論文 / 著書情報
Article / Book Information

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Title(English)	Physics of an attractive Fermi gas in antiparallel magnetic fields
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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Ceaseless progress in ultracold atom experiments allows us to control system parameters at will. For example, the strength of the interaction between atoms can be arbitrarily tuned by varying a magnetic field via Feshbach resonances, which is unprecedented in other fields of physics. This technique applied to two-component Fermi gases led to the realization of smooth evolution from a Bardeen-Cooper-Schrieffer (BCS) superfluid of Cooper pairs to a Bose-Einstein condensation (BEC) of tightly bound molecules. This phenomenon is called ``BCS-BEC crossover." Furthermore, the dimensionality can be tuned by confining atoms with an optical lattice generated by two counterpropagating laser beams. By confining Fermi gases in the two-dimensional (2D) space, the BCS-BEC crossover in 2D has also come to the reach of experimental investigation. In addition to tuning the interaction and dimensionality at will, we can control the quantum statistics and internal degrees of freedom. Therefore, ultracold atoms provide an ideal platform to study quantum many-body systems.

In general, phenomena induced by magnetic fields are important in various fields of physics. Therefore, by taking advantage of the experimental abilities to control system parameters of ultracold atoms at will, it is worthwhile to investigate phenomena induced by magnetic fields with ultracold atoms. However, atoms are electrically neutral, so that their orbital motion does not occur by magnetic fields. So far, enormous research efforts have been devoted to developing experimental techniques to create synthetic magnetic fields. One approach is to optically couple internal states of atoms so that neutral atoms can behave like charged particles in a magnetic field, which provided a new route towards the realization of topological physics with ultracold atoms. This approach was further extended to create ``antiparallel" magnetic fields which are equal in magnitude but opposite in directions for different spin components of atoms.

In this thesis, we investigate the ground-state properties of an attractive Fermi gas with two spin components subjected to antiparallel magnetic fields in the mean-field approximation. Whereas the attractive interaction generally favors the Cooper pairing, the antiparallel magnetic fields lead to the Landau-level formation with opposite chiralities for different spin components of atoms. Therefore, we can expect interesting physics to be realized by competition or cooperation between the Cooper pairing and antiparallel magnetic fields. Moreover, attractively interacting Fermi gases with two spin components in antiparallel magnetic fields may be viewed as a simulator of analogous phenomena in other fields of physics, such as exciton condensation and chiral condensation in a magnetic field, where two particles forming a pair have opposite charges and thus experience opposite Lorentz forces.

Firstly, we study a 2D spin-balanced Fermi gas in antiparallel magnetic fields. We find that the mean-field phase diagram at zero temperature consists of superfluid and quantum spin Hall insulator phases and closely resembles that of the Bose-Hubbard model, which consists of superfluid and Mott insulator phases. The resulting two phases are separated by a second-order quantum phase transition classified into the universality class of either the dilute Bose gas or XY model. We also calculate some physical quantities to elucidate the ground-state properties in the superfluid phase. In particular, we show that the pairing gap is enhanced by antiparallel magnetic fields as a consequence of magnetic catalysis.

Next, we study a 2D spin-imbalanced Fermi gas in antiparallel magnetic fields. By employing the mean-field approximation, we find that the Fulde-Ferrell (FF) state is energetically favored over the Larkin-Ovchinnikov (LO) state in the weak-coupling limit. We then clarify the mean-field phase diagram at zero temperature in the space of the attraction, average chemical potential, and Zeeman field analytically at weak coupling as well as numerically beyond it. We find that the resulting phase diagram shows the rich structures consisting of quantum Hall insulator, unpolarized superfluid, and FF phases separated by various first-order and second-order quantum phase transitions. Moreover, we show that the FF phases occupy the reasonable portions of the phase diagram, so that they may, in principle, be realized by ultracold atom experiments.

Finally, we study a three-dimensional (3D) spin-imbalanced Fermi gas in antiparallel magnetic fields with the ansatz of the FF state. Under the condition that fermions occupy the lowest Landau level, we find that the mean-field thermodynamic potential of a 3D spin-imbalanced Fermi gas in the magnetic fields corresponds to that of a one-dimensional (1D) spin-imbalanced Fermi gas without magnetic fields at weak coupling. We then clarify that the ground-state phase diagram consists of fully polarized normal, unpolarized superfluid, and FF phases. By calculating the collective excitation spectrum, we show that the long-range order exists in the weak-coupling limit, where our system is effectively described by a 1D spin-imbalanced Fermi gas without the magnetic fields.