Fulde–Ferrel–Larkin–Ovchinnikov phase in one dimensional Fermi gas with attractive interactions and transverse spin-orbit coupling

Monalisa Singh Roy\textsuperscript{1,*} and Manoranjan Kumar\textsuperscript{2,†}

\textsuperscript{1}Department of Physics, Bar-Ilan University, Ramat Gan 52900, Israel
\textsuperscript{2}S. N. Bose National Centre for Basic Sciences, Block - 1D, Sector - III, Salt Lake, Kolkata - 700106, India

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We examine the existence and characteristics of the exotic Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) phase in a one dimensional Fermi gas with attractive Hubbard interactions, in the presence of spin-orbit coupling (SOC) and Zeeman field. We show that a robust FFLO phase can be created in the presence of attractive on-site interactions and Zeeman field, and that the addition of SOC suppresses the FFLO order and enhances the pair formation. In absence of SOC, the system shows four phases: Bardeen-Cooper-Schrieffer (BCS), FFLO, multi-mode pairing and fully polarized phases by tuning the Zeeman field \( h \), and the quantum transition between these phases is discontinuous with respect to \( h \). In the presence of SOC, the transition from the BCS to FFLO phase becomes continuous. We present a complete phase diagram of this model both in the presence and in the absence of SOC at quarter electron filling and also explore the effect of SOC on the FFLO phase.

I. INTRODUCTION

The presence of external magnetic and electric fields in superconducting materials give rise to many exotic phases and their effects have been extensively studied since the discovery of superconductivity in 1911\textsuperscript{3}. Over the years, discovery of new superconducting materials and improvements in their synthesis mechanism have yielded steadily increasing superconducting transition temperatures (\( T_c \))\textsuperscript{4}, and more refined applications of superconducting materials in daily life\textsuperscript{5}. At high temperature, strong magnetic field \( h \) destroys the superconducting properties in materials\textsuperscript{6}. Whereas, at low temperatures and low to moderate magnetic fields, these materials give rise to many exotic phenomena like Meissner effect\textsuperscript{7} and Fulde-Ferrel\textsuperscript{8} (FF) and Larkin-Ovchinnikov\textsuperscript{9,10} (LO) phases etc. In Bardeen-Cooper-Schrieffer (BCS) superconductors\textsuperscript{11}, electrons of opposite spins and momenta form Cooper pairs, but in presence of low \( h \) the Fermi energies of \( \text{up spin and down spin} \) electrons shift and the electron pairing process gets affected. Fulde and Ferrel\textsuperscript{8}, and Larkin and Ovchinnikov\textsuperscript{9,10} independently showed that in presence of magnetic field, a robust superconducting order could co-exist with a magnetic order in superconductors, and electron pairs with non-zero momentum can be formed in an inhomogeneous superfluid phase\textsuperscript{12}. Since then, there have been much efforts to realize this phase in various materials, especially in layered superconductors like \( \text{La}_{2−x}\text{Ba}_{x}\text{CuO}_4 \)\textsuperscript{13}, \( \text{CeCoIn}_5 \)\textsuperscript{14}, and organic salts like BEDT–TTCl\textsuperscript{15}. However, this phase is fragile since any impurity or other perturbations can disturb this phase in materials\textsuperscript{16–18}.

In recent years, cold atoms confined in optical lattices have emerged as an excellent alternative playground to explore superconductivity in pristine conditions – to study different pairing mechanisms in it, and effects of various external fields on the superconducting state\textsuperscript{19}. The existence of Bose-Einstein-Condensation (BEC) was demonstrated in a gas of cooled Sodium (Na) atoms by Davis \textit{et al.} in 1995\textsuperscript{20}. Since then, existence of superfluidity has been realized in various Fermi and Bose gases\textsuperscript{21–27}. The physics of these gases trapped in optical lattices are well described by Hubbard like models with effective on-site interactions \( U < 0 \) that are created by tuning Feshbach resonance in the system\textsuperscript{26}. Synthetic spin-orbit coupling (SOC) and Zeeman fields are created through Raman coupling\textsuperscript{27,28}. One dimensional (1D) Fermi gas with attractive interactions shows a BEC phase at very strongly attractive interactions, and a BCS phase with s-wave like pairings for moderate \( U \)\textsuperscript{29}. Introduction of Zeeman field \( h \) in this system takes the system from a BCS phase at a low \( h \), to a partially polarized phase at moderate \( h \), and a fully polarized phase for high \( h \)\textsuperscript{30,31}. This partially polarized phase at moderate \( h \) is proposed to host exotic Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) phase pairings\textsuperscript{8–10}. This phase is characterized by finite momentum of the centre of mass of bound pairs, which manifests itself into twin peaks (at \( \pm k \)) in the pair density correlations in momentum space.

The FFLO phase is more stable in 1D systems due to absence of eddy currents and phase separations which are more common in three dimensional (3D) systems and make it difficult for 3D systems to host the FFLO phase\textsuperscript{12}. In addition, the 1D FFLO phase is expected to host the non-trivial p-wave like pairings in the presence of transverse SOC field\textsuperscript{12,33}. This phase is also proposed to host topological edge modes whose hallmarks are reported to be exponentially decaying energy gaps as a function of increasing system size\textsuperscript{33,35}. There are many studies of model Hamiltonians, ranging from simple Fermi Hubbard models with additional interaction terms to systems with proximity induced superconducting terms, for exploring the existence of the FFLO phase. Lüscher \textit{et al.} studied 1D attractive Hubbard model in the presence of finite spin polarization and showed the existence of FFLO phase and its fingerprint in spatial noise correlations\textsuperscript{36}. Yang used a field theoretic approach to study the non-uniform superconducting states in quasi-1D systems and plotted a schematic phase diagram in the phase space of Luttinger liquid parameter \( K \) and magnetic field \( h \)\textsuperscript{37}. Rizzi \textit{et al.} also studied the attractive Hubbard model to study the stability of the FFLO phase in optical lattices\textsuperscript{38}. Feiguin \textit{et al.} have studied this model with confining parabolic potential in the optical lattice\textsuperscript{31}. In this paper, we have presented systematic theoretical studies of quantum phase diagram of the 1D attractive Fermi gas model Hamilto-
nian subjected to Zeeman field and an SOC field, as a function of on-site interactions $U$.

In this paper, we study a simple model of 1D Fermi gas in the limit of attractive on-site interaction ($U < 0$) to explore the FFLO phase and associated phase transitions at low filling fraction $\nu = 0.25$. We study this system, both (i) in the absence of SOC, and (ii) in the presence of a transverse SOC. We find that the FFLO phase spans a large area of the phase diagram for all electronic densities, both in the absence and in the presence of SOC. We present a complete phase diagram of this model in the phase space of $U$ and $h$, and for SOC strengths $\alpha = 0$ and 0.05.

The paper is organized into four sections. In Sec. II, we introduce the model and the numerical technique. In Sec. III, we discuss the main criteria used for identifying the FFLO phase in the system. We first focus on the case with no SOC, and discuss the different phases in the $h - U$ parameter space of the system. Next, we add a transverse SOC field (in the $x-$direction) and explore its effect on the FFLO phase. We conclude with a brief discussion of the reported results and their possible impact on the current understanding of exotic pairings in 1D ultracold systems and implications thereof in Sec. IV.

II. MODEL AND METHOD

We study the 1D Fermi gas with attractive on-site interactions $U$, in presence of a Zeeman field $h$ and transverse SOC field $\alpha$. The model Hamiltonian of this system can be written as,

$$ H = H_i + H_U + H_Z + H_{SOC}, $$

(1)

where,

$$ H_i = -t \sum_{i,\sigma} \left( C_{i+1,\sigma}^{\dagger} C_{i,\sigma} + h.c. \right), $$

$$ H_U = U \sum_i n_{i,\uparrow} n_{i,\downarrow}, $$

$$ H_Z = -h \sum_i S_i^z, $$

$$ H_{SOC} = + i\alpha \sum_i \left( C_{i,\uparrow}^{\dagger} C_{i+1,\downarrow} + C_{i,\downarrow}^{\dagger} C_{i+1,\uparrow} - h.c. \right), $$

where, $C_{i,\sigma}^{\dagger}$ ($C_{i,\sigma}$) are creation (annihilation) operators and $n_{i,\sigma}$ is the number operator at site $i$, with $\sigma = \uparrow$ or down spin. $t = 1$ defines the energy scale for our calculations. We study the system away from the half-filling limit and in the attractive interaction regime $U \in [-1, -4]$. The quantity $\nu = n/2N$ defines the filling fraction of a system of $N$ sites containing $n$ electrons. In the absence of $U$ and $\alpha$, the spin up and spin down electronic bands split in the presence of the external magnetic field $h$. An attractive $U$ induces intra-band pairing correlations, whereas a transverse SOC generates spin momentum locking along the $x-$axis of the system, thus giving rise to a p-wave like pairing.

We have used the DMRG method for solving the Hamiltonian in Eq. (1). It is a state-of-the-art numerical technique for accurately calculating the low-lying eigenvalues and eigenvectors of low dimensional systems. It is based on the systematic truncation of irrelevant degrees of freedom at every step of the infinite and finite DMRG algorithms. In the fermionic system under study, the spin degrees of freedom are not conserved, hence the Hamiltonian dimension is significantly large. The eigenvectors of the density matrix of the system block corresponding to $m \approx 700$ largest eigenvalues have been retained to maintain a reliable accuracy. More than 10 finite DMRG sweeps have been performed for each calculation to minimize the error in per site energies to less than $1\%$ and the maximum system size studied is $N = 120$.

III. RESULTS

In this section we present the numerical studies investigating the existence of a robust FFLO phase in a 1D ultracold atoms with intrinsic attractive on-site interactions and Zeeman field, first in the absence of SOC and then in presence of a transverse SOC field in $x-$direction and study the effect of finite SOC interactions $\alpha > 0$ on the FFLO phase. In this paper, we show that a robust FFLO phase exists for a wide range of electron fillings $U$, $h$, and $\alpha$, and this phase is distinct from other phases like the BCS and a multi-mode pairing (MMP) phase, which appears just before the system transitions into a fully polarized (FP) phase at high $h$.

To characterize various phases in the system we study the pair density correlations or singlet pair correlation function $P(i,j)$ and its Fourier transform (F.T.). The singlet pair correlation is defined as,

$$ P(i,j) = \langle C_{i,\uparrow}^{\dagger} C_{j,\downarrow}^{\dagger} C_{j,\uparrow} C_{i,\downarrow} \rangle. $$

(2)

Its F.T. of $P(i,j)$ is given by,

$$ P(k) = \sum_k e^{-ikr_{ij}} P(i,j), $$

(3)

where $(r_{ij} = i - j)$, and $i,j$ represent site indices in the system. The single peak in $P(k)$ at $k = 0$ indicate that the electron pairs are formed at zero momentum, i.e., Cooper pair formation at $k = 0$, which is a signature of the BCS phase. Twin peaks at finite momenta in $P(k)$ momentum distribution curve is a hallmark of an underlying FFLO-like pairing whereas electron pairs are formed with a finite momentum. In a mixed BCS-FFLO phase, where both the conventional BCS phase and the FFLO phase co-exist, $P(k)$ shows three peaks – one at zero momentum $k = 0$, and twin peaks at a finite momentum $k_h$. At sufficiently high magnetic field $P(i,j)$ is short range in nature, and $P(k)$ shows two peaks at $\pm k_h$ and a constant value of $P(k)$ between these two momenta, i.e., all the momenta between $\pm k_h$ contribute equally. We call this phase as MMP phase. In a fully polarised phase, $P(k)$ is zero. We also study
two energy gaps – the pair binding energy \( E_b \) or the parity gap, and the excitation energy gap \( \Delta \), defined as,

\[
E_b(n, N) = \frac{1}{2} [E_0(n + 1, N) + E_0(n - 1, N) - 2E_0(n, N)]
\]

\[
\Delta(n, N) = E_1(n, N) - E_0(n, N),
\]

where, \( E_0(n, N) \) and \( E_1(n, N) \) represent the ground state energy and the first excited state energy, respectively, with \( n \) electrons in the system of \( N \) sites. The finite binding energy \( E_b \) is the signature of the BCS phase, whereas the exponential decay of \( \Delta(n, N) \) may indicate the existence of a topological phase.

The other calculated quantities include local charge density with up spin \( n_\uparrow(i) \) and down spin \( n_\downarrow(i) \), and local spin density \( S^z(i) \). We notice that the spatial distributions of these quantities are different for each of the observed phases. In the BCS phase \( n_\uparrow(i) \) and \( n_\downarrow(i) \) have overlapping spiral nature. For the partially polarized phases – FFLO and MMP, \( n_\uparrow(i) \) and \( n_\downarrow(i) \) are separated and difference in the wavelength or pitch angle of the spiral oscillations are observed.

A. In Absence of SOC

In absence of any magnetic field, the system remains in the trivial BCS phase which is characterized by Cooper pairs with zero net momentum. In presence of finite magnetic field \( h \), the system can transition into the FFLO phase, where the electron pairs are formed with net non-zero momentum in presence of finite magnetic field \( h \). This phase is expected to retain quasi-long range correlations, especially in 1D. To ascertain that, in Fig. 1 the F.T. of singlet-pair density correlation, \( P(k) \) vs. \( k \), are plotted for different \( h \) and \( U \), for \( \nu = 0.25 \) and in absence of SOC, i.e., \( \alpha = 0 \). It shows a single peaked structure at \( k = 0 \) at low \( h \), as expected from a trivial BCS phase. Increasing \( h \), two-peaked \( P(k) \) with maxima at \( \pm k_b \) are observed, indicating the presence of an FFLO phase. In the fully polarized (FP) phase at high \( h \), \( P(k) \) is vanishingly small and no peak is observed in \( P(k) \). Between the FFLO and FP phase, there exists a narrow regime of the MMP phase.

In this phase, \( P(k) \) shows a plateau like structure between the twin peaks, i.e., the \( P(k) \) is uniformly distributed between the momenta \( \pm k_b \), which indicates that the momentum of centre of mass of the condensate is distributed between \( \pm k_b \) around the Fermi-momentum. The \( P(i, j) \) is fast and algebraically decaying function. The peak height of \( P(k) \) is significantly smaller in this phase, as compared to the FFLO phase.

In Fig. 1 (a), variation of \( P(k) \) for four values of \( h \) are shown for \( U = -2.00 \). In Fig. 1 (b) the magnetic field \( h = 1.20 \) is kept fixed and \( P(k) \) is plotted for four values of \( U \). Larger value of \( |U| \) increases binding energy, therefore, BCS phase is favoured at higher magnitude of \( U \). and FFLO-like pairing is observed at weakly attractive \( U \) comparatively lower \( h \). For larger \( |U| \), larger magnetic field is required to break the bound electron pairs, hence we notice that \( U = -0.50 \) is already in the FP state for the given \( h \). Whereas, for \( U = -4.00 \) the BCS phase remains intact upto a large \( h \). We also plot the peak height of \( [P_{\text{max}}(k)] \) as a function of \( h \) for \( U = -2.00 \) in Fig. 2, and find that the four phases in this system can be easily identified by the respective plateaus in \( [P_{\text{max}}(k)] \) corresponding to each phase. We also notice that transition from one to the other phase occurs through discontinuous jumps. We plotted \( [P_{\text{max}}(k)] \) as a function of \( 1/N \) in the inset of Fig. 2, and notice that the effect of the finite size is weak in the FFLO and MMP phases, but \( [P_{\text{max}}(k)] \) increases with the system size in the BCS phase.

For further understanding of different phases, the behavior of local charge and spin densities are analyzed for three values of magnetic field \( h \), corresponding to the three phases at \( U = -2.00 \). We ignore the fully polarized regime where all spins are polarized along the direction of magnetic field \( h \) and the charge is uniformly distributed. Fig. 3 shows the spatial profile of the spin densities \( n_{\uparrow}(i) \) and local magnetization, \( S^z(i) = n_\uparrow(i) - n_\downarrow(i) \), for different \( h \). At low \( h = 0.20 \) (Fig. 3(a) ), the up and down spin densities overlap and the
All the phase boundaries are based on the information extracted from \( P(k) \), their maxima, charge and spin density profiles. All the phase boundaries are based on the \( N = 96 \) system size and we note that the finite size scaling of the boundary is very weak. In absence of any \( h \), BCS phase is observed for all values of \( |U| \). Upon increasing \( h \), the system goes from a BCS phase to the partially polarized FFLO phase, then from the FFLO phase to the MMP phase, and finally to the FP phase at high \( h \). The FFLO phase is a dominant phase in the quantum phase diagram and the width of this phase increases with \( |U| \). The magnetic field required for the transition from the BCS to the FFLO phase, \( h_{c1} \), is smooth and linear with \( U \). Similarly, the \( h \) required for the FFLO to the MMP phase transition also varies linearly with \( |U| \), especially in small \( U < 2.5 \) limit.

We also explored the quantum phase diagram at lower fillings \( \nu \) (the lowest filling studied was \( \nu = 0.10 \)), and found that the phase boundaries shift towards lower \( h \), i.e., slope of the \( h_c \) curves increases with decreasing electron filling \( \nu < 0.25 \). This is because, at lower densities, lower \( h \) is sufficient to break the bound pairs in the system.

## B. In Presence of SOC

In this section we explore the effect of small SOC strength \( \alpha = 0.05 \), which is expected to produce a p-wave pairing in superconducting phase for attractive \( U \) interactions. This exotic p-wave like phase is proposed to host topological edge modes\(^{33,42}\), which is important for applications in quantum computation. In the superconducting BCS state, the binding energy of the system should be finite, whereas in the FFLO, MMP and the FP phase unpaired electron should have zero binding energy.

The binding energy is plotted as a function of system size for different \( \alpha \) in Fig. 5 for \( \alpha = 0, 0.05, 0.10 \), and 0.40 at \( \nu = 0.25 \) for \( h = 1 \). We find that \( E_b \) vanishes algebraically with \( N \) for low \( \alpha \), which corresponds to the FFLO phase. For higher \( \alpha \), system goes to the BCS phase and \( E_b \) has finite...
value in the thermodynamic limit. The inset of Fig. 5 shows the variation of the lowest excitation energy gap $\Delta$ with $h$. The inset of Fig. 5 shows fluctuations at the phase boundaries of the $\Delta - h$ plot, for a given system size. The fluctuations at the boundary can be utilised to determine the phase boundaries and we notice that the boundaries determined by this method agree well with those indicated by the pair correlation structure factor $P(k)$ in Fig. 6.

$P(k)$ vs. $k$ is now plotted in Fig. 6, for four values of $U$ at $h = 1.00$, $\nu = 0.25$ and $\nu = 0.25$. The FFLO pairings are observed for weakly attractive $U$, as indicated by the twin peaks in $P(k)$ for $U = -1.00$ and $-2.00$, whereas, a single peaked $P(k)$ is observed for stronger $U = -4.00$, indicative of a BCS phase. At $U = -3.00$, a three-peaked structure is observed, which is signature of an exotic mixture of BCS and FFLO phases. It should be noted that this exotic mixture state is not observed for any value of $h$ and $U$ in absence of $\alpha$. The $[P(k)]_{max}$ is plotted as function of $h$ as shown in the inset of Fig. 6. Contrasting with the inset of Fig. 2, we find that the transition from BCS to FFLO phase now shows a smooth transition through a mixed BCS-FFLO phase, which was earlier discontinuous in absence of SOC. The transition from FFLO to the MMP phase and from MMP to FP phase remains discontinuous with increasing $h$, as before. We also checked the dependence of electronic filling for $\nu \in [0.10, 0.25]$ and found that the FP phase is reached for lower $h$ at lower filling but the qualitative behaviour and sequence of the phases remains the same as the no SOC case.

To understand the effect of $\alpha$ on the system, we study the $P(k)$ vs. $k$ characteristics for different strengths of $\alpha$ in Fig. 7. We find that the FFLO phase is retained at low $\alpha$ (Figs. 7(a) and (b)), and the BCS phase sets in for higher $\alpha$ (Fig. 7(d) and (e)), for a fixed $h$. For intermediate $\alpha$ (Fig. 7(c)), a mixed FFLO-BCS phase is observed.

A quantum phase diagram of this system for a fixed $\alpha = 0.05$ is shown in Fig. 8 based on various criteria. It shows that in absence of $h$, BCS phase is observed for all attractive $U$. Upon increasing $h$, the system goes from first an unpolarized BCS phase to a partially polarized FFLO phase continuously, through a mixed BCS-FFLO phase – which was earlier not observed in absence of an SOC field (Fig. 4). The width of the BCS phase and FFLO phase shrinks in presence of the SOC. Thereafter, increasing $h$ the system goes from the FFLO to the MMP phase. The width of MMP phase increases in large $|U|$ limit, in the presence of SOC. Further enhancing $h$ lead to the FP phase, and width of this phase increases in smaller $|U|$ in presence of SOC. We checked that a similar phase diagram is observed for lower fillings $\nu$ as well, except that the phase boundaries are shifted towards lower $h$. For higher $\alpha$, the phase boundaries are shifted towards higher $h$.

**IV. DISCUSSION AND CONCLUSION**

In this work we study the 1D Fermi gas model Hamiltonian described by Eq. (1) with attractive on-site interactions, SOC, and a Zeeman field, and explore the existence and signatures of the exotic FFLO phase in this system. We present the quantum phase diagram of this model in the $h - |U|$ parameter space, both in absence and in presence of SOC, at
electron filling $\nu = 0.25$. Most of the earlier works have explored the FFLO phase in 1D system at $\nu = 0.50$ and $\nu = 0.25$ and restricted their studies to just characterizing the FFLO phase. We have found the quantum phase diagram of this model (Eq. (1)) in the phase space of $h - |U|$ for different $\alpha$, and provided different criteria to identify the phases observed in this system, including the different partially polarized phases at $\nu = 0.25$. We note that the sequence of phases are the same for lower fillings as well, at least up to $\nu = 0.10$.

We find that on-site interactions $U < 0$ and SOC interactions $\alpha$ promote BCS pairings, whereas the Zeeman field $h$ promotes the FFLO order in the system. In the $h - |U|$ phase space we find four different phases: (i) the BCS phase, (ii) the FFLO phase, (iii) the MMP phase, and (iv) the FP phase. In the trivial BCS phase all the electrons form singlet (Cooper) pairs and have charge density oscillations at low $h$, low $\alpha$ and weak $U$. In the exotic FFLO and MMP phases, commensurate charge and spin oscillations at moderate $h$, moderate $U$, and moderate $\alpha$ are noted. The FFLO phase is characterized by quasi-long range order in the system and correlated singlet pairs with finite momenta, which is reflected through twin-peaks in the F.T. of singlet pair density correlations in the system. We find that both in absence and in presence of SOC field, the FFLO phase occupies a large area of the quantum phase diagram. We also report a new quantum MMP phase which phase exhibits a short range singlet pair density $P_{ij}$ ordering. In this phase $P(k)$ shows a plateau like behaviour between two maxima, i.e., the centre of mass of the electron pairs can take any value between the $\pm k_h$. It is very different from the FFLO phase where the centre of mass of the electron pairs lies at $\pm k_h$, i.e., the momenta where the peaks are sharply defined. In presence of SOC, a mixed state exhibiting both BCS and FFLO pairings is also observed. The phase diagram of the system remains similar for lower electronic fillings $\nu \in [0.10, 0.25]$, except that the phase boundaries shift to lower $h$ for lower $\nu$.

In summary, this work presents a comprehensive study of the quantum phase diagram of a 1D Fermi gas system with intrinsic attractive on site interactions, a Zeeman field, and transverse SOC, and discusses in details various methods of characterizing these phases in similar 1D Fermi gas systems. We show that the FFLO phase dominates the phase diagram and it is robust even in presence of the SOC. This could have potential applications in understanding the unconventional superconductivity phases in low dimensional electron gas. This model can be easily implemented in the trapped cold atoms in optical lattices.

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