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Chiral soliton crystal and superfluid critical velocity in ultracold Bose gases with spin-orbit coupling

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Since a quantum phase transition from superfluid to Mott-insulator was observed in 2002, the experimental and theoretical researches of ultracold atomic gases in optical lattices have rapidly expanded. The optical lattice can be set in motion by choosing different wavelengths of the opposite laser beams. This results in a relative velocity between the Bose Einstein condensates (BEC) and the optical lattice. The BEC superflow in the optical lattice is known to break down when the flow velocity exceeds a critical value. This phenomenon has been confirmed experimentally using a one-dimensional moving optical lattice [1].

A few years ago, NIST experimental groups have succeeded in creating a synthetic spin-orbit coupling (SOC) on the ultracold-gas systems by a two Raman laser scheme [2]. In recent research, the quantum phases of two-component bosons with SOC in an optical lattice were studied [3]. Among them, the phase called striped superfluid consists of two plane waves that spatially interfere to form a periodic density modulation. We focused on the pseudo-spin order in this state when two types of boson are considered up spin and down spin. We theoretically confirmed that when the system is in the striped phase, the spin order forms a peculiar structure similar to the chiral soliton lattice.

The chiral soliton lattice state, which is a periodic array of chiral twists of spins in magnetic materials, has been intensively studied together with its transport characteristics for spintronic device application. We, therefore, investigated the superfluid critical velocity in the striped superfluid phase with the chiral soliton order in the spin sector. We added a finite momentum to the spin-orbit coupled Bose-Hubbard model of the previous study and predicted the critical velocity in this system by calculating the superflow from the mean-field energy. The critical velocity in the striped superfluid phase can be experimentally measured with currently available techniques, thus we try to understand the relationship between the critical velocity and the chiral soliton structure in this system.

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00-00

Spin-orbit coupling in supperfluid mixtures

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We investigate the ground-state properties of two different kinds of spinor mixtures — Bose-Bose and Bose-Fermi mixtures. For each mixture, we consider one species is subjected to a Raman induced spin-orbit coupling while the other species is not. It is clearly shown that, the spin-orbit coupling effect can be transferred from the former to the latter species through the inter-species spin exchange interaction, which consequently leads to quite rich ground-state phase diagrams as well as exotic topological band structures. More strikingly, in the Bose-Fermi mixture we also find that the back action from fermions can effectively increase the spatial period of the bosonic density stripes, and hence makes this phase directly observable in experiment. Our systems provide new and practical platform to explore the physics of spin-orbit coupling.

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00-00

Angular Stripe Phase in Spin-Orbital-Angular-Momentum Coupled Bose Condensates

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We propose that novel superfluid with supersolid-like properties - angular stripe phase [1] - can be realized in a two-dimensional spin-1/2 Bose gas with spin-orbital-angular-momentum coupling [2, 3]. We predict a rich ground-state phase diagram, including the vortex-antivortex pair phase, half-skyrmion phase, and two different angular stripe phases. The stripe phases feature modulated angular density-density correlation with sizable contrast and can occupy a relatively large parameter space. The low-lying collective excitations, such as the dipole and breathing modes, show distinct behaviors in different phases. The existence of the novel stripe phase is also clearly indicated in the energetic and dynamic instabilities of collective modes near phase transitions. Our predictions of the angular stripe phase could be readily examined in current cold-atom experiments with ^{87}Rb and ^{41}K.

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00-00

Ultrafast many-body electron dynamics of Rydberg atoms in optical tweezers arrays

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We are developing a new system where we combine the optical tweezers technique [1] and coherent ultrashort laser pulses to generate arbitrary arrays of strongly-correlated ultracold Rydberg atoms. We utilize holographic technology combined with a high-resolution imaging system to arrange Rb atoms into an arbitrary geometry. Ultrafast coherent control with attosecond precision [2] applied to this highly engineered atom-array will create a strongly-correlated system in which many-body electron dynamics within picosecond to nanosecond timescale could be observed and controlled [3].

The combination of arbitrary atom arrays and ultrafast coherent control will open a new pathway for addressing quantum many-body problems with submicron and attosecond spatiotemporal resolution.

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00-00

Observation of a symmetry-protected topological phase of interacting bosons with Rydberg atoms

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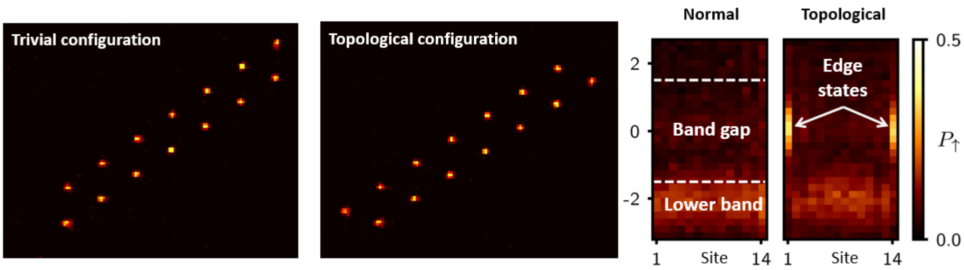
The concept of topological phases is a powerful framework to characterize ground states of quantum many-body systems that goes beyond the paradigm of symmetry breaking. While a few topological phases appear in condensed matter systems, a current challenge is the implementation and study of such quantum many-body ground states in artificial matter.

Here, I will report the experimental realization of a symmetry protected topological phase of interacting bosons in a one-dimensional lattice, and demonstrate a robust ground state degeneracy attributed to protected edge states [1]. The setup is based on atoms trapped in an array of optical tweezers [2-4] and excited into Rydberg levels [5], which gives rise to hard-core bosons with an effective hopping by dipolar exchange interaction [6].



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Vortex Patterns of Atomic Bose-Einstein condensates in a density-dependent Gauge Field

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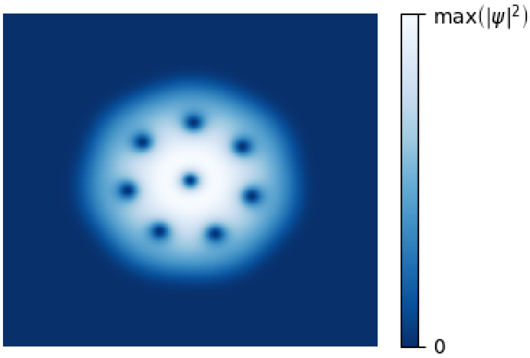
The appearance of quantized vortices in atomic Bose-Einstein condensates heralds the onset of the superfluid state in these macroscopic systems. This is typically achieved by considering the atomic cloud with an additional linear rotation term. Complementary to this, the last decade has seen an enormous effort by the ultracold atom community to engineer so called artificial electromagnetism, where the (charge neutral) atomic cloud can experience orbital, as well as recently more exotic forms of magnetism.

We compute the vortex lattice structures associated with an interacting, or density-dependent gauge potential [1]. Here, the gauge field appears as a nonlinear rotation [2] leading to novel lattice structures. We assess the interplay of the linear and nonlinear rotation, here the nonlinear rotation provides an additional spatially localized modulation of the vorticity in the system, resulting in novel changes to the topology of the condensate.



Ground state density of an atomic BEC under nonlinear rotation

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00-00

Hydrodynamics with spacetime-dependent scattering length

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In ultracold atom experiments, we can realize a simple strongly correlated system in which its interparticle interaction is characterized only by one length scale called scattering length. Furthermore, it is experimentally possible to tune the scattering length and to change it over space and time [1]. In this study, we reveal roles of the spacetime-dependent scattering length by employing hydrodynamic description.

In a system where the interaction is characterized only by the scattering length, there exist universal relations that connect short- and long-distance physics, and the relations are described by Tan's contact that characterizes short-range correlation [2]. In particular, one of the relations shows that the contact is a thermodynamically conjugated variable with the scattering length. We construct hydrodynamic equations consistent with thermodynamic relations that include the scattering length and contact [3]. In our hydrodynamic equations, the scattering length enters constitutive relations uniquely. As a consequence, we find that a leading dissipative correction to the contact density due to the spacetime-dependent scattering length is proportional to the bulk viscosity. Also, when the scattering length is slowly varied over time in a uniform system, the entropy density is found to be produced even without fluid flows in proportion to the bulk viscosity, which may be useful as a novel probe to measure the bulk viscosity in ultracold atom experiments.

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00-00

Quantum fluctuations of vortex lattices in binary Bose-Einstein condensates: Phase diagrams and intercomponent entanglement

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There has been an ever-growing interest in synthetic gauge fields in ultracold atomic gases, which are created by rotating gases or by optically dressing atoms. The former (latter) method has successfully been used to induce mutually parallel (antiparallel) synthetic magnetic fields in binary Bose-Einstein condensates (BECs). Within the mean-field theory appropriate for high filling factors ($\nu \gg 1$), binary BECs in parallel and antiparallel fields show the same phase diagram with five vortex-lattice phases determined by the ratio of the intercomponent interaction $g_{\uparrow\downarrow}$ to the intracomponent one g [1,2,3]. Meanwhile, in the quantum Hall regime with $\nu = O(1)$, the two systems exhibit markedly different phase diagrams [3,4]. It is thus interesting to systematically investigate the roles of quantum fluctuations as the filling factor ν is lowered from the mean-field regime. Here, we study the effects of quantum fluctuations on the ground-state phase diagram by calculating the correction to the ground-state energy due to zero-point fluctuations in the Bogoliubov theory (for a closely related work on excitation modes, see Ref. [5]). We find that the boundaries between rhombic-, square-, and rectangular-lattice phases shift appreciably with decrease in ν. Furthermore, we investigate the intercomponent entanglement arising from quantum fluctuations, and find that for parallel (antiparallel) fields, the entanglement entropy tends to be larger for repulsive (attractive) $g_{\uparrow\downarrow}$, in qualitative agreement with the results for the quantum Hall regime [3,4].

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00-00

Anomalous phase fluctuations of superfluids flowing in a random environment

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The superfluidity in a random environment is a long-standing subject in condensed matter physics. At the ground state, weak disorder does not destroy the off-diagonal long-range order, while for strong disorder a transition to an insulating phase takes place [1]. In this study, we consider superfluids flowing in a weak random potential. Such systems allow dissipationless and stationary matter flow if its velocity is below the critical velocity. Here, we restrict our attentions to the phase fluctuations of the superfluid order parameter in a stationary flow. Within the classical field theory where quantum fluctuations are ignored, we show that the off-diagonal long-range order is destroyed in one and two dimensions for arbitrarily small flow velocities. Furthermore, the correlation function of the superfluid order parameter exhibits an exponential decay and a power-law decay in one and two dimensions, respectively. The underlying physics is that the scattering process of the condensed particles by the disorder has the same effect as virtual thermal excitations characterized by an effective temperature proportional to the square of the flow velocity. We also demonstrate these results by numerical experiments, where the stationary solution of the Gross-Pitaevskii equation with a random potential is calculated. The stability condition of superflow against a spatially localized defect is given by the Landau criterion [2]. This study reveals another mechanism responsible for the breakdown of superflow by a spatially extended disorder.

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Transverse instability and disintegration of domain wall of relative phase in coherently coupled two-component Bose-Einstein condensates

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In Two-component Bose-Einstein condensates with different spin states that are coherently Rabi-coupled, it is known exist a domain wall called a sine-Gordon soliton with a characteristic that the relative phase changes by 2π as a metastable structure. [1] Also, if vortices are prepared for each component, the domain wall forms vortex molecules with a finite length with the vortex as a boundary. However, the domain wall has an unstable parameter region, and it is known that it collapses into multiple fragments, especially depending on the interaction between atoms, the strength of the Rabi coupling, and the length of the wall. [2][3]

We study transverse instability and disintegration dynamics of a domain-wall of a relative phase.We obtain analytically the stationary solution of the domain wall and study numerically the energetic and snake instability with Bogoliubov-de-Genne analysis. It was found that energy instability and snake instability are related. Also, we investigated the dynamics by real-time development of the Gross Pitaevskii equation. It was also found that the dynamics agree with the results of BdG analysis.

From these results, we think that snake instability causes the domain wall collapse. We will describe this details.

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00-00

Shear viscosity and Kovtun-Son-Starinets (KSS) conjecture in an ultracold Fermi gas

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We theoretically investigate the Kovtun-Son-Starinets (KSS) conjecture, stating the existence of the lower bound of the ratio η/s of the shear viscosity η to the entropy density s, as $\eta/s \geq \hbar/(4\pi k_{\rm B})$[1], in the BCS-BEC crossover region of an ultracold Fermi gas. Consistently including strong pairing corrections to both η and s within the same framework of the strong-coupling self-consistent T-matrix approximation (SCTMA), we clarify how η, as well as η/s, behaves in the normal state of an ultracold Fermi gas over the entire BCS-BEC crossover region. The ratio η/s is found to achieve the minimum value $\eta/s \simeq 4.5 \times \hbar/(4\pi k_{\rm B})$, not at the unitarity, but in the BEC regime, $(k_{\rm F}a_s)^{-1} \simeq 0.4$, where $k_{\rm F}$ is the Fermi wavelength and a_s is the s-wave scattering length. This result is consistent with the recent experiment on the shear viscosity η in a ^{6}Li Fermi atomic gas, showing that η takes a minimum value in the BEC side[2,3]. Our result also agrees with the quantum Monte Carlo simulation which found the minimum value of η/s at $(k_{\rm F}a_s)^{-1} \simeq 0.4$[4]. We also point out that the two quantum phenomena, Pauli blocking effect and bound-state formation, are crucial keys to obtain this lower bound.

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Phase diagram of a strongly interacting non-equiibrium Femi gas

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We theoretically investigate *non-equilibrium* properties of a strongly-interacting Fermi gas coupled with two baths with different values of chemical potential. For this purpose, we extend a T-matrix approximation (TMA)[1], which has extensively been used for the study of BCS-BEC crossover physics in the equilibrium case, to the non-equilibrium steady state, by employing the Keldysh Green's function technique. Using this non-equilibrium strong-coupling theory, we obtain the critical temperature and the phase diagram of a non-equilibrium Fermi gas, as shown in Fig. 1. Recently, a non-equilibrium ultracold Fermi gas with tunable dissipation has been realized[2]. In addition, the strongly-correlated non-equilibrium steady state discussed in our work is deeply related to exciton-polariton condensates. Thus, our results would contribute to the further development of many-body physics extended to the non-equilibrium case.

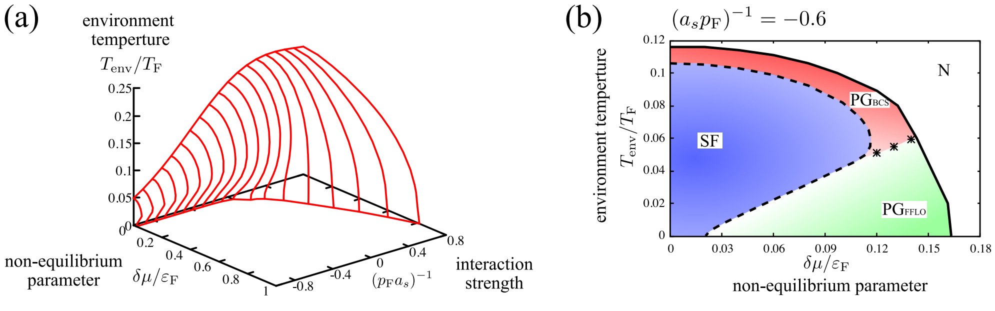

Figure 1: (a) The critical temperature and (b) the phase diagram of a non-equilibrium Fermi gas. Please refer to the poster for more on this figure.

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00-00

Ferromagnetic instability for the single-band Hubbard model in the strong-coupling regime

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Magnetic properties in the simple Hubbard model have attracted interest. One of the interesting examples is the recent observation of the antiferromagnetic state in the optical lattice system. By contrast, the ferromagnetic instability is less understood. In a single-band Hubbard model, the FM instability appears due to the Coulomb interaction when the system has a large density of states (DOS) at the Fermi level, so-called Stoner criterion. On the other hand, the Stoner theory is not applicable in the strong-coupling case. Nagaoka has proved that for a single hole in the Hubbard model on a lattice with closed loops the ground state is a fully polarized ferromagnet in the strong coupling limit, the so-called Nagaoka ferromagnetism. However, it is still controversial how stable such a polarized ordered state is in the system with finite hole density and finite Coulomb interaction.

We study the FM instability in a doped single-band Hubbard model by means of dynamical mean-field theory with the continuous-time quantum Monte Carlo simulations. Examining the effect of the strong correlations in the system on the hypercubic and Bethe lattice, we find that the FM ordered state appears in the former, while it does not in the latter. We also reveal that the FM order is more stable in the case that the noninteracting DOS exhibits a slower decay in the high-energy region. The present results suggest that, in the strong-coupling regime, the high-energy part of DOS plays an essential role for the emergence of the FM ordered state, in contrast to the Stoner criterion justified in the weak-interaction limit [1].

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Calculations for Rényi entropy by using discrete truncated Wigner approximation

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The discrete truncated-Wigner approximation (DTWA) is a semi-classical phase-space method for analyzing many-body dynamics of quantum spin models [1]. In this work, employing the standard DTWA and its generalization derived by the Born-Bogoliubov-Green-Kirkwood-Yvon hierarchy truncation method for the phase-point operator [2], we develop a new computational approach to simulate non-equilibrium dynamics of the second-order Rényi entanglement entropy associated with a few sites, especially for the transverse Ising model in one dimension. To see the performance of our approach, we make a direct comparison with exact results obtained from the exact diagonalization and time-dependent density-matrix renormalization group methods. We show that our numerical simulation can reproduce the exact dynamics of the entropy for a time scale by units of the spin-exchange amplitude when the system parameters are tuned to a semi-classical regime.

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00-00

Flat-band many-body localization and dynamics in the Creutz ladder

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Localization is not necessarily induced by disorder. We show a disorder-free many-body localization in the interacting Creutz ladder. The system was recently realized in cold-atoms in an optical lattice [1]. In a non-interacting case, the flat-band condition leads to distractive interference of hopping and a wannier wavefunction is localized on four adjacent lattice sites. In the flat-band condition both with and without interactions, the level spacing analysis exhibits Poisson-like distribution. This indicates the signal of the disorder-free localization. Calculation of the inverse participation ratio supports this observation. This type of localization is robust to weak disorders, whereas for strong disorders, the system exhibits a crossover into the conventional disorder-induced many-body localization phase. Furthermore, we also study the dynamics of the system for the flat band condition. There, non-ergodic dynamics appear, the system does not thermalize. The localization dynamics depends on particle filling and the strength of interaction. They are phenomena similar to the behavior of a conventional many-body localization. The memory of an initial localized density pattern is preserved for long times [2].

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00-00

Quench dynamics from a Mott insulator to a superfluid in the Bose-Hubbard model : Application of the inhomogeneous Kibble-Zurek mechanism

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We study theoretically Kibble-Zurek mechanism (KZM) associated with a quench dynamics from the Mott insulator to the superfluid quantum phase transition of the Bose-Hubbard model (BHM), which describes the properties of ultracold atoms in an optical lattice. Previous studies have shown that the density of vortices resulted in by the quench obeys a power law of the quench time, and have discussed the relation with the KZM in homogeneous systems [1]. Supposing realistic experiments, we introduce a harmonic trap potential in the BHM and apply the theory of inhomogeneous Kibble-Zurek mechanism (IKZM) [2]. The phase transition takes place in a totally different way from the homogeneous system due to the Mott-lobe structure in the phase diagram. We demonstrate the IKZM based on time-dependent Gutzwiller simulations of the BHM.

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Density fluctuations and mechanical stability in a strongly-interacting Bose-Fermi mixture: Self-consistent T-matrix approach

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We theoretically investigate the mechanical stability of a normal-state Bose-Fermi mixture with a tunable hetero-pairing interaction and a Bose-Bose repulsive interaction. To include hetero-pairing fluctuations associated with a strong Bose-Fermi interaction, we employ the self-consistent T-matrix approximation[1,2], where the thermodynamic self-consistency is automatically guaranteed. Effects of a weak Bose-Bose repulsion is taken into account within the mean-field level. Using this framework, we evaluate the compressibility matrix, to assess the stability of the system against an induced Bose-Bose attraction mediated by Fermi atoms. We clarify how the density collapse of a Bose-Fermi mixture associated with this instability is avoided by a direct Bose-Bose repulsive interaction. In the presence of this competing phenomenon between the induced and direct interaction among Bose atoms, we determine the collapse temperature, as well as the BEC transition temperature, as functions of the Bose-Fermi pairing interaction strength. Since the mechanical stability is crucial for the experimental realization of a resonant Bose-Fermi mixture, our results would be useful for the research for strong-coupling properties of this system.

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00-00

Frustrated Magnetism with Coherently-Coupled Binary Fermi Gases in Triangular Optical Lattices

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We study the combined effects of fluctuations and frustration in frustrated antiferromagnets described by the spin-1/2 easy-axis XXZ model with transverse magnetic fields, and propose its promising quantum simulation with a coherently coupled binary mixture of Fermi atoms in a triangular optical lattice. We perform a cluster mean-field plus scaling analysis to show that the ground state exhibits several nontrivial magnetic phases and a spin reorientation transition caused by the quantum order-by-disorder mechanism. Moreover, we find from Monte Carlo simulations that thermal fluctuations induce an unexpected coexistence of Berezinskii-Kosterlitz-Thouless physics and long-range order in different correlators. These predictions, besides being relevant to present and future experiments on triangular antiferromagnetic materials, can be tested in the laboratory with the combination of the currently available techniques for cold atoms.

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00-00

Topological Thouless pumps in commensurate and incommensurate optical lattices

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Topological quantum pumps[1] can be experimentally realized in cold atoms in optical lattices, by the superposition of two lattices with different, but commensurate spatial periods[2,3]. These systems exhibit a topologically non-trivial phase where the topological invariant coincides with the quantized charge pumped at each pumping cycle. This quantization is analogous to the quantum Hall effect. Moreover, we have shown that the charge transferred at well-defined fractions of the pumping period can be quantized as integer fractions of the Chern number[4]. This fractional quantization is topological in nature and it is a direct consequence of the symmetries of the system, and does not rely on the presence of interactions. Here, we describe how to extend these findings to the case of quasiperiodic quantum pumps, which can be obtained by the superposition of two different lattices with incommensurate spatial periods. These quasiperiodic systems have no translational symmetry: It is therefore not possible to define the topological invariant as an integral of the Berry curvature in the momentum space. We will discuss here how to extend the definition of Chern number to the quasiperiodic case, and describe the transport signatures of the corresponding nontrivial topological phases.

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00-00

Continuous Phase Transition without Gap Closing in Non-Hermitian Quantum Many-Body Systems

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Quantum phase transitions have long been a subject of active research in quantum many-body physics. In conventional quantum many-body systems described by local and Hermitian Hamiltonians, continuous phase transitions are accompanied by closing of the excitation gap [1]. Thus two gapped ground states which are connected without gap closing are generally considered to belong to the same quantum phase [2]. Meanwhile, non-Hermitian physics [3] has recently attracted widespread attention. Some fundamental principles in conventional Hermitian systems break down in non-Hermitian systems, and alternative ones have yet to be established. In particular, the role of energy gaps in quantum phase transitions has remained unclear in non-Hermitian many-body systems.
In this study, we find that a continuous quantum phase transition can occur without gap closing in non-Hermitian quantum many-body systems. In such a transition, the susceptibility exhibits a singularity due to the nonorthogonality of eigenstates. This mechanism makes a sharp contrast with the Hermitian case, in which such singularity is due to gap closing. To illustrate this novel quantum phase transition, we construct an exactly solvable non-Hermitian model by introducing non-Hermiticity to Kitaev's toric-code model [4].

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00-00

Trapping of Erbium atoms for quantum degenerate Erbium-Lithium mixture experiments

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A mixture of cold atoms with a large mass imbalance is a powerful tool to explore various physical phenomena. In few-body physics, Efimov states with angular momentum made up of two heavy Fermions and one light Boson are expected [1]. In many-body physics, impurity problems such as Anderson's orthogonality catastrophe [2] can be simulated by selectively localizing only the heavy atoms in an optical lattice. By restricting heavy Fermions to two dimensions p-wave superfluidity may be induced by a surrounding Bose-Einstein condensate of light atoms in three dimensions mediating the interaction between the Fermions [3]. Previously, we have conducted experiments using Ytterbium as a heavy element and Lithium as a light element. Unfortunately, our research led to the conclusion that there are no useful Feshbach resonances to control the interaction between Ytterbium and Lithium [4]. To overcome this problem, we are currently enhancing the experiment by adding Erbium as an additional heavy species element to the setup. Theoretical calculations predict an abundance of Feshbach resonances between Erbium and Lithium [5]. We have prepared a 401 nm laser source with an output power of about 600 mW for Zeeman slowing and imaging of the Erbium atoms. A new 583 nm laser source with about 300 mW serves to form the necessary narrow linewidth magneto-optical trap (MOT). As an atom source a newly designed three species oven is used. We have succeeded in trapping Erbium atoms into a MOT and observed them via absorption imaging. Currently, we are working on the optimization of the experimental setup in order to prepare a sufficient number of atoms in the MOT with the goal to create a quantum degenerate Erbium and Lithium mixture. In the presentation, we report on the latest results and outline future experiments using the ultracold Erbium and Lithium mixture.

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Nonequilibrium dynamics of Fermionic Hubbard model under periodic driving

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A study of ultrafast dynamics and control of strongly correlated systems under periodic driving is a fascinating research field. So far, there has been intensive studies about the control (Floquet engineering) and the validity of the effective static descriptions using the Floquet Hamiltonian. Under continuos periodic driving, a (nonintegrable) system is expected to reach the infinite temperature. Here, interesting questions are whether the system drops by a quasi-steady state (Floquet prethermal state) on the way to the infinite temperature and for how long this state can survive.
In this work, we study dynamics of the Fermionic Hubbard model in the strongly correlated regime under periodic driving using the nonequilibrium version of the dynamical mean-field theory(DMFT)[1]. We mainly focus on resonant excitations to reveal existence of the Floquet prethermal states and validity of description of the Floquet effective Hamiltonian. In particular, we investigate cases where the Floquet effective Hamiltonian is described by the Hubbard model in the weak coupling regime and reveal the effects of the higher order corrections to the effective model. In addition, in order to check validity of the DMFT predictions and controllability of the cold atom experiments, we make a direct comparison between them [2]. Without any adjusting parameters, we found semi-quantitative agreement for various conditions between the theory and the experiment, which suggests that the theoretical tool and the quantum simulator are valuable tool to study nonequilibrium dynamics in strongly correlated systems.

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00-00

Instability of a dark soliton by quantum fluctuations in a one-dimensional lattice Bose gas

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A dark soliton in a one-dimensional superfluid Bose gas is a major low-energy excitation, and its properties have been studied extensively in both theory and experiment [1]. In this work, we numerically analyze the dynamics of dark solitons in an optical lattice including quantum fluctuations within the truncated Wigner approximation. In the classical regime, the dynamical instability of solitons depends largely on whether the kink of the soliton is located at a lattice site or a link of two sites. In our numerical simulations, the strength of quantum fluctuations was gradually increased from the classical regime. The results demonstrate that even weak quantum fluctuations significantly affect the stability of solitons at any locations. This finding enables us to distinguish the instability of the dark soliton due to quantum fluctuations from the classical dynamical instability by observing the difference in dynamics between the two types of dark solitons.

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00-00

Raman-Sideband Cooling in an Optical Triangular Lattice

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Frustrated spin systems belong to one of the most demanding problems of magnetism and condensed matter physics. The simplest realization of geometrical spin frustration is the triangular lattice with antiferromagnetic interactions. A rich variety of characteristic spin configurations can arise due to competition between the interactions and the geometry of the lattice [1]. Recently, there have been considerable advances in the direction of simulating quantum magnetism by using a quantum gas microscope (QGM) technique [2]. In our group, we are engineering an experimental setup of ^{87}Rb atoms in an optical triangular lattice with QGM, which will enable us to acquire insights into real-space properties in the frustrated spin system. The QGM measurement is associated with heating of atoms due to photon scattering and therefore requires a cooling mechanism. We adopt a Raman-sideband cooling (RSC) scheme for that purpose. This cooling is based on Raman transitions, which can be utilized to resolve the motional sidebands in the optical lattice (Fig. 1 (a)). We successfully resolved the sidebands and also observed the effect of the RSC in the optical triangular lattice (Fig. 1(b)). In this poster, we will report our recent experimental results.

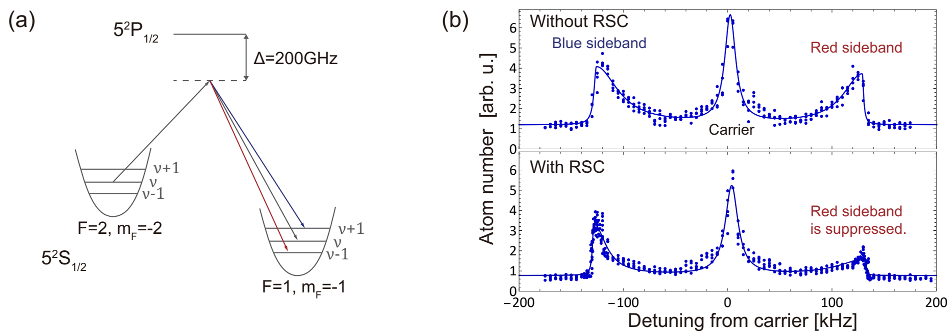

Figure 1: (a) Raman scheme for ^{87}Rb. (b) Raman spectra in the optical triangular lattice without and with RSC.

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00-00

Universality of Few Charged Particles

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From ions and charged impurities in ultra-cold systems to protons in nuclei, charged particles are important in physical systems that display universality. But it has been shown that the Coulomb interaction complicates the universal description, because it limits the spatial extent of the wave function [1].
In our systematic study of the interplay between universality and Coulomb interaction [2], we were able to show that there is a continuation of the known universal effects if the Coulomb interaction is weak (i.e. scattering length a_C is smaller than the Coulomb length D), and a new kind of universality if the Coulomb interaction is strong (i.e. $a_C \gg D$).
This new kind of universality manifests itself in the fact that a range correction is needed at leading order.
We used analytic derivation in a zero-range model approach for the two-body system and verified our results using the Gaussian Expansion Method [3] with Gaussian potentials of varying ranges. Drawing from our conclusions in the two-body sector, this also enabled us to assess the universal states in the three- and four-body sector. We mainly focussed on predicting the binding energies, but were also able to derive formulae for other observables, for example the root mean square (rms) radius.
We also identified systems in which these universal results should play a role and can be used to understand their properties.

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00-00

Quantum droplet of one-dimensional bosons with a three-body attraction

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Ultracold atoms offer valuable opportunities where interparticle interactions can be controlled at will. In particular, by extinguishing the two-body interaction, one can realize unique systems governed by the three-body interaction, which is otherwise hidden behind the two-body interaction. Here we study one-dimensional bosons with a weak three-body attraction and show that they form few-body bound states as well as a many-body droplet stabilized by the quantum mechanical effect [1]. Their binding energies relative to that of three bosons are all universal and the ground state energy of dilute droplet is found to grow exponentially as $E_N/E_3 \to \exp(8N^2/\sqrt{3}\pi)$ with increasing the particle number $N \gg 1$. The realization of our system with coupled two-component bosons in an optical lattice is also discussed.

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Quantum and Thermal Effects of the Triangular SU(3) Heisenberg Model in a Magnetic Field

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The SU(N) model, which has extended spin degrees of freedom, is expected to have complex magnetic orders at low temperatures. The latest advances in ultracold atom experiments can now deal with SU(N) symmetric systems. The SU(N=3,6) symmetric Mott-insulator states have been successfully realized with ytterbium atoms [1] and the spin correlation of the SU(N=2,4) Fermi gas of ytterbium in an optical dimerized cubic lattice has been studied; in particular, one can see that the SU($N>2$) system can be cooled down to lower temperatures than the SU(2) system [2,3]. Here we focus on the SU(3)-symmetric extension of the Heisenberg model on the triangular lattice. At zero temperature and zero magnetic field, density matrix renormalization group (DMRG) and exact diagonalization studies have found the ground state to have a three-sublattice order [4,5]. For finite magnetic fields, although the SU(3) Heisenberg model has an accidental continuous degeneracy in the classical ground-state manifold, which is induced by geometric frustration, the order-by-disorder selection has not been discussed.

In this work, we first perform a quantum analysis of the ground state by means of a numerical cluster mean-field method with two-dimensional DMRG solver [6]. We consider the quantum effects on the magnetization process and find the quantum stabilization of the 2/3 magnetization plateau, in which mixed magnetic and spin-nematic orders occur. At finite temperatures, we construct and employ a new framework of Monte Carlo simulations based on direct product wave-functions. We determine the phase diagram in the temperature-magnetic field plane. In particular, we show that the 2/3 magnetization plateau appears in an extended region and a new phase emerges at low magnetic fields.

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00-00

Slave-Boson Mean-Field Analysis of Superconductivity in the SU(3) *t*-*J* Model

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The *t*-*J* model is well known as an effective Hamiltonian for high critical temperature cuprate superconductors which takes into account strong correlation. In this model, the double occupancy of each site is prohibited and the exchange interaction between neighboring localized spins and electron hopping between adjacent lattice sites are considered. The model is very difficult to solve exactly and therefore an approximate calculation such as the mean-field approximation is used [1].

In this work, we perform the analysis of the superconductivity in the SU(3) *t*-*J* model which describes 3-flavor fermions. The *t*-*J* model has attracted revived attention in recent years because it can be simulated by experiments with ultracold atomic gases in optical lattices [2]. Recently, experiments using ultracold atomic gases with $N(> 2)$ components are being explored and the SU(3) and SU(6) Mott insulating states of ultracold fermions with ytterbium (^{173}Yb) atoms in optical lattices have been reported [3,4]. As the next stage, research for the realization of magnetism and superconductivity with SU(*N*) symmetry is actively pursued.

We extend the slave-boson mean-field analysis of the *t*-*J* model to the SU(3)-symmetric case. Here the electron creation operator is represented by the product of a 3-flavored spinon (fermion) creation operator and a holon (boson) annihilation operator [5]. We transform the Hamiltonian using two types of bond operators and apply the mean-field approximation. We compare the free energies of several mean-field solutions and determine the phase diagram in the temperature-hole doping plane. In particular, we discuss the exotic superconducting states that appear in this model.

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00-00

Effects of disorder and interaction on topological Thouless pumping of ultracold fermions

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In 1983 Thouless discussed quantization of particle transport in one dimensional periodic potential with adiabatic periodic modulation [1]. He showed that the amount of transported charge in one pumping cycle is determined by a topological invariant Chern number introduced in the context of the integer quantum Hall effect. This topological pumping may be considered as a dynamical version of the integer quantum Hall effect. It has been recently realized experimentally using ultracold atoms in dynamically controlled optical lattices [2-4].
The prominent feature of the topological pumping is robustness to perturbation. As long as the energy gap does not close during the pumping cycle, the Chern number is not changed and accordingly the quantization of the pumped charge does not depend on the detail of pumping cycle, even in the presence of potential disorder and interaction [5, 6]. We study their effects on the topological pumping using an ultracold Fermi gas of ytterbium atoms in a dynamically controlled optical superlattice. The strengths of the disorder and interaction are compared with the relevant energy scales in a theoretical model.

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Ferromagnetism in the SU(n) Hubbard model with nearly flat band

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We present rigorous results for the SU(n) Fermi-Hubbard model. It describes correlated multi-component fermions with SU(n) symmetry and can be realized with ultra-cold atoms [1]. However, rigorous results for the SU(n) ($n > 2$) case are rare. Here we study the SU(n) Hubbard model on a peculiar one-dimensional lattice with repulsive interaction and derive rigorous results. We first study the model with a flat band at the bottom of the single-particle spectrum. We prove that the ground states are SU(n) ferromagnetic when the number of particles is half the number of lattice sites. This SU(n) ferromagnetism was also discussed in ref. [2]. Then we perturb the flat-band model and make the bottom band dispersive. We find that SU(n) ferromagnetism in the ground states of the perturbed model at the same filling can be proved if each local Hamiltonians (independent of the total system size) is positive semi-definite (p.s.d.). The positive semi-definiteness can be checked numerically since the local Hamiltonian becomes a finite-dimensional matrix. The parameter region in which the local Hamiltonian is p.s.d. is shown in Fig. **??**. Furthermore, we prove that the local Hamiltonian is p.s.d. for sufficiently large interaction and band gap.

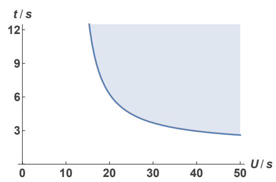

Figure 1: The local Hamiltonian is p.s.d. in the shaded region. U is a Coulomb interaction and s, t are energy scales for the bottom and top bands, respectively.

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00-00

Non-Hermitian fermionic superfluidity subject to inelastic collisions in ultracold atoms

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In recent years, non-Hermitian (NH) quantum systems have been actively studied both experimentally and theoretically. It has been revealed that non-Hermiticity drastically alters the properties of a number of quantum phenomena that have been established in the Hermitian physics [1,2]. Such theoretical predictions have been confirmed experimentally by using optical systems and ultracold atoms. However, since most of the previous studies dealt with single-particle physics, understanding of many-body physics in NH systems is yet in its infancy. Motivated by recent experimental advances in ultracold fermionic atoms, we analyze a non-Hermitian (NH) BCS Hamiltonian with complex-valued interactions arising from inelastic scattering between fermions [3]. We develop a mean-field theory to obtain a NH gap equation for order parameters, which are similar to but different from the standard BCS ones because of the inequivalence of left and right eigenstates in the NH physics. We find unconventional phase transitions unique to NH systems: the superfluidity breaks down and reappears with increasing dissipation, featuring non-diagonalizable (exceptional) points, lines, and surfaces in the quasiparticle Hamiltonian for weak attractive interactions. As for strong attractive interactions, the superfluid gap never collapses but is enhanced by dissipation due to an interplay between the BCS-BEC crossover and the quantum Zeno effect.

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00-00

Rigorous Results for the Ground States of the Spin-2 Bose-Hubbard Model

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We present rigorous and universal results for the ground states of the $f = 2$ spinor Bose-Hubbard model. The model includes three two-body on site interaction terms, two of which are spin dependent while the other one is spin independent. We prove that, depending only on the coefficients of the two spin dependent terms, the ground state exhibits maximum or minimum total spin or SU(5) ferromagnetism. Exact ground-state degeneracies and the forms of ground-state wave function are also determined in each case. All these results are valid regardless of dimension, lattice structure, or particle number. Our approach takes advantage of the symmetry of the Hamiltonian and employs mathematical tools including the Perron-Frobenius theorem and the Lie algebra $\mathfrak{so}(5)$.

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Entanglement transport and thermalization in an isolated many-body system

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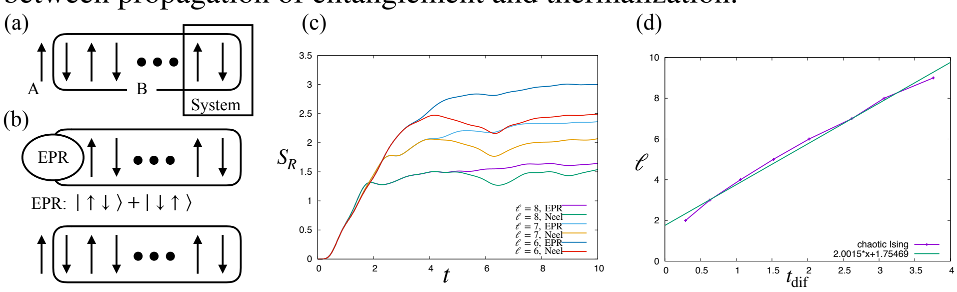
Recently, entanglement structure is considered to be essential for understanding quantum many-body systems. One of the important quantities that characterizes entanglement structure is entanglement entropy (EE). EE has been studied in various systems. In particular, it is remarkable that EE has been successfully measured in cold atom experiments [1]. On the other hand, thermalization in isolated quantum systems has recently attracted much attention [2]. The entanglement structure is a key to understand the thermalization mechanism of a pure quantum system.

In this work, we focus on transport properties of entanglement in isolated quantum systems that exhibit thermalization. Specifically, we study time-evolution of EE in the Ising model with the next-nearest-neighbor term as well as the transverse and longitudinal magnetic fields. We consider a spin chain which consists of a single spin (A) and the bulk part (B) (see Fig. (a)). To quantify the propagation of EE, we compare time-evolution of the two cases with different initial settings: the one with entanglement between A and B, which has EPR pair on the left edge of the chain, and the one without it (see Fig. (b)). We calculate the time evolution of EE for various sizes of the subsystem. We find that the linear increase of the EE in the initial stage before the saturation is due to the local production of EE. The propagation speed can be estimated by the time at which the EEs for the two cases show deviation. We demonstrate that EE propagates ballistically with a constant velocity even if the system is non-integrable (Fig. (d)). Based on these results, we will discuss the relation between propagation of entanglement and thermalization.



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00-00

Intercomponent entanglement spectra in binary Bose-Einstein condensates

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The entanglement spectrum provides useful probes of topological phases and other exotic systems. It is defined as the full eigenvalue spectrum of the entanglement Hamiltonian $H_{\mathrm{e}} = -\ln \rho_A$, where ρ_A is the reduced density matrix of the subsystem A. While the general correspondence between the edge states and the ES has been proved for topological phases [1], the ES between coupled Tomonaga-Luttinger liquids shows a variety of dispersion relations such as square root and gapped, depending on the type of the coupling [2]. Here, we study the intercomponent ES in d-dimensional binary Bose-Einstein condensates (BECs) as shown in Fig. 1. For homogeneous BECs (with $B_\uparrow = B_\downarrow = 0$), we obtain the ES with anomalous square-root and gapped dispersion relations for $\Omega \neq 0$ and $\Omega = 0$, respectively. For two-dimensional vortex lattices with $\Omega = 0$ under parallel ($B_\uparrow = B_\downarrow$) and antiparallel ($B_\uparrow = -B_\downarrow$) synthetic fields, the ES shows a square-root dispersion relation. We relate these intriguing ES with the emergence of certain long-range interactions in the entanglement Hamiltonian.

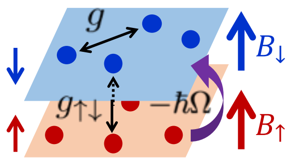

Figure 1: Binary BECs with intracomponent and intercomponent interactions g and $g_{\uparrow\downarrow}$ and the Rabi coupling Ω under synthetic magnetic fields $B_\uparrow$ and $B_\downarrow$.

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00-00

Using Active Learning to design the adiabatic evolution

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We have used the Active Learning (AL) idea to design the adiabatic evolution. We have applied our method to the Grover search problem and find that it performs well to find a good evolution of a time-dependent Hamiltonian that fulfills the expected fidelity at the cost of labeling just hundreds of data instances. In real experiments, when labeling is difficult, time-consuming and costly which means you can only do limited times of experiments, this pragmatic method can perform better with less training. This method can also be applied to more complicated problems, provided that you can encode your problem into optimizing several parameters.

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