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Competing orders in one-dimensional half-integer fermionic cold atoms: A conformal field theory approach

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Abstract

The physical properties of arbitrary half-integer spins $F = N - 1/2$ fermionic cold atoms loaded into a one-dimensional optical lattice are investigated by means of a conformal field theory approach. We show that for attractive interactions two different superfluid phases emerge for $F \geqslant 3/2$: A BCS pairing phase, and a molecular superfluid phase which is formed from bound-states made of $2N$ fermions. In the low-energy approach, the competition between these instabilities and charge-density waves is described in terms of $\mathbb{Z}_N$ parafermionic degrees of freedom. The quantum phase transition for $F = 3/2, 5/2$ is universal and shown to belong to the Ising and three-state Potts universality classes respectively. In contrast, for $F \geqslant 7/2$, the transition is non-universal. For a filling of one atom per site, a Mott transition occurs and the nature of the possible Mott-insulating phases are determined.
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1. Introduction

Ultracold atomic physics has attracted a lot of interest in recent years with the opportunity to study strongly correlated effects, such as high-temperature superconductivity, in a new context [1]. In particular, loading cold atomic gases into an optical lattice allows for the realization of bosonic and fermionic lattice models and the experimental study of exotic quantum phases [2]. A prominent example is the toolbox to engineer the three-dimensional Bose–Hubbard model [3] and the observation of its Mott insulator—superfluid quantum phase transition with cold bosonic atoms in an optical lattice [4].

Ultracold atomic systems also offer an opportunity to investigate the effect of spin degeneracy since the atomic total angular momentum F, which includes both electron and nuclear spins, can be larger than $1/2$ resulting in $2F+1$ hyperfine states. In magnetic traps, these $2F+1$ components are split, while in optical traps these (hyperfine) spin degrees of freedom are degenerate and novel interesting phases might emerge. For instance, Bose–Einstein condensates of bosonic atoms with a nonzero total spin F are expected to display rich interesting structures in spin space like in superfluid ^{3}He. In this respect, various exotic superfluid condensates (including nematic ones), Mott-insulating phases, and non-trivial vortex structures have been predicted recently in spinor bosonic atoms with $F \geqslant 1$ [5–11]. These theoretical predictions might be checked in the context of Bose–Einstein condensates of sodium, rubidium atoms [12] and in spin-3 atom of ^{52}Cr [13]. The spin-degeneracy in fermionic atoms, like ^{6}Li, ^{40}K or ^{173}Yb, is also expected to give rise to some interesting superfluid phases [14–18]. In particular, a molecular superfluid (MS) phase might be stabilized in multicomponent attractive Fermi gas where more than two fermions form a bound state. Such a non-trivial superfluid behavior has already been found in different contexts. In nuclear physics, a four-particle condensate like the α particle is favored over deuteron condensation at low density [19] and it may have implications for light nuclei and asymmetric matter in nuclear stars [20,21]. This quartet condensation can occur in the field of semiconductors with the formation of biexciton [22]. A quartetting phase, which stems from the pairing of Cooper pairs, also appears in a model of one-dimensional Josephson junctions [23]. A possible experimental observation of quartets might be found in superconducting quantum interference devices with (100)/(110) interfaces of two d-wave superconductors [24]. In particular, the $hc/4e$ periodicity of the critical current with applied magnetic flux has been interpreted as the formation of quartets with total charge $4e$ [25]. Finally, a bipairing mechanism has also been predicted in four-leg Hubbard ladders [26].

Recently, the emergence of quartet and triplet (three-body bound states) has been proposed to occur in the context of ultracold fermionic atoms [27–32]. Much of these studies have been restricted to the special case of an SU(n) symmetry between the hyperfine states of an n-component Fermi gas. In this paper, we investigate the generic physical features of half-integer spins $F = N - 1/2$ fermionic cold atoms with s-wave scattering interactions loaded into a one-dimensional optical lattice. The low-energy physical properties of $2F + 1 = 2N$-component fermions with contact interactions are known to be described by a Hubbard-like Hamiltonian [5]:

$$\mathcal{H} = -t \sum_{i,\alpha} \left[c^{\dagger}_{\alpha,i} c_{\alpha,i+1} + \text{H.c.}\right] - \mu \sum_i n_i + \sum_{i,J} U_J \sum_{M=-J}^{J} P^{\dagger}_{JM,i} P_{JM,i}, \tag{1}$$

where $c^{\dagger}_{\alpha,i}$ ($\alpha = 1, \ldots, 2N$) is the fermion creation operator corresponding to the $2F + 1 = 2N$ atomic states and $n_i = \sum_\alpha c^{\dagger}_{\alpha,i} c_{\alpha,i}$ is the density operator on site i. The pairing operators in Eq. (1) are defined through the Clebsch–Gordan coefficients for forming a total spin J from

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