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High-T_c Superconductivity within t - t'- J - J' Model

K. Roy, N.K. Ghosh

Author's Affiliations:	
K. Roy	Department of Physics, University of Kalyani, Kalyani, West Bengal 741235, India
N.K. Ghosh	Department of Physics, University of Kalyani, Kalyani, West Bengal 741235, India
Corresponding author:	**N.K. Ghosh,** Department of Physics, University of Kalyani, Kalyani, West Bengal 741235, India **E-mail:** nkg@klyuniv.ac.in
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ABSTRACT	The behaviour of high-T_c cuprates in its ground state has been examined within the t-t'-J-J' model using an exact method. The role of next-nearest-neighbor (NNN) hopping (t') and exchange (J') interactions on the charge gap, spin gap and effective exchange interaction has been investigated. Charge gap shows a gapped behavior. Spin gap curves establish a gapless behavior at small t'/t and J'/t. Also, it appears that effective exchange interaction is very much relevant in the present system
KEYWORDS	High-T_c cuprates; Extended hopping and exchange interactions; Effective exchange interaction.

1. INTRODUCTION

The two-dimensional t-J model [1, 2] and its various extensions [3, 4] have been successfully applied to explain various anomalous properties of strongly correlated electron systems including high-T_c cuprates (HTC). Considering t-J model at low doping and using slave-boson formulation, it has been observed [5] that the instability of the d-wave superconducting state to internal phase fluctuations gives way to $d+is^*$ superconductor. The most studied extended interactions of the model are next-nearest-neighbor (NNN) hopping [6], the Coulomb repulsion between nearest-neighbor (NN) [7] and electron-phonon (EP) interactions [8]. It has been observed that NNN hopping enhances the critical temperature T_c [9]. Angle resolved photoemission spectroscopy (ARPES) experiments on high-T_c cuprates strongly suggest the relevance of EP interaction in these materials [10].

Using an exact method, the ground state phase diagrams of the Hubbard model extended by various NN and NNN interactions showed [11] that NNN interactions have significant effects on the properties of the system described by the model. Effect of NNN hopping and magnetic interactions on d_{x2-y2}-wave superconducting phase has also been studied [6] and the existence of the d-wave superconducting phase has been established. The 2D t-J model extended by inter-site Coulomb repulsion term (a t-J-V model) manifests the characteristics of high-T_c cuprates at a hole-doping $< h >= 0.25$ [12]. The physical parameter range J/t~0.4 [13] is important for the t-J model to reproduce qualitatively the main experimental features of high-T_c superconductors. In high-T_c cuprates, the role of NNN antiferromagnetic exchange interaction is very much relevant [6, 14]. The study of the two-hole binding energy suggests that two holes tend to bind for higher values of diagonal exchange interaction J' [14]. The effect of this interaction (J') on some characteristics of HTC at T=0 and T≠0 has also been examined [15].

Considering all the above discussions, we have examined the influence of J' and t' on charge gap, spin gap and effective exchange interaction within the t-J Hamiltonian containing J' and t'. All calculations are made in an 8-site tilted square cluster with 2-holes [16] using exact diagonalization (ED) method applying periodic boundary conditions. The ED method is followed here to avoid any discrepancy in the result owing to approximations

made. To minimise the effect induced by the finite size, interactions are limited within NNN sites and correlations up to two lattice distances have been considered.

2. FORMULATIONS

Our Hamiltonian is

$$H = H_{t-J} + H_{t'} + H_{J'} \quad (1)$$

$$\text{Where, } H_{t-J} = -t\sum_{<i,j>\sigma}\left(c_{i\sigma}^{\dagger}c_{j\sigma} + H.c.\right) + J\sum_{<i,j>}\left[\overrightarrow{S_i}.\overrightarrow{S_j} - \frac{1}{4}n_i n_j\right] \quad (2)$$

$$H_{t'} = -t'\sum_{[p,q]\sigma}(c_{p\sigma}^{\dagger}c_{q\sigma} + H.c.) \quad (3)$$

$$H_{J'} = J'\sum_{[p,q]}\left[\overrightarrow{S_p}.\overrightarrow{S_q} - \frac{1}{4}n_p n_q\right] \quad (4)$$

Where $H_{t'} and\ H_{J'}$ are the NNN hopping and exchange interactions respectively, <*i*, *j*> and [p, q] are summations over NN and NNN sites respectively. In this study, average hole concentration is <*h*>=0.25 and total spin component along the z-direction $S_z^{tot} = 0$.

We have calculated here the charge gap defined as

$$\Delta_c = \frac{1}{2}[E_0(N+2,0) + E_0(N-2,0) - 2E_0(N,0)] \quad (5)$$

And also spin gap defined as

$$\Delta_s = E_0(N,1) - E_0(N,0) \quad (6)$$

Where $E_0(N,S)$ represents the ground state energy of *N* particles with spin *S*.

The effect of the presence of *J'* in the Hamiltonian on the possible pairing mode has been examined following the variation of the nature of effective exchange interaction defined as

$$J_{eff} = \frac{\sum_{<i,j>}\langle\psi_0|(\overrightarrow{S_i}.\overrightarrow{S_j} - {}^1/_4 n_i n_j)|\psi_0\rangle}{\sum_{<i,j>}\langle\varphi_0|(\overrightarrow{S_i}.\overrightarrow{S_j} - {}^1/_4 n_i n_j)|\varphi_0\rangle} \quad (7)$$

Where $|\varphi_0>$ and $|\psi_0>$ are the ground states of $H_{t\text{-}J}$ and *H* respectively.

3. RESULTS AND DISCUSSIONS

Keeping in mind the superconductivity of cuprates, average hole-density is taken as <*h*>=0.25 (2-hole state) and *J*/*t*=0.3 [17]. Considering spin-singlet ground state, appropriate for the *t*-*J* model [18], we set $S_z^{tot} = 0.0$.

The dependence of the charge gap Δ_c on *J'*/*t* and *t'*/*t* is plotted as shown in Figur 1. It is seen that a gapped behavior exists in the characteristics. It is further observed that Δ_c attains a peak at a particular *J'*/*t* and then decreases rapidly with *J'*/*t*. With the increase of *t'*/*t*, Δ_c decreases.

Variation of the spin gap Δ_s with *J'*/*t* and *t'*/*t* has been depicted in Figure 2. Measuring spin gap we can estimate the amount of energy required for a transition from the singlet ground state to triplet state. From the figure it is clear that the magnitude of the charge gap Δ_c is much larger than Δ_s. Spin gap decreases with both NNN hopping and exchange interactions. When the values of *t'*/*t* are small, i.e., *t'*/*t* = -0.2, -0.1, 0.0 we observe a transition in the spin gap characteristics. The existing spin gap vanishes at a larger *t'*/*t* for a smaller *J'*/*t*. Moreover, a mixing of triplet and singlet spin ground states is observed in the region of smaller *t'*/*t*.

To identify the possible pairing mechanism in high- T_c superconductors, the effective exchange interaction J_{eff} might play an important role [19, 20]. Also, the interaction J_{eff} is dependent on *J'* and *t'*, the NNN exchange and hopping interactions respectively. So, to verify the influence *t'* and *J'* on J_{eff}, we have shown the variation of J_{eff} against *J'* for various *t'* in Figure 3. With the increase of *J'*, the interaction J_{eff} decreases. The variation of J_{eff} is similar to the nature of *d*-wave pairing susceptibility [16]. Thus, it can be said that the effective exchange interaction may give indication of the possible pairing mechanisms in high-T_c cuprates.

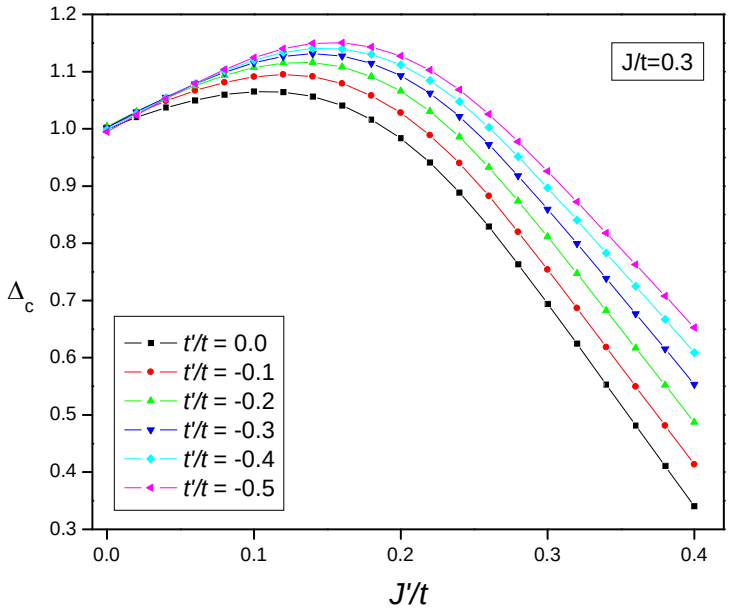

Figure 1: Charge gap Δ_c for various J'/t and t'/t.

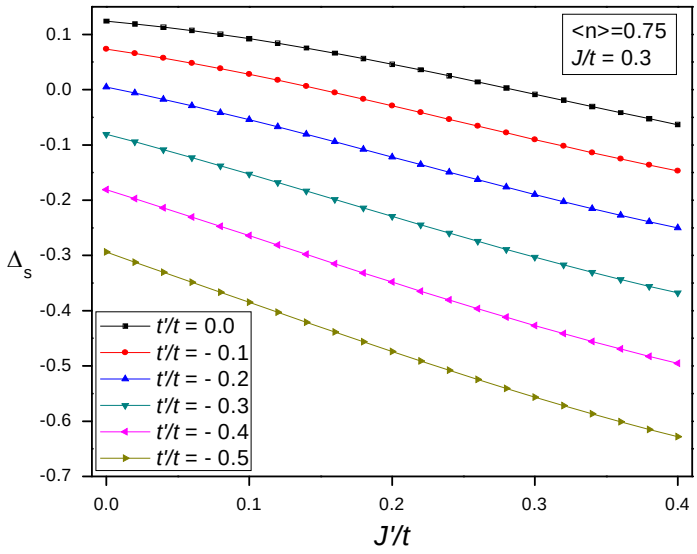

Figure 2:.Spin gap vs. J'/t for different values of t'/t.

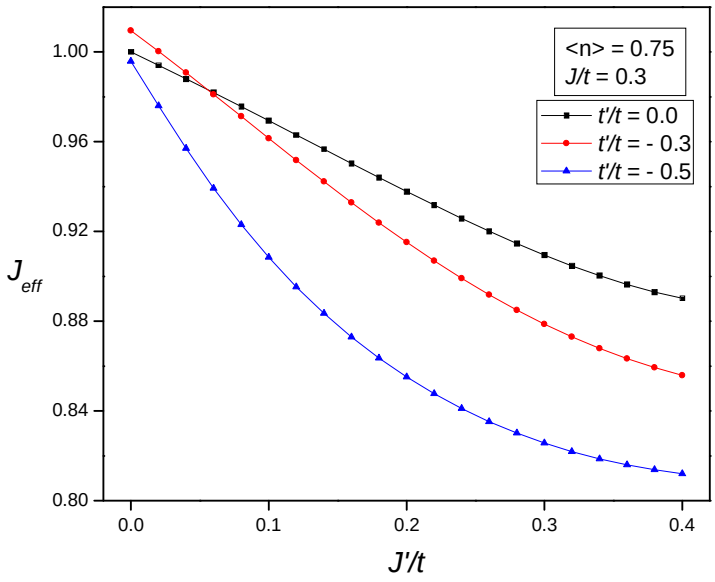

Figure 3: Dependence of J_{eff} with J'/t for various t'/t.

4. CONCLUSIONS

In this communication, some ground state characteristics of high-T_c cuprates using t-t'-J-J' model have been investigated. The findings of the study are summarised below:

- Results show that the charge gap and the spin gap decreases with NNN hopping.
- At smaller t'/t, overlapping of singlet and triplet ground states is possible.
- Moreover, effective exchange interaction behaves similarly with the d-wave pairing susceptibility in high-T_c cuprates.

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REFERENCES

[1]. F. C. Zhang and T. M. Rice, *Phys. Rev. B 51*, 3759 (1988)
[2]. K. Müller, *J. Supercond. Nov. Magn. 27*, 2163 (2014)
[3]. H. Tasaki, *Phys. Rev. Lett. 75*, 4678 (1995)
[4]. K. Roy, *et al., Eur. Phys. J. B 92*, 270 (2019)
[5]. A. V. Mallik *et al., Phys. Rev. Lett. 124*, 147002 (2020)
[6]. N. S. Mondal and N. K. Ghosh, *Pramana-J. of Phys.74*, 115 (2010)
[7]. J. D. Sau and S. Sachdev, *Phys. Rev. B 89*, 075129 (2014)
[8]. N. S. Mondal and N. K. Ghosh, *Physica B 406*, 3723 (2011)
[9]. R. Raimondi, J. H. Jefferson and L. F. Feiner, *Phys. Rev. B 53*, 8774 (1996)
[10]. A. Lanzara *et al., Nature (London) 412*, 510 (2001)
[11]. Zs. Szabo, *Phys. Rev. B 59*, 10007(1999)
[12]. P. Pal, *et al., Chinese J. Phys. 56*, 958 (2018)
[13]. M. Calandra and S. Sorella, *Phys. Rev. B 61*, R11894 (2000)
[14]. K. Roy, *et al., Eur. Phys. J. B 91*, 64 (2018)
[15]. K. Roy, *et al., Bull. of Pure and Appl. Sc. 37D*, 27 (2018)

[16]. K. Roy and N. K. Ghosh, *Bull. of Pure and Appl. Sc. 39D*, 66 (2020)
[17]. A. H. Nevidomskyy, *et al., Phys. Rev. B 77*, 064427 (2008)
[18]. Y. Hasegawa and D. Poilblanc, *Phys. Rev. B 40*, 9035 (1989)
[19]. J. A. Riera, *Phys. Rev. B 40*, 833(R) (1989)
[20]. V. Barzykin and D. Pines, *Advances in Physics 58*, 1 (2009)

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