Possible High Temperature Superconductivity in Systems with Nested Fermi Surface Pockets

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Abstract

We propose that superconductivity with high T_c can be achieved in systems having two disconnected Fermi surfaces which are nested to some extent. The idea is exemplified on the Hubbard model on lattices where dimers are coupled into various types of two dimensional arrays. Using fluctuation exchange method along with the Eliashberg equation, T_c of these systems is evaluated to be $3 \sim 5$ times higher than that of the Hubbard model on a simple square lattice, which is a model for the high T_c cuprates.

Key words: high T_c superconductivity ; disconnected Fermi surface ; dimer array lattice ; Hubbard model

Seeking a mechanism for high temperature superconductivity is a great theoretical challenge. Due to the generally low energy of the phonons, purely electronic pairing mechanism have attracted much attention from the early days, and especially after the discovery of high T_c superconductivity in the cuprates. In particular, the possibility of superconductivity in the Hubbard model on a two dimensional (2D) square lattice, a simplest electronic model for the cuprates, has been intensively studied, where spin fluctuation theories using fluctuation exchange (FLEX) method have estimated T_c of the $d_{x^2-y^2}$-wave superconductivity to be $O(0.01t)$ (t is the nearest neighbor hopping integral). [1] Since $t \sim 0.4$eV for the cuprates, this estimation is consistent with the experimentally observed T_c of up to 150K, but at the same time one should be aware that it is *two orders of magnitude lower* than the kinetic energy scale t.

In our view, a reason for this reduction of T_c is that the $d_{x^2-y^2}$ gap has nodal lines that intersect the Fermi surface. Such a sign change in the gap function is usually a 'necessary evil' for spin fluctuation pairing in that the pair scattering processes $[\boldsymbol{k}\uparrow, -\boldsymbol{k}\downarrow] \to [\boldsymbol{k}+\boldsymbol{Q}\uparrow, -\boldsymbol{k}-\boldsymbol{Q}\downarrow]$, mediated by the dominant spin fluctuations with wave vector $\boldsymbol{Q}$, have to accompany a sign change in the gap function ϕ, i.e., $\phi(\boldsymbol{k})\phi(\boldsymbol{k}+\boldsymbol{Q}) < 0$. In the case of the square lattice, this requirement leads to the $d_{x^2-y^2}$ pairing, where the gap function has nodes that intersect the Fermi surface, thereby resulting in a reduction of T_c.

From this viewpoint, two of the present authors have recently proposed that superconductivity with

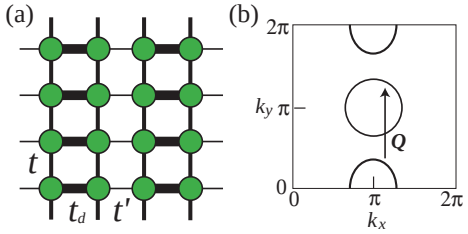

Fig. 1. (a) The two band lattice, where the thickness of the lines represent the magnitude of the hoppings. (b) The Fermi surfaces of the model in (a). $\boldsymbol{Q}$ is the nesting vector.

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much higher T_c can be achieved in systems having two pocket-like Fermi surfaces, where the two Fermi surfaces are nested to some extent. Here, the dominant pair scattering processes take place between the two Fermi surfaces, so that the sign change in the gap function takes place *across*, not *on*, the Fermi surfaces.[2]

Such a situation can be realized in the Hubbard model on the lattice shown Fig.1(a).[2] This is a two band model when $t' < t_d$ in that there are two inequivalent sites in a unit cell. When t_d is not too large compared to t', and the band filling n is close to half-filling, the two bands intersect the Fermi level to result in two pocket-like Fermi surfaces around $\boldsymbol{k} = (\pi, 0)$ and $\boldsymbol{k} = (\pi, \pi)$, which are nested to some extent (Fig.1(b)). We have evaluated T_c of this system using FLEX along with the Eliashberg equation, where we find a maximum T_c of $0.09t$. This is about $3 \sim 4$ times higher than that of the Hubbard model on a square lattice. We attribute the origin of the high T_c to the form of the gap function, which indeed changes sign across the two bands, but stays nearly constant within each band.

Such a form of the gap function can be interpreted in terms of a real space picture by looking at the system as *dimers coupled into an array*, where we refer to the two-site unit bridged by the largest hopping t_d as

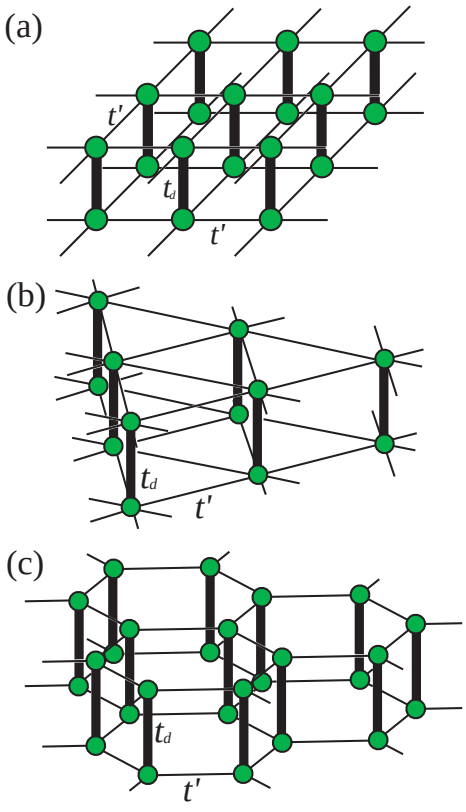

Fig. 2. Dimers coupled into square (a), triangular (b), or honeycomb (c) lattices

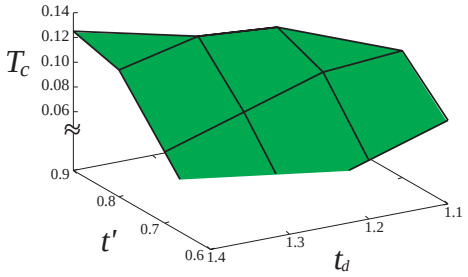

Fig. 3. T_c as a function of (t', t_d) for the square lattice (Fig.2(a)) with $U = 8$ and $n = 0.95$.

dimers. Namely, it is natural to consider that the singlet pairs are mainly formed between electrons residing on different sites within a dimer due to the antiferromagnetic interaction $\propto t_d^2/U$ between the two sites. Then, the gap function has s wave symmetry within each band because the pairing occurs within a unit cell, while it changes sign across the two bands because the pairs are formed between different sites.

This intuitive picture leads us to further consider the Hubbard model on a series of 2D lattices in which dimers, vertically placed against the 2D plane this time, are coupled into various types of arrays. We consider here the Hubbard model on lattices where dimers are coupled into square, triangular, or honeycomb lattices, as shown in Fig.2. These systems again have two pocket-like Fermi surfaces, nested to some extent, when t_d/t' is not too large and the band filling is close to half-filling.

T_c evaluated by FLEX+Eliashberg equation for the square lattice case (Fig.2(a)) is shown in Fig.3 as a function of (t', t_d). Similar results are obtained for the triangular and the honeycomb lattices. As can be seen, T_c again comes close to or even exceeds 0.1.

The present results show that the Hubbard model on these 'dimer array' lattices generally exhibits superconductivity with high T_c. If $t_d \sim$ few hundred meV, which is typical for d electron systems, $T_c \sim 0.1$ corresponds to a very high T_c of few hundred K.

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