課題名（タイトル）：

光格子における超流動 Fermi 気体のバンド構造

利用者氏名：渡辺 元太郎
所属：和光研究所 仁科加速器研究センター 理論研究部門 中務原子核理論研究室

1. 本課題の研究の背景、目的、関係するプロジェクトとの関係

Ultracold gases in optical lattices provide a new frontier of research where many remarkable phenomena can be observed and investigated. By using Feshbach resonances one can tune the interaction between atoms and investigate the crossover between the Bardeen-Cooper-Schrieffer (BCS) state and a Bose-Einstein condensate (BEC), passing through a resonant regime where the scattering length is very large and the system exhibits universal properties (unitary regime). Here, "universal" means that the properties of the system does not depend on details of interparticle potential. Therefore, study of unitary Fermi gases is also useful for other systems, such as neutron gases in inner crusts of neutron stars, where the neutron-neutron scattering length is much larger than the interparticle separation. Our final aim thus includes learning neutron star crusts by simulating neutron star matter using cold atom gases as well as understanding the cold atom gas systems themselves.

Interplay between the non-linearity and the periodic potential is one of the important issues of the ultracold atomic gases in optical lattices and it gives rise to various intriguing phenomena. However, unlike for BECs, little has been explored so far on this issue for superfluid Fermi gases in optical lattices. One of a handful exceptions is the swallowtail band structure in the BCS-BEC crossover which has been explored by ourselves in our previous project using RICC.

That project on the swallowtail band structure has been finished successfully and our results have been published in the recent volume of the Physical Review Letters [G. Watanabe, S. Yoon, and F. Dalfovo, Phys. Rev. Lett. **107**, 270404 (2011)]. This paper was also selected as a research highlight in Asia Pacific Physics Newsletter.

In spring 2012, in collaboration with Dr. Nakatsukasa, we started working on period doubling phenomenon in superfluid Fermi gases in optical lattices. Density wave is one of the most fundamental phenomena in condensed matter physics. In Bose-Einstein condensates (BECs) in a periodic potential, non-linearity of the interaction term gives rise to stationary states whose period does not coincide with that of the external potential; instead, a multiple of it. However, it has been found that the period-doubled states in BECs are energetically unfavorable compared to the normal Bloch states and in many cases they are also dynamically unstable.

As for superfluid Fermi gases, on the other hand, there is no study about period doubling and the problem is totally open. Superfluid Fermi gases in the BCS-BEC crossover provide a very intriguing question of how period-doubled states evolve between the BCS and BEC limits. The problem of the period doubling can be even more important in Fermi superfluids, due to the possible implications in superconducting electrons in solids and superfluid neutrons in neutron stars.

In this project, we study states with various periods (mainly, period 1, 2, and 3) of Fermi superfluids in a 1D periodic potential in the

BCS-BEC crossover. The first purpose of this project is to explore whether we have period-doubled states in Fermi superfluids. If we find the existence of the period-doubled states in Fermi superfluids, we shall look into how they evolve along the BCS-BEC crossover and solve the following questions.

1) Difference and similarity between Fermi superfluids and BECs. We shall pursue unique properties of period-doubled states of Fermi superfluids which are absent for BECs.

2) Stability of the period-doubled states along the BCS-BEC crossover. The main question is whether we have dynamically stable period-doubled states in some parameter region.

3) Experimental consequences of period-doubled states in the BCS-BEC crossover.

4) A criterion for appearance of the period-doubled states in the BCS side.

2. 具体的な利用内容、計算方法

To study the period-doubling phenomena in ultracold superfluid Fermi gases, we use a mean-field theory based on the Bogoliubov - de Gennes (BdG) equations. We study the whole region along the BCS-BEC crossover including the unitary regime at zero temperature focusing on the situation in which the lattice potential is relatively weak as in the recent experiments. In such a situation, the tight binding description is not adequate and a full numerical approach based on the BdG equations is called for. Although approximate, this approach captures basic features along the whole BCS-BEC crossover, including the formation of molecules and the most challenging unitary limit where, for uniform 3D configurations, the predictions are in reasonably good agreement with ab initio Monte Carlo simulations. The BdG equations apply also to situations where the density varies over distances of the order of the healing length.

3. 結果

Using numerical simulations based on the BdG equations, we have found that the period-doubled states can be energetically favorable compared to the normal Bloch states in the BCS side. This is in sharp contrast to the situation of the period-doubled states in BECs. Going to the deep BCS regime, the period-doubling nature is mainly possessed by the pairing field, which decreases to zero. We thus speculate that our period-doubled states emerge due to the superfluidity. We have also found that, in some parameter region, the period-doubled states are energetically favorable even compared to period-tripled states.

4. まとめ

In summary, we have started our new project on period doubling in superfluid Fermi gases along the BCS-BEC crossover in collaboration with Dr. Nakatsukasa. We have found that period-doubled states exist as stationary states in Fermi superfluids and it can be energetically favorable compared to normal Bloch states in some parameter region. Further study is necessary to understand the period-doubling phenomena in Fermi superfluids.

5. 今後の計画・展望

Currently, we are investigating stability of the period-doubled states and are carrying out further study to understand the connection between the period doubling and superfluidity.

In the period-doubled states, complicated quasiparticle energy spectra arise from the interconnection between the positive and negative branches of the BdG equations due to the band folding. Understanding the emergence of the period-doubled states in terms of the quasiparticle energy spectrum might enable us to find an interesting connection between the period doubling and superfluidity.

We have found that the period-doubled states can be energetically favorable compared to the normal Bloch states in the BCS side. Now, it is very important to study the dynamical stability of these period-douled states. We will approach this issue using the framework of Quasi-particle random phase approximation (QRPA). This is a linear stability analysis based on the time-dependent BdG equations. QRPA calculations demands large computing resources and we are going to perform these calculations using RICC.

平成 24 年度　RICC 利用研究成果リスト

【論文、学会報告・雑誌などの論文発表】

Toshiki Maruyama, Gentaro Watanabe, and Satoshi Chiba: *Molecular Dynamics for Dense Matter*, Prog. Theor. Exp. Phys. 1, 01A201 (2012).

Gentaro Watanabe and Toshiki Maruyama: *Nuclear pasta in supernovae and neutron stars*, in Neutron Star Crust, edited by C. A. Bertulani and J. Piekarewicz (Nova, New York, 2012) [invited review].

Gentaro Watanabe and Sukjin Yoon: *Aspects of superfluid cold atomic gases in optical lattices*, to appear in JKPS special topic issue on cold atoms and molecules [invited review].

【国際会議、学会などでの口頭発表】

Gentaro Watanabe, Sukjin Yoon, and Franco Dalfovo: Swallowtail band structure of the superfluid Fermi Gas in an optical lattice, 43rd Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics (DAMOP 2012) (Anaheim, California, 8 June 2012).

Gentaro Watanabe: 冷却原子気体で探る中性子星物質ーその可能性と課題, Kickoff Symposium on "Nuclear matter in neutron stars uncovered by experiments and observations" (RIKEN, Japan, October 26-27, 2012) [invited].

【その他】

Gentaro Watanabe, Sukjin Yoon, and Franco Dalfovo: *Swallowtail Band Structure of the Superfluid Fermi Gas in an Optical Lattice*, Research Highlights in Asia Pacific Physics Newsletter 1, 15 (2012).