# 論文の内容の要旨

論文題目：**Theoretical Study on Efimov Physics in Ultracold Atoms**

**（冷却原子気体における Efimov 状態の物理の理論的研究）**

氏名： 遠藤　晋平

## Abstract

Universality refers to particular features that do not depend on microscopic details of individual systems. While most of the textbook examples of the universality concern many-body systems, there are also remarkable universal features in few-body systems. Among them, the Efimov states have attracted the widening interest since they were observed in ultracold atoms in 2006. The Efimov states are three-body bound states which appear when the s-wave scattering length between the particles is much greater than the range of the interaction. Close to the resonance, the length scale characterizing the interaction diverges, and the system becomes scale invariant. It follows that an infinite series of three-body bound states appear, and that they show characteristic discrete scale invariance. Since they were found theoretically in 1970 by V. Efimov, there have been a number of studies on Efimov states for various kinds of systems, such as $^4$He clusters, nuclear halo states, ultracold atoms, and a quantum spin system. Since the Efimov states and their characteristic discrete scale invariance have recently been observed in ultracold atoms, the Efimov states and their associated few-body phenomena have attracted widening interest both theoretically and experimentally.

In this thesis, I theoretically study the Efimov physics and related phenomena, focusing on the following topics:

## (i) Universal three-body physics for a mass-imbalanced Fermi system

For a system of two identical fermions and one distinguishable particle which interact via a short-range potential with a large s-wave scattering length, two classes of universal three-body bound states have been known to appear in different regimes of the mass ratio: the Efimov trimers and the Kartavtsev-Malykh trimers, which feature the discrete and continuous scale invariance, respectively. I have found the third class of universal three-body bound states, which I call the ``crossover trimers". The crossover trimers show neither the discrete nor continuous scale invariance. I have identified the regions of these three classes of trimers as a function of the mass ratio and the s-wave scattering length, and shown that the Kartavtsev-Malykh trimers and the Efimov trimers can continuously transform into each other via the crossover trimers as the mass ratio and the s-wave scattering length are varied.

Owing to the presence of the crossover trimers, the Kartavtsev-Malykh trimers dissociate into a particle and a dimer when the s-wave scattering length is varied, inducing resonances in the particle-dimer scattering. I have calculated the elastic particle-dimer scattering lengths in arbitrary angular-momentum channels, and shown that the particle-dimer resonances indeed occur. From the resonance positions, I have found accurate values of the critical mass ratios at which the Kartavtsev-Malykh trimers in the higher angular-momentum channels appear.

Mass-imbalanced fermionic mixtures have been achieved recently in ultracold atoms, and there has been a growing experimental interest in their few-body and many-body behaviors. In particular, a precursor of the Kartavtsev-Malykh trimers have been observed in a fermionic mixture of $^{40}$K and $^{6}$Li atoms in 2013. The work presented in this thesis would be helpful for investigation of few-body and many-body physics in the mass-imbalanced Fermi systems.

## (ii) Universal three-body parameter

In the Efimov physics, the three-body parameter fixes the short-range three-body phase and hence the scale of the energy spectrum. Until quite recently, it has been widely held that the three-body parameter should depend on the short-range part of the inter-atomic potential, and hence vary almost randomly between different atomic species and hyperfine states. However, mounting evidence in recent experiments suggests otherwise. While some theoretical studies have reproduced the universal behavior in the three-body parameter, the underlying physical mechanism has remained unclear and controversial. I have elucidated the physical origin of the universal three-body parameter. I propose that a non-adiabatic deformation of the three-body wave function induced by a universal two-body correlation results in a universal three-body repulsion, which prevents three particles from coming close and renders the three-body parameter universal. This mechanism is verified by reproducing the universal three-body repulsion with a simple model wave function.

The mechanism found in this work suggests a universal relation between the three-body parameter and the effective range for broad classes of two-body potentials. This may stimulate further investigation of the three-body parameter of the Efimov physics in many fields of physics.

## (iii) Effective interaction between heavy particles immersed in a Fermi sea of light fermions

For a system of two heavy particles resonantly interacting with one light fermion, the Efimov states appear. Recently, it has been shown numerically that the formation of the Efimov states is suppressed when the number of light fermions is increased so that they form a Fermi sea. I show that this is also true for $N$ heavy particles. To be more specific, I consider $N$ heavy particles immersed in a Fermi sea of light fermions, and study the interaction between the heavy particles induced by the surrounding light fermions. With the Born-Oppenheimer method, I have analytically shown that the induced interaction vanishes for any $N$ in the limit of high light-fermion density. The induced interaction vanishes even in the unitarity regime. This suggests that the formation of the Efimov states and their associated $N$-body bound states is suppressed in the presence of the dense Fermi sea. I have ascribed the vanishing induced interaction to the screening effect in the neutral Fermi system.