Bulletin of Pure and Applied Science Physics, Vol.41D No.2, July-December 2022 P.65-69 Original Research Article

Print version ISSN 0970 6569 Online version ISSN 2320 3218 DOI: 10.5958/2320-3218.2022.00013.6 Available online at www.bpasjournals.com

Strong Correlation Effects and Localization in Metallic Systems

Amita Sharma*

Author's Affiliations: Department of Physics, R.D.S. College, Muzaffarpur, B.R.A.B.U., Muzaffarpur, Bihar 842001, India.

***Corresponding author:** **Amita Sharma**
Department of Physics, R.D.S. College, Muzaffarpur, B.R.A.B.U., Muzaffarpur, Bihar 842001, India.
E-mail: dramitasharma63@gmail.com

Received on 28.04.2022
Revised on 21.09.2022
Accepted on 29.10.2022
Published on 15.12.2022

ABSTRACT We have studied strong correlation effects and localization in metallic systems. Strong correlation effects and localization occurred in metallic systems due to strong electron-electron interactions and strong electron phonon coupling. Strong electron-phonon interactions have been found in such materials as cuprates, fullerides and manganites. The interplay of electron-electron and electron-phonon interactions in these correlated systems leaded to coexistence of or competition between various phases such as super conductivity, charge-density-wave or spin–density wave phases or formation of novel non Fermi liquid phases, polarons, bipolarons and so on. We have considered Holstein-Hubbard model for our work. The Holstein-Hubbard model provides on over simplified description of both electron-electron and electron-phonon interactions, it retains to be the relevant ingredients of a system in which electrons experience simultaneously an instantaneous short range repulsion and a phonon-mediated retarded attraction. In spite of its formal simplicity, it is not exactly solvable even in one dimension. So quantum simulators of Fermi-Hubbard modes based on either fermionic atoms inoptical lattice or electrons in artificial quantum dot crystals have been used. In our work a classical analog simulator was theoretically proposed for the two site Holstein-Hubbard model based on light transport in engineered waveguide lattices, which is capable of reproducing the temporal dynamics of the quantum model in Fock space as spatial evolution in photonic lattice. We have found that in the strong correlation regime the periodic temporal dynamics exhibited by the Holstein-Hubbard Hamiltonian, related to the excitation Holstein polarons has been explained in terms of generalized Bloch oscillations of a single particle in a semi-infinite inhomogeneous tight binding lattice. Light transport in two dimensional photonic lattices simulated in Fock space the hopping dynamics of two correlated electrons on a one dimensional lattice and exploited to visualize such phenomena as correlated tunneling of bond electron-electron molecules and their coherent motion under the action of d.c. or a.c. fields. The obtained results were found in good agreement with previous results.

KEYWORDS Strong Correlation, Localization, Electron-Electron Interaction, Electron-Phonon Coupling, Fermi Liquid, Polaron, Quantum Simulation, Quantum Dot, Photonic Lattice, Fock Space, Tunneling.

How to cite this article: Sharma A. (2022). Strong Correlation Effects and Localization in Metallic Systems. *Bulletin of Pure and Applied Sciences- Physics,* 41D (2), 65-69.

INTRODUCTION

Realization of quantum analog simulators of many body problems have been based mainly on atoms [1-3], trapped ions [4-6], nuclear magnetic resonance [7] and single photons [8,9]. At the few photon level interaction is generally mimicked using purely linear optical systems by measurement-induced non linearity [10]. Simplified models of many body condensed matter physics have been simulated such as frustrated Heisenberg dynamics in a spin $-\frac{1}{2}$ tetramer. The propagation of classical light in waveguide based optical lattices has provided an experimentally accessible test bed to mimic in a purely classical setting single particle coherent phenomena of solid state physics [11-12], such as Bloch oscillations [13], dynamic localization [14] and Anderson localization [15] to mention a few. The possibility to simulate Bose-Hubbard models of few interacting bosons or fermions in coupled waveguide linear optical structures using classical light beams has been proposed by Longhi [16]. The main idea is that the temporal evolution of a few interacting particles in Fock space can be conveniently mapped into linear spatial propagation [17]. One of the simplest theoretical model that accounts for the interplay between these two types of interactions is the Holstein-Hubbard model [18-20]. As quantum simulators of Fermi-Hubbard models based on either fermionic atoms in optical lattices [21-22] or electrons in artificial quantum dot crystals have taken into account for our work.

METHOD

The two site Holstein-Habbard model has been considered for our work. This describes two correlated electron hopping between two adjacent sites of a diatomic molecule, each of which exhibited an optical mode with frequency Ω. This model has been often used in condensed matter physics as a simplified model to describe some basic features of polaron and bipolaron dynamics. The two site Holstein-Hubbard Hamiltonian have has been separated into two terms. One describes a shifted oscillator that does not couple to the electronic degrees of freedom and has been disgarded. The other describes the effective electron-phonon system where phonon couple directly with electronic degree of freedom. The corresponding Hamiltonian with $\hbar = 1$ is written as

$$\hat{H} = \hat{H}_e + \hat{H}_{ph} + \hat{V}_{e-ph}$$

Where

$$\hat{H}_e = -t\sum_{\sigma\uparrow,\downarrow}\left(\hat{c}^{\dagger}_{1,\sigma}\hat{c}^{\dagger}_{2,\sigma} + \hat{c}^{\dagger}_{2,\sigma}\hat{c}_{1,\sigma}\right)$$

$$+U\left(\hat{n}_{1.\uparrow}\hat{n}_{1.\downarrow} + \hat{n}_{2.\uparrow}\hat{n}_{2.\downarrow}\right)$$

$$\hat{H}_{ph} = \Omega\hat{b}^{\dagger}\hat{b}$$

$$\hat{V}_{e-ph} = \frac{g}{\sqrt{2}}\left(\hat{n}_1 - \hat{n}_2\right)\left(\hat{b} + \hat{b}^{\dagger}\right)$$

$\hat{c}^{\dagger}_{i,\sigma}\left(\hat{c}_{1,\sigma}\right)$ are the fermionic creation (annihilation) operators for the electron at site 1 with spin σ. $\hat{n}_{1,\sigma} = \hat{c}_{1,\sigma}\hat{c}^{\dagger}_{1,\sigma}$ and $\hat{n}_1 = \hat{n}_{1.\uparrow} + \hat{n}_{1.\downarrow}$ are the electron occupation numbers, g is the one site electron-phonon coupling strength t_d is the hopping amplitude between adjacent sites, U is the onsite coulomb interaction energy and $\hat{b}^{\dagger}\hat{b}$ is creation (annihilation) bosonic operator for the oscillator. For the two site two electron system there are six electronic states. Three of these states are degenerate with zero energy $\hat{H}_e\left|\psi_{Ti}\right\rangle = 0$ where $i = 1,2,3$ and belong to the triplet states. The triplet states are not coupled with the 'b' oscillator and can be disgarded. The three other eigen states of $\hat{H}_e$ denoted by $\left|-\right\rangle, \left|s+\right\rangle$ and $\left|s-\right\rangle$ have been constructed from the singlet states. The electron-phonon interaction term $\hat{V}_{e-ph}$ couples the electronic eigen states $\left|-\right\rangle$ and $\left|s\pm\right\rangle$ of $\hat{H}_e$ with the phonon states $\left|n\right\rangle_{ph} = \left(1/\sqrt{n!}\right)\hat{b}^{\dagger n}\left|0\right\rangle_{ph}$ of $\hat{H}_{ph}$ have been taken into account for our work.

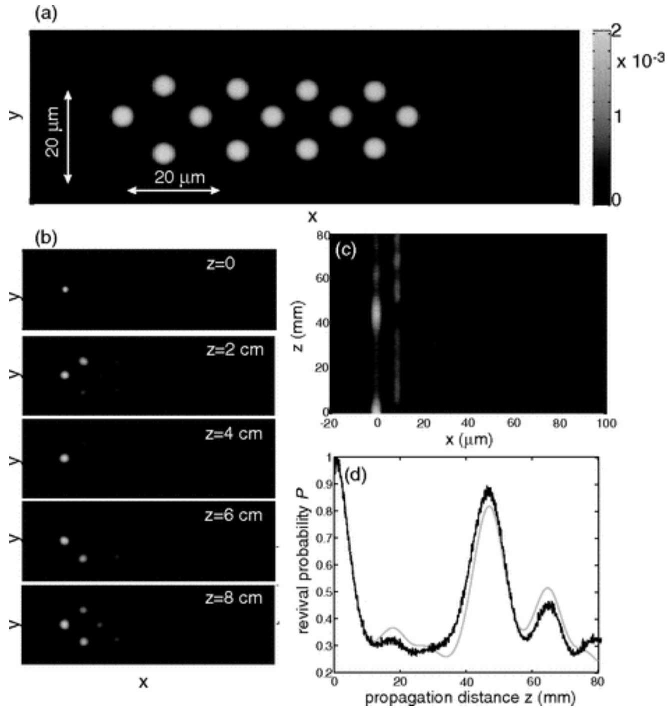
RESULTS AND DISCUSSION

Graph (1) shows results obtained in the moderate correlated regime $U = 0.2mm^{-1}$, corresponding to $cos\,\theta \simeq 0.851$, $sin\,\theta \simeq 0.526$. In this case $k_n \neq \rho_n$ and thus the two zigzag chains forming the array are noticeably asymmetric. The strong correlation regime is attained when the on-site interaction strength U is much larger than the hopping amplitude 't' corresponding to $cos\,\theta \simeq 1$ and $sin\,\theta \simeq 0$. In this case $\rho_n \simeq 0$ and thus the phonon modes are coupled to the electronic degree of freedoms solely via the two dressed states $\left|-\right\rangle$ and $|S+> \simeq -|+>$, whose energy levels are nearly degenerate and equal to U and $E_+ \simeq U\left\{\frac{1+4t^2}{U^2}\right\}$ respectively. In Fock space, the electron-phonon coupling dynamics is thus reduced to the coupled equations for occupation amplitudes 'f_n' and 'g_n'.

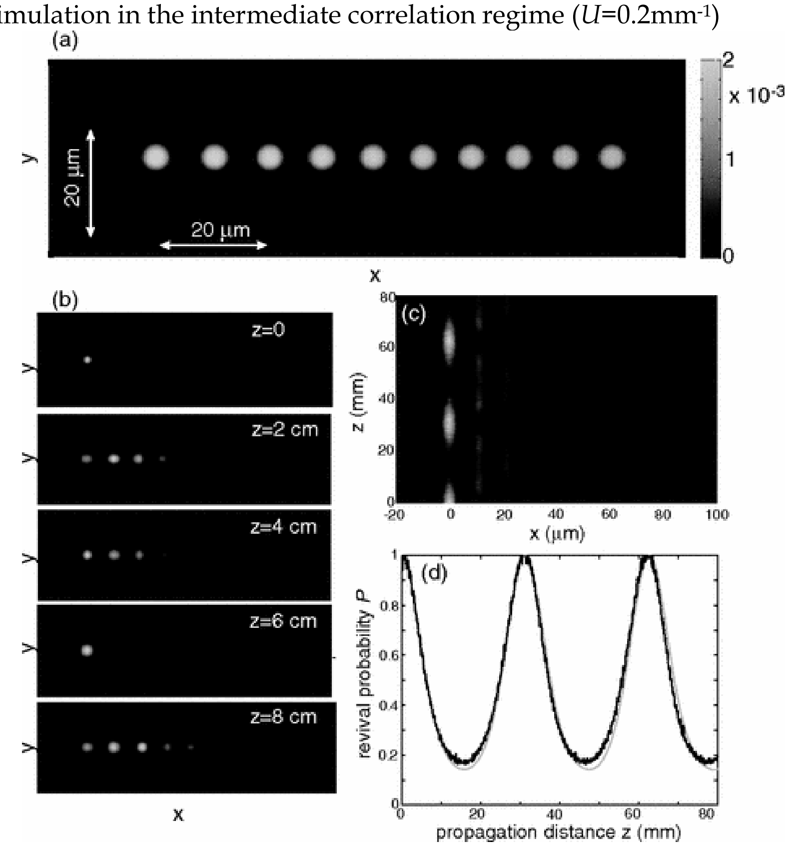
$$i\frac{df_n}{dt} = \left(U + \Omega_n\right) f_n - k_n g_{n-1} - k_{n+1} g_{n+1}$$

$$i\frac{dg_n}{dt} = \left(E_+ + n\Omega\right) g_n - k_n f_{n-1} - k_{n+1} f_{n+1}$$

Where $k_n = \sqrt{2ng}$, correspondingly, the optical analog simulator reduces to a simple linear chain of wave guides with nonuniform spacing as shown in graph (2)(a). The optical simulation of the Holstein-Hubbard model in the strong correlation regime is shown in graph (2) for parameters values $g = 0.1mm^{-1}$, $t = 0.1mm^{-1}$, $\Omega = 0.2mm^{-1}$ and $U = 10mm^{-1}$. The dynamics of occupation amplitudes shows in this case is a topical periodical behavior with a period given by $\frac{2\pi}{\Omega}$. In our optical simulator the periodic revival is clearly visualized by the self imaging property of the waveguide array in which the initial light periodically returns into the initially excited waveguide as shown in graph (2). Such a periodic behavior has been explained after obtaining that in the strong correlation regime $U \rightarrow \infty$, the phonon modes couple solely to two dressed electronic states $\left|-\right\rangle$ and $\left|+\right\rangle$. The obtained results were compared with previously obtained results of theoretical and experimental research works and found in good agreement.



Graph 1: Optical simulation in the intermediate correlation regime (U=0.2mm^{-1})



Graph 2: The Strong correlation regime (U = 10mm^{-1}) with the oscillation frequency Ω=0.2mm^{-1}

CONCLUSION

We have studied strong correlation effects and localization in metallic systems due to strong electron-electron interactions and strong electron-phonon coupling. Our photonic analog simulator enabled to map the temporal dynamics of the quantum system in Fock space spatial propagation of classical light waves in the evanescently coupled wave-guides of the array. We have found that in the strong correlation regime the periodic temporal dynamics related to the excitation of Holstein polarons with equal energy spacing were obtained as a periodic self imaging phenomenon of the light beam along the waveguide array in terms of generalized Block oscillations of a single particle in bending lattice. The obtained results were found in good agreement with previously obtained results.

REFERENCES

[1] M. Lewenstein, Adv. Phys. 56, 247, (2007).
[2] S. Trotzky et al., Nat. Phy. 6, 998, (2010).
[3] H. Weimer, M. Miller, I. Lesanovsky, P. Zoller and H. P. Bchler, Nat. Phys. 6, 382, (2010).
[4] M. Johanning, A. F. Varon and C. Wunderlich, J. Phys. B, 42, 154009, (2009).
[5] A. Friedenauer, H. Schmitz, J. T. Glueckert, D. Porras and T. Schaetz, Nat. Phys. 4, 757, (2008).
[6] K. Kim, M. S. Chang, S. Korenblit, R. Islam, E. E. and C. Monroe, Nature 465, 590, (2010).
[7] J. Zhang, T. C. Wei and R. Laflamme, Phys. Rev. Lett. 107, 010501, (2011).
[8] R. Kaltenbaek, J. Lavoie, B. Zeng, S. D. Bartlett and K. J. Resch, Nat. Phys. 6, 850, (2010).
[9] X. S. Ma, B, Dakic, W. Naylor, A. Zeiling and P. Walther, Nat. Phys. 7, 399, (2011).
[10] E. Knill, R. Laflamme and G. J. Milburn, Nature, 409, 46, (2001).
[11] S. Longhi, Laser Photon, Rev. 3, 243, (2009).
[12] A. Szameit and S. Nolte, J. Phy. B, 43, 163001, (2010).
[13] R. Morandotti etal, Phys. Rev. Lett. 83, 4756, (1999).
[14] S. Longhi etal, Phys. Rev. Lett. 96, 243901, (2006).
[15] T. Schwartz etal, Nature 446, 55, (2007).
[16] S. Longhi, J. Phys. B, 44, 051001, (2011).
[17] D. N. Christodoulides, F. Lederer and Y. Silberberg, Nature 424, 817, (2003).
[18] G. D. Mohan, Many Particle Physics (Kluwer Academic/ Plenum, New York, 2000)
[19] J. Zhong and H. B. Schutter, Phys. Rev. Lett. 69, 1600, (1992).
[20] C. R. Proetto and L. M. Falicov, Phys. Rev. B, 39, 7545, (1989).
[21] T. Esslinger, Ann. Rev. Cond. Matter Phys. 1, 129, (2010).
[22] T. Byrnes, N. Y. Kim, K. Kusudo and Y. Yamamoto, Phys. Rev. B, 78, 075320, (2008), A. Singha etal, Science 332, 1176, (2011).

****