IAS Workshop on Quantum Simulation of Novel Phenomena with Ultracold Atoms (May 6-7, 2019)

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Diagnosing Kondo Effects of Fermionic Alkaline-earth Atoms through a Dipole Oscillation

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Recent technical developments of controlling alkaline-earth atoms [1] and the experimental confirmation of the antiferromagnetic interaction between stable and metastable states of ^{171}Yb [2] have paved the way for multiorbital quantum analog simulators. A natural next step is the analog simulation of some characteristic physics and the exceptionally well-understood physics of the multiorbital system is the Kondo effect [3], the anomalous temperature dependence of the electrical conductivity. However, ultracold atoms are electrically neutral: one cannot measure the electrical conductivity. In order to find quantities which show Kondo-effect-like behaviors instead of the electrical conductivity, we numerically simulate the dynamics of the Kondo model at finite temperatures by means of matrix product states. By eliminating the autocorrelation problem of the minimally entangled typical thermal states algorithm [4] with the applications of Trotter gates, we succeed in performing efficient numerical simulations of the finite temperature dynamics of the Kondo models. From our simulations of the dynamics induced by the sudden shift of the trap potential, we find that the center-of-mass velocities of itinerant atoms show Kondo-effects-like logarithmic temperature dependences and this temperature dependence disappears when the interaction between itinerant and localized atoms is set to ferromagnetic.

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Quantum Droplet in a Mixture of Rb and Na Bose-Einstein Condensates

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According to the mean-field theory, an atomic Bose-Einstein condensate (BEC) will collapse when the interaction between atoms is attractive. However, the mixture of two BECs with attractive interspecies interaction can be stabilized by the beyond mean-field Lee-Huang-Yang correction in the format of self-bound quantum droplets [1, 2, 3]. In this poster, I will present our progress in studying the heteronuclear quantum droplet with the double BEC of Rb and Na atoms. With the help of an interspecies Feshbach resonance, we have created double BECs with nearly arbitrary interaction strengths and signs. When setting the interspecies scattering length to larger enough negative values, we observe the self-bound behavior as the signature of the Na-Rb droplet during the time of flight expansion upon releasing the mixture from the optical trap. Future plan for studying the phase diagram and formation dynamics will also be discussed.

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Bistability of Bose-Einstein Condensates with a Local Loss Term and Pinning Potentials

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Recent technological advances in ultracold atom experiments allow for introducing couplings to environment, namely dissipation, in a well-controlled manner [1,2]. In particular, the experimental group at Technische Universitat Kaiserslauten has reported the observation of unexpected bistability in a Bose-Einstein condensate in the presence of local one-body dissipation created with an electron beam [1]. To clarify the origin of the bistability under the local particle loss, we construct a simple mean-field model that describes the bistability of superfluids. In this work, we will show that exact solutions of the Gross-Pitaevskii equation with a local particle loss term and pinning potentials of the delta function type. Based on the exact solutions, we show that the bistability appears in the wide range of the parameters. We point out that the pinning potentials play an essential role for the discontinuous jump. We also find that unidirectional hysteresis phenomena appear in some parameter region, which is called anomalous hysteresis [3].

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Study of the Interacting Su-Schrieffer-Heeger Model in Optical Lattices: The Relationship with the Gross-Neveu Model on Lattice

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Motivated by recent experimental progress of cold-atoms in an optical lattice, a theoretical study for a quantum simulation which includes properties of both high-energy physics (especially lattice gauge theories) and topological condensed matter phenomena has been started [1,2,3]. In this poster, we report a study of the interacting N-component Su-Schrieffer-Heeger (SSH) model, which is feasible for a real experimental system. This model not only exhibits symmetry-protected topological (SPT) phase originated from BDI symmetry class in topological classification but also has a relation to the lattice Gross-Neveu Wilson model, which includes essence of lattice QCD in high energy physics. On the base of the relationship between the two models, we carry out the large-N expansion for the interacting SSH model and obtain the large-N groundstate phase structure. We found that the SPT phase boundary is modified by interaction effects. The modification is expected to come from the dynamical mass generation effect from interactions. This effect is known to occur in the lattice Gross-Neveu model. Furthermore, for large interaction regime, the interacting SSH model possess a density-wave like phase corresponding to the Aoki phase, which is a peculiar phase in the lattice Gross-Neveu model. Also, we estimated the large-N results compared with the phase structure of single component interacting SSH model by using the exact diagonalization. We found that the large-N phase structure fairly captures the single component result. Finally, we propose an implementation method to realize the single component interacting SSH model. The system may be also a quantum simulator of the lattice Gross-Neveu model.

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Bose Polarons in an Ultracold Mixture of ^{87}Rb and ^{23}Na Atoms

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We report the progress on investigating the Bose polaron problem with a mixture of ultracold Bose-Bose mixture of ^{23}Na and ^{87}Rb atoms. We prepare the Bose polaron by immersing heavy ^{87}Rb impurities in the Bose-Einstein condensate of ^{23}Na and use injection radio frequency spectroscopy to investigate the polaron spectrum while the impurity-BEC interaction is tuned by a Feshbach resonance. In particular, we plan to study the dependence of the polaron energy on impurity concentration, which may provide information on interaction between polarons.

Semi-classical Dynamics of a Dark Soliton in a One-dimensional Bose Gas in an Optical Lattice

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Since a dark soliton in a one-dimensional Bose gas in the superfluid phase is one of main low-energy excitations, its properties have been actively studied both in theory and in experiments. In this study, we use the truncated Wigner approximation to analyze numerically the dynamics of dark solitons in an optical lattice in the semi-classical regime. By changing gradually the strength of quantum fluctuations from the classical regime, we reveal that even weak quantum fluctuations significantly affect the stability of dark solitons. From this result, we propose that one can distinguish whether the origin of the dark-soliton instability is classical or quantum by observing the difference in dynamics between the two types of solitons.

Interactions and Collective Excitations in a SU(*N*) Fermi Gas

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Ultracold fermions with SU(*N*>2) symmetry provide a unique platform to explore quantum dynamics and interaction effects in the large spin systems that have no analogue in condensed matter physics. In this poster, we present a set of experiments on the measurement of contact parameters and collective excitations with a SU(*N*) Fermi gas of ^{173}Yb atoms. First, the short-range interaction effect is studied via Tan's contact parameters in a multi-component Fermi gas with SU(*N*>2) symmetry. The s-wave contact parameter is experimentally measured by recording the high-momentum tail of weakly interacting fermions. For a tunable number of spin component *N* with a fixed number of atoms per component, we verify the linear increase in the contact with *N* providing experimental confirmation of SU(*N*) interactions. Next, we measure collective excitations of a harmonically trapped two-dimensional SU(*N*) Fermi gas. Various collective modes are investigated with a tunable number of spin component *N* showing a decrease in the ratio of quadruple and dipole mode with *N*. Our work will pave the way for the experimental study of interacting SU(*N*) Fermi gases with large spin.

A New Apparatus for Quantum Simulation with Ultracold Dipolar Erbium Atoms

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Recently Lanthanide atoms such as dysprosium and erbium have attracted significant attention in quantum simulation with ultracold atoms due to their large magnetic moment and meta-stable excited states. Here, we report on the realization of the magneto-optical trap (MOT) operating on the singlet $\left(4f^{12}6s^{2}\ {}^{3}H_{6} \rightarrow 4f^{12}({}^{3}H_{6})6s6p({}^{1}P_{1})\right)$ transition as well as our other on-going efforts for a versatile erbium apparatus in which various exotic states of matter, such as quantum droplets, can be emulated. This broad-line MOT leads us to implement a bi-chromatic MOT, consisting of singlet and triplet transitions $\left(4f^{12}6s^{2}\ {}^{3}H_{6} \rightarrow 4f^{12}({}^{3}H_{6})6s6p({}^{3}P_{1})\right)$ which increases the repetition rate of experiment [1].

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Theoretical Modeling of Cold-atom Simulations for Frustrated Quantum Magnetism

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We study frustrated quantum states of Bose gases in a triangular optical lattice with spatially anisotropic hoppings of isosceles type. In order to prepare a system of frustrated quantum gases without serious heating, we propose an experimental protocol using the combination of the phase-imprinting techniques and the statistical ensemble with *negative* absolute temperature [1]. These experimental operations enable us to access the quantum states of a system described by the Bose-Hubbard model with sign-inverted hoppings. When the sign of the hopping amplitude is inverted from the naturally-occurring one, the relative local phase of the Bose-Einstein condensate tends to be π on neighboring sites, resulting in a frustrated situation for the triangular lattice. We theoretically simulate the time evolution of the state within the time-dependent Gutzwiller approximation, and show that the frustrated superfluid-Mott insulator transition occurs along the protocol that we propose. We also perform a more quantitative analysis on the quantum critical point with and without frustration by means of the numerical cluster mean-field method with a density matrix renormalization group solver [2]. We find that the Mott insulating region is significantly enhanced due to interplay of geometrical frustration and quantum fluctuations. The present study opens a realistic path towards quantum simulations with cold atoms for the studies on frustrated quantum systems.

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Observation of Nodal-line Semimetal with Spin-orbit Coupled Fermions in Optical Lattices

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Observation of topological phases beyond two-dimension (2D) has been an open challenge for ultracold atoms. Here, we realize for the first time a 3D spin-orbit coupled nodal-line semimetal in an optical lattice and observe the bulk line nodes with ultracold fermions. The realized topological semimetal exhibits an emergent magnetic group symmetry. This allows to detect the nodal lines by effectively reconstructing the 3D topological band from a series of measurements of integrated spin textures, which precisely render spin textures on the parameter-tuned magnetic-group- symmetric planes. The detection technique can be generally applied to explore 3D topological states of similar symmetries. Furthermore, we observe the band inversion lines from topological quench dynamics, which are bulk counterparts of Fermi arc states and connect the Dirac points, reconfirming the realized topological band. Our results demonstrate the first approach to effectively observe 3D band topology, and open the way to probe exotic topological physics for ultra-cold atoms in high dimensions.

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