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Competition between Abelian and Zeeman magnetic field effects in a two dimensional ultracold gas of fermions

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ABSTRACT

The ground state of ultracold fermions in the presence of effects of orbital and Zeeman magnetic fields is analyzed. Five different states are found: unpolarized superconducting state, partially and fully polarized normal states and phase separated regions, partially or fully polarized. The system, in the presence of orbital synthetic magnetic field effects, shows non-monotonous changes of the phase boundaries when electron concentration is varied. We observe not only reentrant phenomena, but also density dependent oscillations of different areas of the phase diagram. Moreover the chemical potential shows oscillatory behavior and discontinuities with respect to changes in the number of fermions.

1. Introduction

Using quantum simulators with fully controllable Hamiltonian parameters, which can describe real situations in condensed matter physics, is a desire of the solid state community. Such simulators can reflect the main properties of the physical system and with the ability to separate the effects that are indissoluble in the bulk materials, may become a standard technique. Many different

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many-body models are recently realized by exploiting ultracold atoms. The Bose- and Fermi–Hubbard (FH) Hamiltonians are realized with the help of optical lattices and therefore quantum phase transitions can be analyzed in great detail. The different quantum phases that exist in such systems can be detected using various techniques.

Recent experimental approaches are developed in order to simulate synthetic magnetic gauge fields, both Abelian and non-Abelian, especially in the context of quantum Hall effects. Spielman's group succeeded in creating an external synthetic magnetic, Abelian and non-Abelian, gauge field coupled to neutral gases [1]. Bloch et al. generated large tunable effective magnetic fields for ultracold atoms using photon-assisted tunneling in an optical superlattice [2,3]. Also Ketterle et al. [4] created uniform magnetic fields with flux piercing the plaquette equal $\phi = \pi$. A major goal of these experiments is to achieve the quantum Hall regime with a very high effective flux density and to model materials where the strong correlations play the crucial role [5,6]. This opens an avenue to study effects not achievable in conventional solid state physics [7,8]. Experiments in which fermionic (or bosonic) gases are loaded into optical lattices have also been carried out [9–12]. Both the depth of the periodic trapped potential and the geometry can be fully controlled. In this way, strongly correlated systems with different geometries of the lattice can be analyzed.

Another experimental aspect is the investigation of spin-polarized superfluidity in the context of cold atomic Fermi gases. They lay down one of the most investigated directions of studies in the range of condensed matter physics and ultracold quantum gases. Experimental groups from MIT [13,14] and from the Rice University [15] investigated Fermi gases (^{6}Li) with unequal numbers of fermions with down ($\downarrow$) and up ($\uparrow$) spins ($N_\downarrow \neq N_\uparrow$ – systems with *population imbalance*). Experiments have indicated the presence of a phase separation region in the system, between the unpolarized BCS and the polarized normal state.

The possibility to create population imbalance in conventional superconductors can be realized by applying an external magnetic field, but this field is shielded by the orbital motion of electrons (the Meissner effect). However, a mixture with arbitrary population ratio can be prepared in atomic Fermi gases. Hence, the influence of the Zeeman magnetic field on superfluidity can also be investigated in these systems.

In the presence of the Zeeman magnetic field (h), the densities of states are different for the particles with spin down and spin up and there exists a mismatch between the Fermi surfaces. The population imbalance leads to states with nontrivial Cooper pairing. One example of such pairing is the so-called Fulde–Ferrell [16] and Larkin–Ovchinnikov [17] (FFLO) state. In this state the formation of Cooper pairs across the spin-split Fermi surface with non-zero total momentum ($\vec{k} \uparrow, -\vec{k} + \vec{q} \downarrow$) takes place. However, the observation of such a state is very difficult in superconducting systems because of the strong destructive influence of the orbital effect on superconductivity.

A different kind of pairing and phase coherence that can occur in such systems is the spatially homogeneous spin-polarized superconductivity (the so-called breached pair (BP) state). It is characterized by a gapless spectrum for the majority spin species [18–20]. The state of this type was originally considered by Sarma [21], who studied the case of a superconductor in an external magnetic field within the BCS theory. All orbital effects were neglected. It was shown that self-consistent mean field solutions with gapless spectrum ($\Delta(h)$) are energetically unstable at $T = 0$, contrary to the fully gapped BCS solutions. On the other hand, a non-zero temperature can lead to the stabilization of a spin-polarized state.

The Fermi–Hubbard system in an external Zeeman magnetic field has a very rich phase diagram, which was analyzed using mean field theory [22–31], exact numerical studies (Quantum Monte Carlo (QMC) simulations and density-matrix renormalization group (DMRG)/tensor network states (TNS)) of the 1D attractive Hubbard model with fermion population imbalance [32–36]. These last results show that the FFLO state can be obtained in one-dimensional systems, which is consistent with the fact that h_c^{FFLO} diverges as $T \rightarrow 0$ in $d = 1$. The ground state consists of five regions: superconducting, normal and phase separated in two dimensions (2D). The last two can be partially or fully polarized. The main goal of our present work is to investigate the ground state of the FH system in the presence of both Zeeman and orbital magnetic field. The presence of the Peierls factor introduces an additional change of the quantum mechanical phase of the fermionic atoms. This results not only in changes of the hopping amplitude, but in consequence modifies the density of states. Engineering the Landau