opening exciting directions with direct relevance to the HEPs mission. These systems should enable us to uncover the nature of quantum matter in regimes that are not computationally accessible on classical computers, by using quantum information tools such as atom-by-atom access and control.

3 Exploring the Entanglement Frontier

Another highly interesting connection between HEP and QIS has emerged in the form of the AdS/CFT duality, namely, a conjectured duality between certain conformal field theories and gravity. This correspondence maps strongly interacting quantum field theories onto weakly interacting gravitational theories that may be easier to study and solve. The gauge-gravity correspondence is also related to the holographic principle: the conformal field theory lives on the boundary of the anti de Sitter space in which gravity acts. According to this correspondence, all exact quantum observables in gravity are accessible as some (generally complex) many-body quantum operators in the entangled non-gravitational quantum system at the boundary. Therefore, it is of great interest to experimentally produce such quantum entangled systems, to study their dynamics and to probe this duality. Programmable quantum simulators such as those based on Rydberg atoms in configurable tweezer arrays can be used to perform quantum simulation of quantum entanglement phenomena relevant to this duality. Different types of entanglement dynamics, from fully scrambled to those featuring slow entanglement growth (associated e.g. with the so-called quantum many-body scars) can be explored in such systems. Dynamical aspects, such as the transfer of information between the pair of Rydberg chains dual to an eternally traversable wormhole, can be studied. In particular, quantum information is predicted by transfer between the chains only after it has been sufficiently scrambled by the chaotic Hamiltonian of the starting Rydberg chain. In that scrambled form, the information is encoded in multi-partite correlations, and thus is less sensitive to single qubit errors, showing some connection with quantum error correction. Characteristic features of the gravitational collective description such as the gravitational time dilation in the interior of the wormhole map to the effective clock rate of the qubit once it is encoded in a coherently scrambled form. One aim could be to utilize the insights from gauge gravity correspondence to design and test novel, efficient protocols for quantum error correction and fault-tolerant quantum computation.