Summary of thesis:
Dynamical quantum effects in cluster dynamics of Fermi systems

Jun'ichi Ozaki

In the thesis, we report dynamical quantum effects in cluster dynamics of Fermi systems, with a focus on cluster-cluster collision dynamics and cluster drag dynamics in a cloud.

Recently non-equilibrium dynamics of cold atom systems has been enthusiastically targeted, because cold atom systems are ideal as isolated quantum systems configured, whose parameters can be modified dynamically in laboratory. The cold atom systems are composed of confined dilute atom gases, in which lattice potential can be applied by optical standing waves, the strength and sign of interaction are tunable by Feshbach resonance, and spin-dependent potential are also available.

In cold atom systems, the dynamics after a sudden change of system parameters, so-called quantum quench, has been explored. Of these experiments, the dynamics of collision and mixing of two fermion clouds released from spin-dependent traps [A. Sommer, et al., Nature **472**, 201 (2011)] motivates us to study collision dynamics between two fermion clusters in one-dimensional Fermi systems. We focus on quantum effects in dynamics, differences between the full-quantum calculation and a semiclassical treatment, and elucidate the underlying mechanism.

Also, dynamics induced by a gradual change of parameters in real time still has to be investigated. Such a dynamics is completely different from the quantum quench dynamics, in that the change of the system parameters in time continuously causes the energy excitation and dissipation in the system. Of these dynamics, especially we explore drag dynamics of a fermion cluster trapped by a moving trap in a fermion cloud, interacting with cluster particles in contact interaction. Drag dynamics is one of the basic concepts of dynamics; recently spin drag dynamics has been studied in situations different from ours.

In the last few decades, also numerical methods for strongly correlated systems have dramatically developed. Of these methods, the density matrix renormalization group (DMRG) is one of the most effective numerical methods for calculation of target states (e.g. ground states) in one-dimensional quantum lattice systems. The basic idea and the procedures

of DMRG, including time-dependent DMRG, are demonstrated in detail; the real-space parallel DMRG and the implementation in Fermi--Hubbard model are discussed.

We study (i) collision dynamics of two fermion clusters and (ii) typical drag dynamics of several fermions in a fermion cloud in one-dimensional continuous systems, with particular emphasis on non-trivial quantum many-body effects in systems whose parameters change (i) suddenly or (ii) gradually in real time. We adopt the Fermi-Hubbard model and the time-dependent DMRG to calculate the dynamics of those systems, and we explain the simulation results by using our concise models. Finally we clarify the origin of the non-trivial quantum effects in dynamics, by comparing the results and models with semi-classical or mean-field treatments. Although the analysis in the present work is restricted to one-dimensional systems, our simplified models can provide some important implications even for two or three dimensional systems; the investigation of the quantum effects is essential to intuitive understandings of non-equilibrium dynamics in quantum systems.

(i) Collision dynamics of two fermion clusters with contact interaction is simulated. We calculate reflectance and transmittance of the clusters. We elucidate that the quantum effects become extremely strong with the interaction strength, leading to the transmittance much more enhanced than expected from semiclassical approximation. We propose a concise model as an extension of the Bethe ansatz, which unveils the origin of the quantum effects and also explains the overall properties of the simulation results clearly. This model provides an intuitive perspective of the collision dynamics with contact interaction. Some potential applications, such as repeated collisions, are addressed.

(ii) Typical drag dynamics of several fermions in a fermion cloud in one-dimensional continuous systems is simulated. We calculate the drag force on a trapped fermion cluster in a cloud of another fermion species with contact interaction. A non-trivial peak in the resistance force is observed in the high cloud density region, and it is clarified that the peak cannot be explained by a naive mean-field theory, although the other characteristics of the cloud density dependence are explained. This implies that some internal degrees of freedom have a crucial role in the excitation process. We also propose a criterion of efficient ways in diffusive transport in a fermion cloud.