Spinless Fermionic Ladder in the presence of a Magnetic Field

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Abstract

In this article, I will be discussing our present work on two-leg spinless fermionic ladder in the presence of a magnetic field. Our work is motivated from a theoretical study conducted by Carr et. al. in Phys. Rev. B 73, 195114 (2006). We are using the density matrix renormalization group (DMRG) technique and Lanczos to understand the influence of magnetic field on a U-V model initially in the weak coupling regime. Our aim is to examine the phase diagram at intermediate and strong coupling.

The use of magnetic fields has played a vital role in realizing various properties of condensed matter systems, ranging from Landau quantization [1] for the free Fermi gas to the fractional quantum Hall effect for an interacting system [2]. With the recent advances in ultra-cold atoms, experimentalists have found a way to test various theories in condensed matter. They can tune interactions by Feshbach resonance [4], and by using the atoms internal spin degree of freedoms multiple leg system can also be created [5],[6] . This provides a good platform to experimentally verify our results.

In this project, we are studying a U-V model for spinless fermions on a two leg ladder with complex hoppings. A theoretical study have been conducted in previous literature using the bosonization approach, in the weak coupling regime [3]. However, a comprehensive study from an exact technique like DMRG is still required.

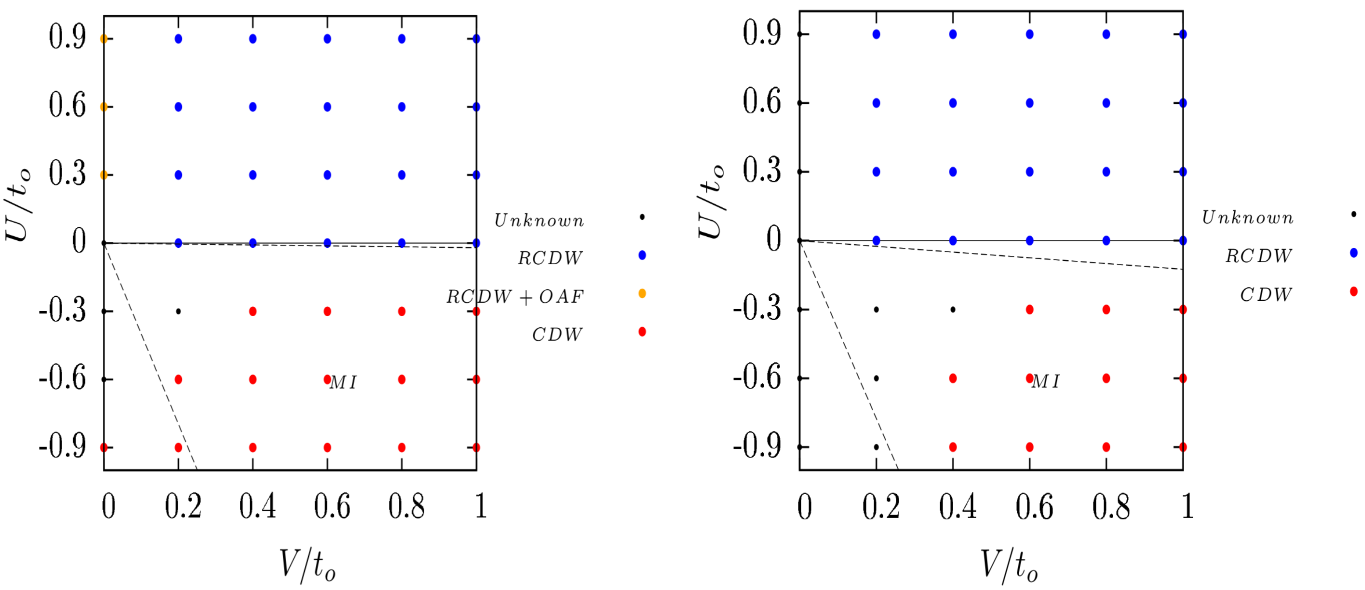
Our Hamiltonian is:

$$\begin{aligned} H &= -\frac{1}{2}\sum_{i,\sigma}\left[t_{\parallel}(\sigma)c^{\dagger}_{i,\sigma}c_{i+1,\sigma} + h.c.\right] - t_{\perp}\sum_{i}\left[c^{\dagger}_{i,+}c_{i,-} + h.c.\right] \\ &+U\sum_{i} n_{i,+}n_{i,-} + V\sum_{i,\sigma} n_{i,\sigma}n_{i+1,\sigma} \end{aligned} \quad (1)$$

where, $c_{i,\sigma}$ is the electron annihilation operator on the chain $\sigma = \pm$ at the site i; $n_{i,\sigma} = c^{\dagger}_{i,\sigma}c_{i,\sigma}$ are the occupation number operators; $t_{\perp}$ and $t_{\parallel}(\sigma)$ are the transverse and longitudinal hopping amplitudes, respectively. The last two terms in equation (1) describes nearest neighbour inter- and intra-chain interactions. The longitudinal hopping amplitude can be written as $t_{\parallel}(\pm) = t_0 e^{\pm i\pi\phi}$, where ϕ is the magnetic flux per plaquette. For the remaining part of this article we will be working with the quantity $\tau = t_{\perp}/t_0$, defined as the ratio of hopping parameters.

We began our work by studying the case when $\phi = 0$ (i.e. when there is no magnetic field) in the weak coupling regime. The phase diagram of this case is available in literature [3] and we have succesfully verified it for different values of τ at half filling using DMRG (see figures 1a and 1b).

The phase diagrams comprises mainly of two phases. For repulsive interchain and intrachain interations (i.e. when $U, V > 0$), we see a relative charge density wave (RCDW). For attractive interchain interaction ($U < 0$) and repulsive intrachain interaction ($V > 0$) we see a charge density wave (CDW). When $V = 0$ and $U > 0$ we see an overlap of both RCDW and orbital anti-ferromagnetic (OAF) phase.



(a) $\tau = 0.1$

(b) $\tau = 0.25$

Figure 1: U *vs* V phase diagram at $\phi = 0$, filling $n_e = 0.5$, for different τ's and system size 24×2 using DMRG, in the weak coupling regime. The dashed lines are the phase boundaries defined by $U/2V = 2 + \tau^2$ and $U/2V = -\tau^2$. The red dots are the CDW phase, blue points are RCDW phase and orange points are the OAF phase.

Next, we attempted to reproduce the phase diagram mentioned in [3] for $\phi \neq 0$ at half filling, in the weak coupling regime. We have identified some of the phases in the phase diagram. For example, the existence of CDW phase for $U < 0$, $V > 0$ and the existence of RCDW phase for $U > 0$, $V > 0$. We didn't calculate the pair correlations ($c_{i-}c_{i+}$) yet, that's why we never see the Luther Emery Liquid (LEL) phase for $U < 0$,

$V > 0$ for higher values of ϕ. We are still missing phases like OAF, bond density wave (BDW) and relative BDW phases at their respective regions in our phase diagram.

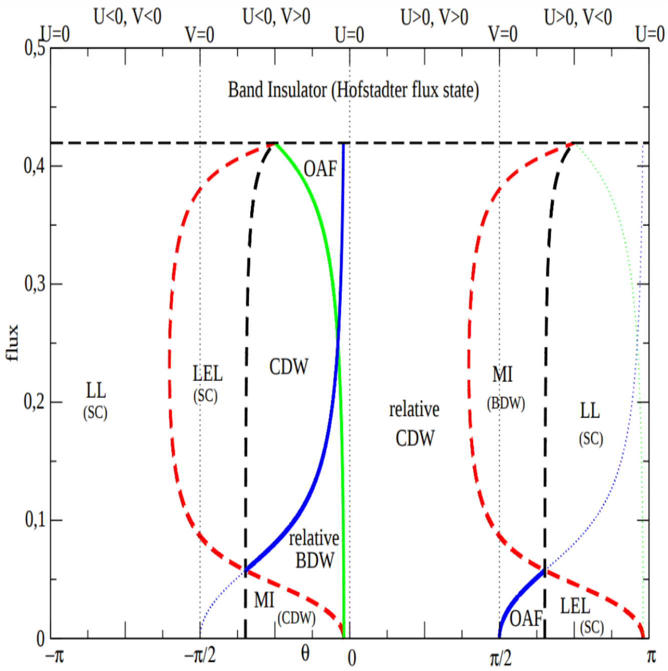


Figure 2: ϕ *vs* θ phase diagram for $\tau = 0.25$, at half filling in literature [3].

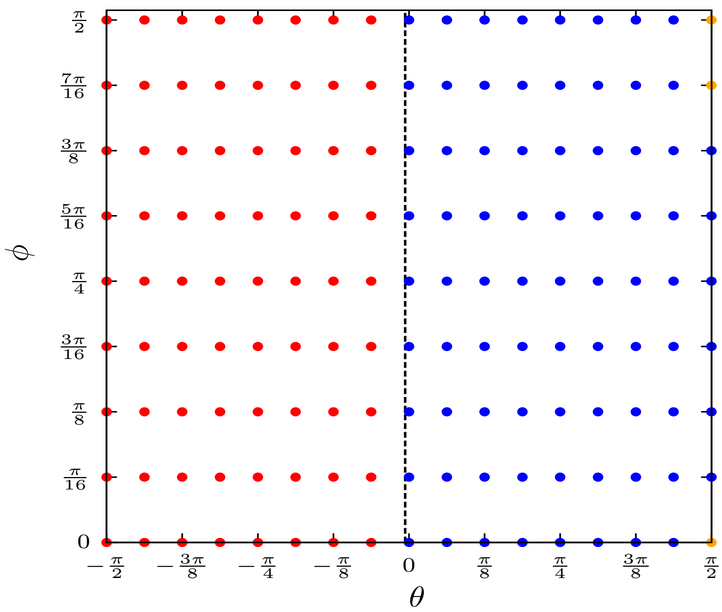


Figure 3: ϕ *vs* θ (where $\theta = \tan^{-1}(U/2V)$) phase diagram for $\tau = 0.25$, at half filling and system size 12×2 using Lanczos, in the weak coupling regime. The red dots are the CDW phase, blue points are RCDW phase and orange points are the OAF phase.

References

[1] L.D. Landau and E.M. Lifshits, Quantum mechanics non-relativistic theory, 3rd ed., Oxford, Pergamon Press (1977).

[2] D.C. Tsui, H.L. Stormer, and A.C. Gossard, Phys. Rev. Lett. 48, 1559 (1982).

[3] S.T. Carr, B.N.Narozhny, and A.A. Nersesyan, Phys. Rev. B 73, 195114 (2006).

[4] Markus Greiner and Simon Fölling, Nature 453, 736738 (2008).

[5] A. Celi, P. Massignan, J. Ruseckas, N. Goldman, I.B. Spielman, G. Juzelinas, and M. Lewenstein, Phys. Rev. Lett. 112, 043001 (2014).

[6] M. Mancini, G. Pagano, G. Cappellini, L. Livi, M. Rider, J. Catani, C. Sias, P. Zoller, M. Inguscio, M. Dalmonte, L. Fallani, Science 349, 6255, 1510-1513 (2015).