Kim, D.-H.; Kinnunen, Jami; Martikainen, J.-P.; Törmä, Päivi

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Published in:
PHYSICAL REVIEW LETTERS

DOI:
10.1103/PhysRevLett.106.095301

Published: 04/03/2011

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Exotic Superfluid States of Lattice Fermions in Elongated Traps


Department of Applied Physics, Aalto University, P.O. Box 15100, 00076 AALTO, Finland
NORDITA, 106 91 Stockholm, Sweden

(Received 11 October 2010; revised manuscript received 4 December 2010; published 28 February 2011)

We present real-space dynamical mean-field theory calculations for attractively interacting fermions in three-dimensional lattices with elongated traps. The critical polarization is found to be 0.8, regardless of the trap elongation. Below the critical polarization, we find unconventional superfluid structures where the polarized superfluid and Fulde-Ferrell-Larkin-Ovchinnikov-type states emerge across the entire core region.

DOI: 10.1103/PhysRevLett.106.095301

PACS numbers: 67.85. –d, 03.75.Ss, 05.30.Fk, 71.10.Fd

The nature of pairing in spin-polarized fermion systems is a fundamental problem in many areas of physics, including superconductors in a strong magnetic field, neutron-proton pairing in nuclear matter, and color superconductivity in high density QCD. Non-BCS pairing mechanisms have been proposed for spin-polarized fermions. The Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) states exhibit finite-momentum pairing, causing spatially oscillating pair potentials. In the polarized superfluid states, so-called Sarma or breached-pair states, zero-momentum pairing occurs, having excess unpaired particles. In trapped ultracold Fermi gases, momentum pairing occurs, having excess unpaired particles. The Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) states exhibit finite-momentum pairing, causing spatially oscillating pair potentials. In the polarized superfluid states, so-called Sarma or breached-pair states, zero-momentum pairing occurs, having excess unpaired particles. In highly elongated traps, as we approach the critical polarization, we find that the FFLO-type states emerge with spatially oscillating pair potential across the trap center. For comparison, we present also Bogoliubov–de Gennes (BdG) mean-field calculations.

Our real-space DMFT solves the attractive Hubbard model with an anisotropic trapping potential at $T = 0$,

$$\mathcal{H} = -t \sum_{\langle ij \rangle \sigma} c_{i \sigma}^\dagger c_{j \sigma} - U \sum_i n_i n_i + \sum_{i \sigma} (V_i - \mu_\sigma) n_{i \sigma},$$

where $c_{i \sigma}^\dagger (c_{i \sigma})$ creates (annihilates) a fermion with spin $\sigma$ at site $i$, the density operator $n_{i \sigma} = c_{i \sigma}^\dagger c_{i \sigma}$, and $\mu_\sigma$ denotes the chemical potential. The hopping $t$ between neighboring sites $\langle ij \rangle$ is set to unity. The on-site interaction $U$ is chosen as the unitarity value for the cubic lattice, $U \approx 7.915$ [24]. The trapping potential is given as $V_i = V_0 \left[ x^2 + y^2 + \left( z/l_x \right)^2 \right]$ where $V_0$ and $\alpha$ are the trap strength and aspect ratio. In the 3D lattice with size $L_x \times L_y \times L_z$, the coordinates of sites are assigned as $\xi_{l_x} = \xi - \frac{l_x}{2}$, where $\xi \in \{x, y, z\}$, and $\xi = \frac{l_x}{2}, \ldots, \frac{l_x}{2} - 1$.

The real-space DMFT is constructed for inhomogeneous systems by considering local, yet site-dependent, self-energy terms, which explicitly include trap effects beyond the local density approximation (LDA). This approximation in the DMFT allows $s$-wave pairing [20]. The impurity problem now becomes site dependent and must be solved for each site with an efficient solver. We employ the exact diagonalization method to solve a 7-orbital impurity Hamiltonian with a superconducting bath [20] which provides a good convergence (cf. [25]) in our reliability tests. There are two advantages in choosing the exact diagonalization method: it is easy to consider the generalized Anderson model required to describe the superfluid phases;
potentials are adjusted to fix the total particle number \( N = N_1 + N_\downarrow \approx 210 \) with the polarization \( P = (N_1 - N_\downarrow)/N \). The particle density is below quarter filling at all lattice sites. The trap strength is given as \( V_0 = 0.02a^{2/3} \) to keep the volume constant. The lattice size varies accordingly with \( \alpha: (L_x, L_y, L_z) = (24, 24, 24) \) for \( \alpha = 1 \), (16, 16, 40) for \( \alpha = 2.5 \), (16, 16, 40) for \( \alpha = 5 \), (14, 14, 80) for \( \alpha = 7.5 \), and (14, 14, 100) for \( \alpha = 10 \). The lattice size becomes a bottleneck in the real-space DMFT. The computation took \( \sim 10^9 \) CPU seconds in supercomputers.

Figure 1 shows how the distribution of particles and their superfluid characteristics change with polarization \( P \) in an elongated trap with aspect ratio \( \alpha = 7.5 \). The density difference \( \delta n_i = n_{i\uparrow} - n_{i\downarrow} \) and the pair potential \( \Delta_i = \langle c_{i\uparrow}^\dagger c_{i\downarrow} \rangle \) characterize the superfluid structure: for small \( P \)'s, the particles at the trap center are fully paired superfluid (dark gray, \( \delta n = 0 \), finite \( \Delta \)) and surrounded by unpaired particles (light gray, \( \delta n \neq 0 \)). The small bumps in \( \Delta \) are found along the axial (\( z \)) direction, which can be interpreted as an analog of the proximity effect at a superconductor-ferromagnet interface [26]. As \( P \) increases further, we find that two features become noticeable in \( \Delta \). For \( P \gtrsim 0.7 \), an oscillatory structure in \( \Delta \) emerges across the trap center, indicating that FFLO-type states may exist in this elongated system. When \( P \) reaches 0.8, a transition to the normal phase occurs, as indicated by the complete suppression of \( \Delta \).

We study the transition to the normal phase systematically with the order parameter, \( \eta = \sum_i |\Delta_i|^2/N_i \), averaged over the whole system. In Fig. 2(a), it turns out that the behavior of \( \eta(P) \) and the critical polarization \( P_c \approx 0.8 \) is insensitive to the trap aspect ratios that we have examined. Moreover, we find that our \( P_c \) agrees with \( P_c \approx 0.78 \) found in the experiments [15,16], and the quantum Monte Carlo (QMC) results in continuum with LDA [27,28]. The order parameter is comparable to the condensate fraction measured in [15].

On the other hand, we find that pairing in the superfluid core in our systems is unconventional. Figure 2(b) indicates the coexistence of finite polarization and order parameter at the center. This characterizes the polarized superfluid core and is apparent at intermediate or even at low \( P \)'s for large \( \alpha \). In contrast to the order parameter, the behavior of the central polarization depends on \( \alpha \). The LDA calculations, based on the conventional DMFT for homogeneous lattices at \( T = 0 \), show a first-order transition from the fully paired superfluid phase to the partially paired normal phase without the intermediate polarized superfluid phase. However, the LDA cannot consider the inhomogeneous exotic phase observed in Fig. 1, and it ignores the interface effects that may contribute to the polarized superfluidity. While the potential role of finite-size effects should not be ruled out, we have tested also \( N = 320 \) and found the same features.
Let us discuss in detail how the cloud structure and the pairing evolve as \( P \) increases. Figure 3 presents the axial profiles of densities \( n_{1z} \), their difference \( \delta n \), and the pair potential \( \Delta \) along the \( z \) axis. The data with \( \alpha = 7.5 \) are shown as a representative example. The fully polarized edges are well separated from the superfluid core with the partially polarized intermediate regions, while the central region shows nonuniform \( \Delta \) that changes with \( P \). Our LDA data (not shown) gives the three-shell structure: the fully paired superfluid core, partially polarized normal state shell, and fully polarized edges. This perfectly agrees with those from the QMC calculations with LDA [28]. While, at low \( P \)'s, our real-space DMFT presents a similar shell structure, the density profiles indicate the exotic superfluid phase at high \( P \)'s that is not accessible by the LDA with conventional DMFT.

At very low polarization \( P = 0.08 \), the core is fully paired, and small oscillations of \( \Delta \) appear in the partially polarized intermediate shoulders of \( \delta n \). As \( P \) increases, polarization becomes finite at the center, leading to the wide dip area with finite \( \delta n \), indicating the polarized superfluid core. The dip region gets narrower with increasing \( P \) while the shoulders with small \( \Delta \) oscillations get wider.

When \( P \) increases further, the dip in \( \delta n \) finally disappears, and the FFLO-type oscillations in \( \Delta \) spread across the trap center, as plotted for \( P = 0.74 \) in Fig. 3. As \( P \) approaches \( P_c \), the amplitude of \( \Delta \) becomes smaller and finally vanishes at \( P_c \). Along with the oscillating \( \Delta \), we also find the corresponding oscillations in \( \delta n \) with a half period of \( \Delta \). This is consistent with the prediction of the FFLO-type phase in one dimensional (1D) systems [29]. However, our systems still show 3D features: at low \( P \)'s, density profiles are similar to the LDA data in 3D while fully paired edges together with the FFLO phase at the center are expected in the strictly 1D system [17,29].

We find that these FFLO-type oscillations emerging across the trap center, rather than residing just at the edges, are found only in highly elongated traps with the trap aspect ratios \( \alpha \approx 5.0 \) among the examined values of \( \alpha \)'s. The dependence of the core phase on \( \alpha \) is summarized in Fig. 4. For \( \alpha = 1.0 \) and 2.5, we have found the oscillations of \( \Delta \) reside only at the edges for all \( P < P_c \). The diagram in Fig. 4 separates the phases of the central region of the traps into fully paired superfluid (SF), polarized superfluid (pSF), FFLO, and normal (N). The FFLO-type phase can be signaled by the disappearance of the central dip in \( \delta n \), as shown in Fig. 3. The boundary between SF and pSF is rather unclear because \( \delta n \) becomes finite gradually with increasing \( P \). However, our calculations show a tendency for the central polarization to grow faster as the trap gets more elongated.

The nature of the polarized superfluidity found in our real-space DMFT calculations at \( T = 0 \) can be very subtle. It has not been clear yet how stable pSF is at \( T = 0 \), especially in a trap. The breached-pair state is in general energetically unstable toward the phase separation at a weak coupling at \( T = 0 \) [30,31]. For a strong coupling, an earlier DMFT calculation in half-filled homogeneous cubic lattices found that the pSF may be stable down to a very low temperature [32], while other calculations suggested that the density difference may decay exponentially with decreasing temperature in quarter-filled infinite dimensional lattices [33]. In our LDA calculations, we have observed a sharp SF-N transition without an intermediate pSF phase. The stability issue can be more complex in our trapped asymmetric systems. We have found nonstandard (pSF)-FFLO-N-type structures in the elongated traps, which cannot be explained with LDA.

Our real-space DMFT inspires the question: how different are the results qualitatively from those given by the BdG static mean-field theory, incorporating a trapping potential [34]? The DMFT is based on a discrete lattice system, nevertheless we choose to compare it to a BdG approach without a lattice (the density of our lattice fermions is well below the quarter filling). In Fig. 5, we observe very high \( P_c \) (~0.95) and the strong deformation of the core shape at high \( P \)'s. These features are in clear contrast with those found in our real-space DMFT. The DMFT accurately describes local quantum fluctuations which are missing in the BdG theory that does not properly include interactions in the normal state. Such effects cause the large deviation in \( P_c \) in the strongly interacting regime.

The explicit test for the trap aspect ratio sheds light on the comparison between the experiments [13,15] and [14].
between the phases are drawn for guidance. /C11

FFLO-type phase is identified for with the central polarization larger than 0.005. At higher

evolves into the polarized superfluid (pSF). The pSF is specified

paired superfluid (SF) is found at low

dependence of the phase of the central region of the trap. Fully

plotted as a function of polarization

P

majority population

potential profiles that we have found in elongated traps

amplitude of the oscillating pair potential across the trap

like phase emerges at high polarizations close to

Pc

because of computational limitations, we have not found

are in good agreement with [13,15,16]. While the very

and the three-shell density profiles that we have found out

lattice fermions considered here, the critical polarization

Despite the difference between dilute gases and low-filling

The exotic superfluid phases found in our study suggest

The exotic superfluid phases found in our study suggest

that high polarizations P ≲ Pc can be an interesting area

for future experiments with spin-imbalance Fermi gases. In

our calculations at T = 0, we have found that the FFLO-

like phase emerges at high polarizations close to Pc. The

amplitude of the oscillating pair potential across the trap

center is expected to be still significantly large, which

implies that it may be experimentally accessible at low

but finite temperatures. In addition, the density and pair

potential profiles that we have found in elongated traps

reveal the 3D characteristics which are essentially different

from the profiles predicted in strictly 1D. This emphasizes

the possibility for the experimental observation of the

FFLO phase in 3D systems.

This work was supported by the Academy of Finland

(Projects No. 21362, No. 217043, No. 217045, No. 210953, No. 135000, No. 139514) and EuroQUAM/FerMix, and conducted as a part of a EURYI scheme grant (see www.esf.org/euryi). Computing resources were provided by CSC—the Finnish IT Centre for Science and the Triton cluster at the Aalto University.

*paivi.torma@hut.fi