MOTT INSULATOR AND SUPERFLUID PHASES IN BOSONIC SUPERLATTICES

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ABSTRACT

We study the ground-state phase diagram of boson chains on a 2-period superlattice using the density matrix renormalization group method. New insulators for commensurate densities were found, differentiated by the arrangement of the particles in the unit cell, which was corroborated by analysis of the density versus the potential strength. Also, phase transitions between insulators for $\rho \geq 1$ were seen, and a maximum in the behavior of the von Neumann entropy in the critical region was revealed, which suggests a superfluid phase between the insulators.

INTRODUCTION

We study the chains of particles in l-period superlattices, whose arrangement is characterized by a unit cell with l sites, where for instance there is an energy difference (λ) between one site and the other $l-1$ sites [?, ?]. Through mean-field approximation, Buonsante and Vezzani [?] described an ultracold system and found that at zero temperature, insulator domains appeared for fractional densities. More recently, Dhar *et al.* [?] showed new insulators in the 2-period superlattice. They demonstrated insulators at $\rho = 1/2$ and $\rho = 1$, and a phase transition between the Mott insulator and the new insulator phase when λ is near the strength of the local interaction U at $\rho = 1$. However, although the above results describe the behavior for particular densities of one-dimensional boson systems on superlattices, the phases for densities larger than one, the localization of the particles, and the state of the system around the critical point remain unclear.

MODEL

One-dimensional systems of bosons in superlattices are described by the modified Bose-Hubbard model, defined as:

$$H = -t\sum_i (a^\dagger_{i+1}a_j + H.c.) + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) \quad (1)$$

$$+\sum_i \lambda_i \hat{n}_i,$$

where t is the hopping parameter, $a^\dagger_i$ (a_i) creates (annihilates) a boson at site i, U represents the local interaction, $\hat{n}_i = a^\dagger_i a_i$ is the number operator, and λ_i denotes the shift in the energy levels of the sites in each unit cell. We set our energy scale taking $t = 1$ and the interaction parameter $U/t = 10$. The 2-period superlattice has two sites per unit cell, which is represented in Fig. ??.

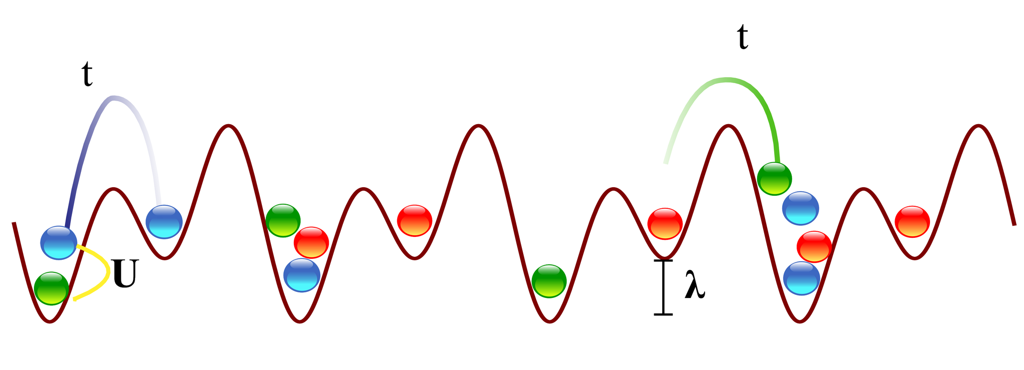

Figure 1: Schematic representation of the 2-perid superlattice.

RESULTS

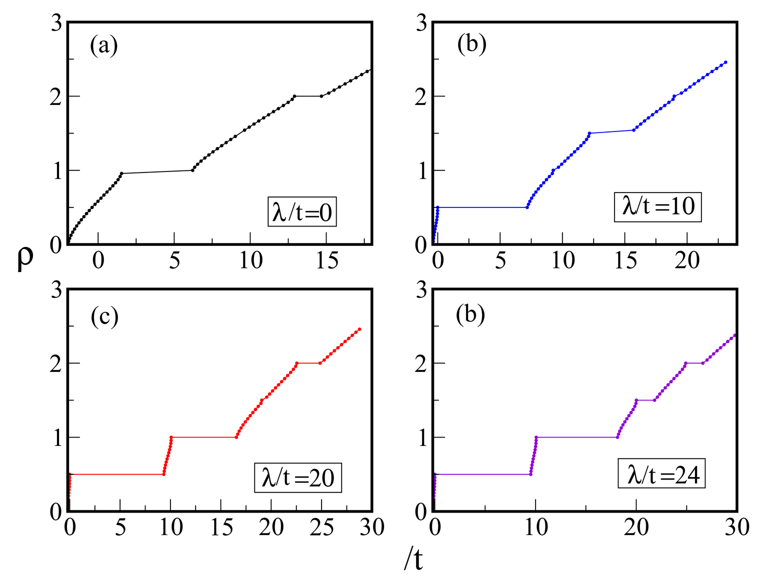

Figure 2: Findings of the density at values of λ/t between 0 and 24.The homogeneous system of bosons is represented in Fig.(a). Fig. (b) shows plateaus at semi-integer densities, while the plateaus at integer densities are fewer than in the previous case.In Fig.(c),the plateau at $\rho = 3/2$ is not present, and this happens when $\lambda/t \approx 2U$. Finally, the presence of insulators at all commensurate densities are given in Fig. (d).

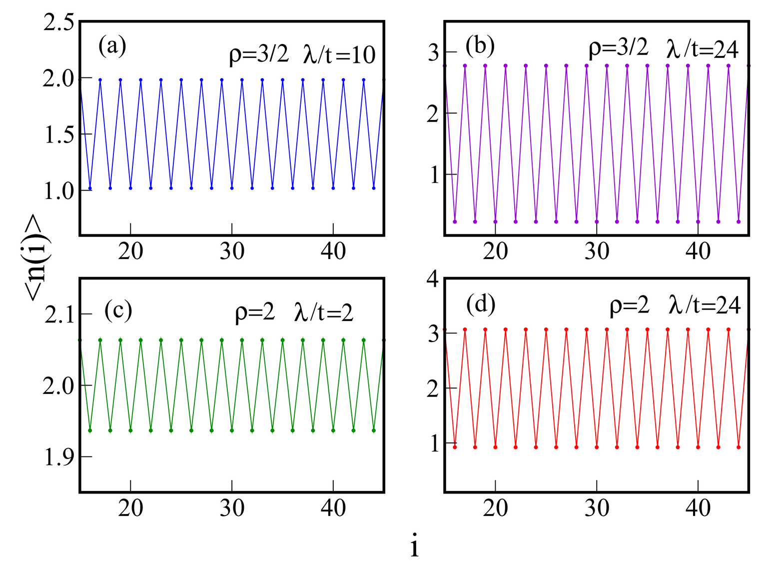

Figure 3: On-site number density plotted against lattice site index with $L = 50$ sites at density $\rho = 3/2$ and $\rho = 2$. The lines are visual guides. It can be observed that the configuration $\{2, 1, 2, 1, \ldots\}$ is shown in Fig.(a). Data in Fig.(b) suggests $\{3, 0, 3, 0\}$ when λ increases. From Fig.(c), it can be seen that the configuration of particles is around two, which is itself in a Mott insulator phase. It can be seen in Fig.(d), that the system is organized as $\{3, 1, 3, 1, \ldots\}$.

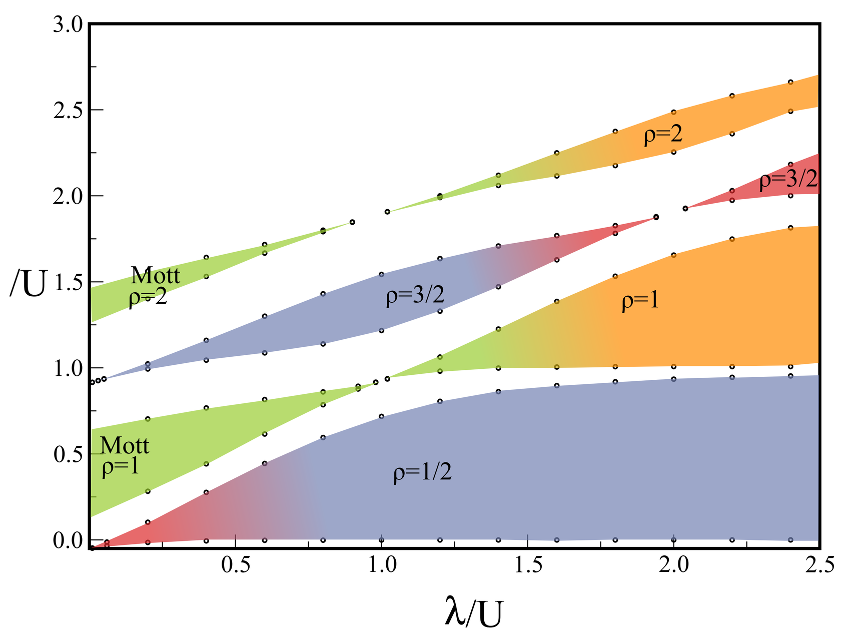

Figure 4: Phase diagram of the 2-periodic superlattice. The points represent the boundaries in the DMRG method. The gap size for $\rho = 1/2$ remains constant for large values of λ/U, and the remaining integer and semi-integer densities have insulator regions and transitions between them for values of densities $\rho \geq 1$ with λ values near U and $2U$.

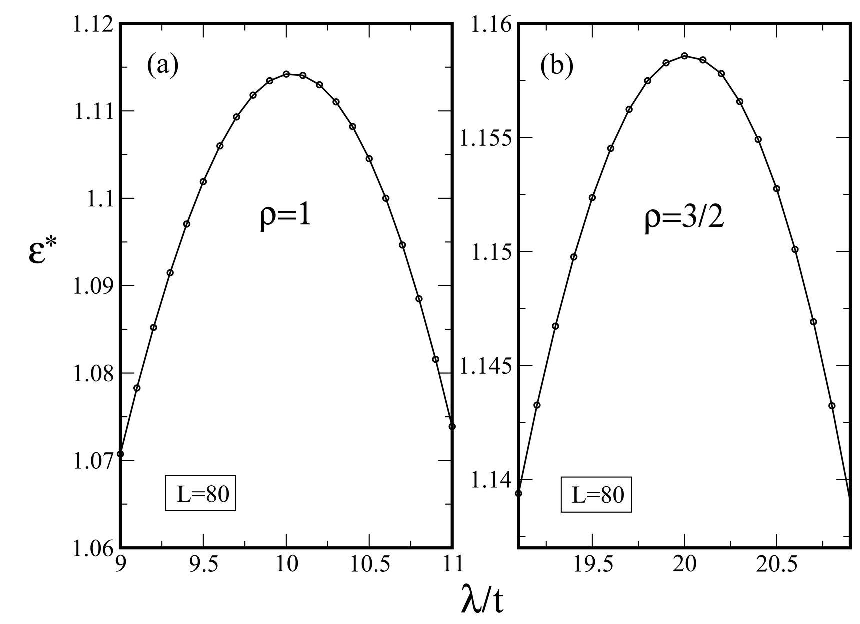

Figure 5: Average von Neumann entropy for a lattice with size $L = 80$ and density (a) $\rho = 1$ and (b) $\rho = 3/2$. This is given by $\epsilon^* = \frac{1}{L}\sum_i \epsilon_{\nu N}(i)$. The results show a maximum for values around the transition region, which implies a significant growth in the degrees of freedom and a superfluid phase

THEMODYNAMIC LIMIT

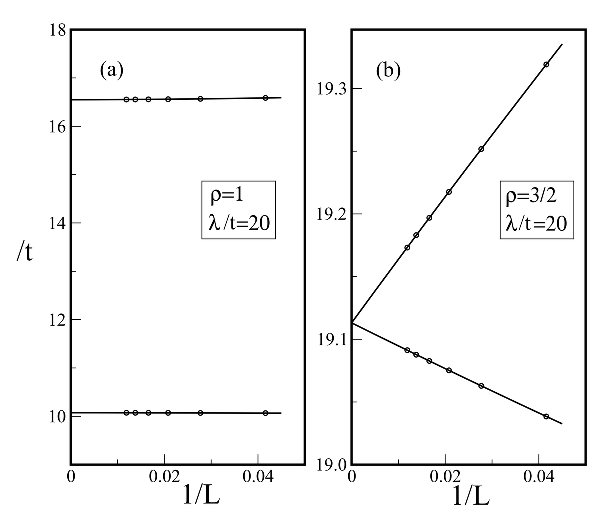

Figure 6: The chemical potential μ/t versus $1/L$, with L the size of the lattice. a) exhibits an insulator state and b) exhibits a superfluid phase at the thermodynamic limit.

CONCLUSION

Using the density matrix renormalization group method, we determined the chemical potential of the 2-period superlattice at the thermodynamic limit and found the phase diagram. For a small energy difference (λ), we observe that insulator regions with a peculiar charge distribution appear for semi-integer densities, which doesn't occur for integer densities, for which the Mott insulator phase still appears.The size of the new insulator phases for densities less than one increases with λ but then stabilizes, and these phases remain in the phase diagram. On the other hand, for densities $\rho \geq 1$, we always found a superfluid region that separates two insulator phases. For integer densities, the system starts in a Mott insulator phase, but for $\lambda > U$ the system exhibits a new insulator phase. The most surprising result is that the new insulator for $\rho \geq 1$ is unstable with increasing λ, and we obtain an insulator phase for values of $\lambda > U$, which depends on the density. Between the insulator phases, we always have a superfluid phase, a result that was confirmed using von Neumann entropy.

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