論文の内容の要旨

Shortcuts to Adiabaticity Applied to Many-Body Systems
(多体系における断熱時間発展の加速)

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Adiabatic control is known as a method that enables us to stably realize target processes. Such adiabatic time evolution is the key concept of quantum annealing, which recently attracts much attention due to realization of quantum annealers by D-Wave Systems. Adiabatic control has been also utilized to produce various states including entangled states. However, adiabatic control of quantum systems often suffers from decoherence due to the requirement of long operation time. Recently much attention has been paid to shortcuts to adiabaticity, which enable us to speedup adiabatic time evolution. Such acceleration of adiabatic time evolution is realized by adding counter-diabatic terms to a Hamiltonian or by designing time-dependence of a Hamiltonian.

In this thesis, we study shortcuts to adiabaticity for many-body systems. In particular, we focus on two many-body systems. One of them is classical spin systems. Here we introduce exact counter-diabatic terms for generic classical spin systems. We also show that this method can be applied to quantum annealing through a classical model of quantum annealing. The other of them is bosonic Josephson junctions, which consist of two interacting Bose-Einstein condensates. Here we propose approximate counter-diabatic terms for bosonic Josephson junctions. We also show that this method can be applied to produce a macroscopically entangled state in a bosonic Josephson junction.

Shortcuts to adiabaticity for classical spin systems

Our study of shortcuts to adiabaticity for classical spin systems is motivated by quantum annealing, which is recently known as a quantum-mechanical heuristic algorithm to solve combinatorial optimization problems. In quantum annealing, the solution of a given problem is encoded into the ground state of a problem Hamiltonian. We first prepare the ground state of a driver Hamiltonian whose ground state is trivial, for example, the transverse-field Hamiltonian whose ground state is the quantum paramagnetic state, which is a uniform superposition of all the states in the computational basis. Then, we gradually transform a Hamiltonian of the system from the driver Hamiltonian to the problem Hamiltonian. The

adiabatic theorem ensures that the system results in the ground state of the problem Hamiltonian, i.e., we obtain the solution of the problem, if change of the Hamiltonian in time is slow enough. The degree of difficulty of a given problem depends on the size of the minimum energy gap during a process because the adiabatic condition requires annealing time roughly proportional to inverse square of the energy gap in order to keep adiabaticity. Therefore, instances that show first order transitions during processes, which in general cause exponentially small energy gap, are hardly solved by quantum annealing within practical annealing time. It means that an instance that can be easily solved by quantum annealing has at least no first order transition during a process, and thus the ground state does not show drastic change. Then the question is if quantumness is really required to solve such a problem, or in other words, if duration of quantum annealing cannot be approximately described by classical time evolution. Indeed, some studies that reproduce the results of quantum annealers by using classical algorithms have been reported.

Based on this situation, we study shortcuts to adiabaticity for classical spin systems. Here we construct counter-diabatic terms for generic classical spin systems. We rely on the fact that any state of a generic classical spin system can be described by a product state of two-level systems and dynamics of each classical spin is governed by the similar equation of motion of a two-level system under an effective field. That is, we construct counter-diabatic terms for generic classical spin systems by utilizing a counter-diabatic term for a two-level system. Then, counter-diabatic terms for generic classical spin systems are given by additional time-dependent external fields. We show that our method actually enables us to track an instantaneous stationary state within arbitrary time, i.e., to realize fast classical adiabatic time evolution. Realization of classical adiabatic time evolution implies that, starting from the ground state of an initial Hamiltonian, our method results in the ground state of a final Hamiltonian if neither first order transitions nor criticality take place during a process. The important point is that we do not have to know details of tracked stationary states. We apply this method to a classical model of quantum annealing and also discuss possible improvement of performance to solve problems. We find that easy instances can be solved with probability one and within arbitrary time in principle, whereas our method is unfortunately not so efficient to solve combinatorial optimization problems as well as other known algorithms. Our method could give insight into quantum annealing.

Shortcuts to adiabaticity for bosonic Josephson junctions

Entanglement is widely utilized as a resource of quantum science and technologies. In particular, the theory of quantum metrology ensures that large entanglement enables us to improve precision of estimation of unknown parameters in interferometry. Motivated by recent manufacturing technologies, generation of macroscopically entangled states is of great interest. It is also important to produce macroscopically entangled states in various physical systems in order to estimate various parameters. However, for atomic systems, a number of particles forming large entangled states is still limited up to a dozen of particles. A bosonic Josephson junction, which consists of two interacting Bose-Einstein condensates, is one of the candidates to produce a macroscopically entangled state. Indeed, existence of a cat state, which is a superposition of macroscopically distinct states, as the ground state of a bosonic Josephson junction is predicted. Nevertheless, no experiment that produces a cat state in a bosonic

Josephson junction has been reported. This is because decoherence easily destroys a cat state. In order to minimize bad influence of decoherence, acceleration of generation is of great interest.

Therefore, we are motivated to study shortcuts to adiabaticity for bosonic Josephson junctions in order to speedup adiabatic generation of a cat state. Here we construct approximate counter-diabatic terms for bosonic Josephson junctions by using the Holstein-Primakoff transformation with the harmonic approximation and a counter-diabatic term for a harmonic oscillator. The key point is to take account of finite-size corrections that enable us to avoid divergence of counter-diabatic terms, which is observed in previous works. The form of approximate counter-diabatic terms is given by the two-axis counter-twisting interaction. Although the two-axis counter-twisting interaction has not been realized in experiments yet, but a lot of experimentalists try to realize it because it enables us to create not only a cat state but also a squeezed state within a short time. We show that our method suppress some of diabatic transitions in the fast generation regime and a bosonic Josephson junction actually forms a two-peak structure. We also show that this generated state with a two-peak structure is actually macroscopically entangled state showing the large quantum Fisher information. We expect that the two-axis counter-twisting interaction will be realized and our generation scheme will implemented in experiments, and thus a cat state will appear in a bosonic Josephson junction.