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

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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 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).

Interestingly, in the case of BECs in one-dimensional (1D) optical lattices, the energy band shows loop structures (called the "swallow-tail" structure) due to the nonlinear effects provided the interaction is strong enough compared to the lattice potential. Such loop structures result in, e.g., a breakdown of the Bloch oscillation, etc. Main purpose of this project is to explore whether there exist such loop structures in Fermi superfluids, especially focusing on the most intriguing unitary regime in the BCS-BEC crossover, and to find out a criterion for appearance of the loop.

2. 具体的な利用内容、計算方法

In this project, in order to investigate the band structure of 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

We just started this project at the beginning of February 2010. We expect that we will obtain results which is worth reporting publicly in the beginning of the next academic year (the academic year of 2010). Results which we have obtained so far are as follows.

1) We have found that the energy band has a swallow-tail-like structure in the crossover region between the BCS and BEC limits.

2) Around unitarity, where the scattering length diverges, the width of the swallow tail has a maximum.

3) In the BEC region, the width of the swallow tail increases by approaching the unitarity because of an increase of the intermolecular interaction energy. On the other hand, in the BCS region, the increase of the width of the swallow tail is due to the enhancement of the paring field by approaching the unitary regime.

4. まとめ

We have started to study the band structure of the ultracold superfulid Fermi gases in one-dimensional periodic potentials. We have found a swallow-tail band structure and are studying its behavior along the BCS-BEC crossover.

5. 今後の計画・展望

We need to further study various parameters systematically to obtain a complete understanding of this phenomena. We are now performing such numerical calculations using RICC. We also want to understand the behavior of the width of the swallow tail analytically based on the knowledge obtained from our numerical calculations. We expect that we will obtain a conclusive result by summer in the next academic year.

6. RICC の継続利用を希望の場合は、これまで利用した状況（どの程度研究が進んだか、研究においてどこまで計算出来て、何が出来ていないか）や、継続して利用する際に行う具体的な内容

So far, We have studied a limited parameter region, and our understanding is incomplete. We need to obtain a complete and overall picture. For this purpose, we will perform further numerical calculations for various sets of parameters. At the present moment, a simple and analytical understanding (i.e., a criterion for appearance of the swallow tail, etc.) is also lacking. We will pursue this issue with the help of the knowledge obtained by the numerical calculations.

7. 利用研究成果が無かった場合の理由

We just started this project in the beginning of February 2010.

平成 21 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】

本プロジェクトそのものの成果ではないが、これに密接に関係するプロジェクトでの成果として、以下の論文を挙げておく。

G. Watanabe, F. Dalfovo, F. Piazza, L. P. Pitaevskii, and S. Stringari:
"Critical velocity of superfluid flow through single-barrier and periodic potentials"
Phys. Rev. A 80, 053602 (2009).

【その他】

Gentaro Watanabe
"Properties of superfluid unitary Fermi gases in an optical lattice"
Poster presentation in the Conference on "Research Frontiers in Ultra-Cold Atoms"
(ICTP, Trieste, Italy, 4-8 May 2009).