# Triplet superconductivity in the repulsively interacting electron system on a triangular lattice: a possibility of magnetic-field-induced superconductivity

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**Abstract**

A disconnected Fermi surface as exemplified by dilute electrons in the triangular lattice has been theoretically shown by Kuroki and Arita to work favorably for spin-triplet pairing mediated by ferromagnetic fluctuations due to the electron-electron repulsion. Here we propose that a relatively small magnetic field can ensure the realization of the triplet superconductivity, where the mechanism is anisotropic ferromagnetic fluctuations and the coupling of longitudinal spin fluctuations with the ferromagnetic spin wave. We have confirmed the idea with a quantum Monte-Carlo study in combination with the dynamical cluster approximation, where the magnetic field is shown to enhance the pairing in the $\uparrow\uparrow$ channel.

*Key words:* triplet superconductivity; magnetic field; Hubbard model; ferromagnetic spin fluctuation

While a fascination toward spin-triplet superconductivity from ferromagnetic spin fluctuation has a long history, its realization in microscopic models is known to be rather difficult[1]. Recently, Kuroki and Arita have shown, with the fluctuation exchange approximation, that spin-triplet pairing instability mediated by ferromagnetic spin fluctuation becomes dominant in the low density repulsive Hubbard model on the triangular lattice[2]. The Fermi surface then consists of two disconnected parts, and the nodal lines of pairing gap function can be inserted between the pieces of Fermi surface, which is a good news for pairing, since most of the pairing scattering processes contribute positively to the pairing vertex. However, it is still a subtle problem whether or not the triplet pairing does indeed take place, so we want to have some stabilizing mechanism.

Phenomenologically, on the other hand, various authors have proposed various ideas to enhance triplet pairing instability. Monthoux *et al.*[3] have shown that the Ising-like anisotropy in the spin fluctuations favors the triplet superconductivity in the $zz$ channel. In the context of the ferromagnetic superconductivity in $UGe_2$, $ZrZn_2$ and UGeRh, Kirkpatrick *et al.*[4] have shown that the ferromagnetic spin-fluctuation mediated superconductivity should have a higher $T_c$ in the ferromagnetic phase than in the paramagnetic phase due to the coupling of longitudinal spin fluctuations with transverse spin waves.

Our new idea here is — if we apply an external magnetic field to a system close to ferromagnetism, anisotropy in the spin fluctuation should be quite readily achieved. The Zeeman energy introduces a magnetic anisotropy in the spin fluctuation, while the mangetic-field induced spin polarization gives rise to spin waves. Thus the purpose of the present study is to show that a relatively small magnetic field should realize the triplet pairing instability in the low density Hubbard model on the triangular lattice.

We take the standard repulsive Hubbard model on with the Zeeman energy $h \equiv g\mu_B B$ included. We ap-

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ply the magnetic field **B** parallel to the plane to ignore orbital effects. We set the Coulomb repulsion $U$ to be equal to the band width $W$, which is taken to be 2 here. The one-electron band dispersion for the triangular lattice, $\varepsilon = 2t[\cos(k_x) + \cos(k_x) + \cos(k_x + k_y)]$, has two dips so that the Fermi surface become disconnected when the band is less than quarter-filled ($n < 0.5$).

We adopt the quantum Monte-Carlo (QMC) method in combination with the dynamical cluster approximation (DCA), formulated recently by Jarrell *et al*[5]. We choose the cluster size $N_c = 4\times4$, which is large enough to treat the anisotropic pairing considered here.

Figure 1(a) shows the temperature dependence of the pairing susceptibilities for $n = 0.2$ and $n = 0.4$. We can see that $\chi(h = 0)$ grows toward $T = 0$ for $n = 0.2$, which is consistent with the FLEX result[2]. We can also see that $\chi^{\uparrow\uparrow}(h = 1.0\times10^{-2})$ is greater than $\chi(h = 0)$ for $n = 0.2$ and $n = 0.4$. While the enhancement of $\chi^{\uparrow\uparrow}(h = 1.0 \times 10^{-2})$ above $\chi(h = 0)$ for $n = 0.2$ decreases toward $T = 0$, its magnetic-field dependence for a fixed $T = 1/16$ in Fig. 1(b) indicates that $\chi^{\uparrow\uparrow}(h)$ first increases and then starts to decrease for $h > h_{\max}$.

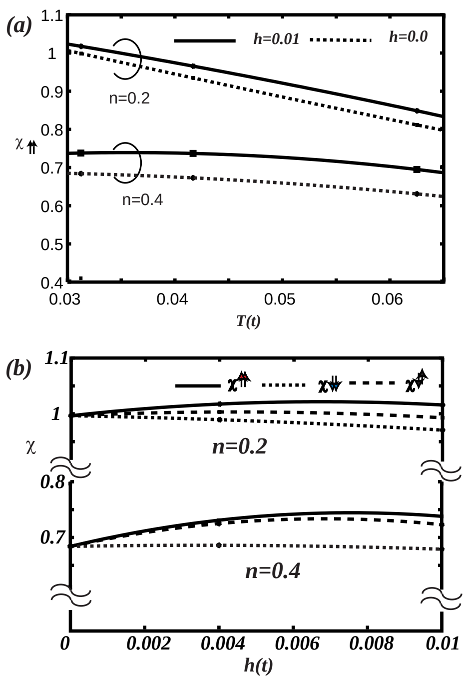


Fig. 1. The triplet pairing susceptibilities versus temperature (a) and magnetic field (b) for the Hubbard model on the triangular lattice with $n = 0.2$ and $n = 0.4$.

These behaviors can be understood as follows. For a fixed $B$ (or $T$), the spin polarization increases as $T$ ($B$) is decreased (increased), so that the majority-spin Fermi surface becomes simply-connected, which pushes the system back to the usual situation where the triplet pairing is hard to realize. Conversely, $\chi^{\uparrow\uparrow}$ continues to be enhanced at low $T$ if we decrease $B$ accordingly, since $h_{\max}$ decreases with $T$.

Thus, if the derivative of $\chi$ with respect to $h$ continues to be positive around $T_c$ at which $\chi(h = 0)$ diverges, we may expect that $T_c$ is enhanced for a relatively small magnetic field ($h \sim 0.01$), as depicted schematically in Fig. 2. Note that the value $h = 0.01$ corresponds to $O(10T)$ for the band width $\sim O(1\text{ eV})$.

In summary, we have propose that a relatively small magnetic field can ensure the realization of triplet superconductivity.

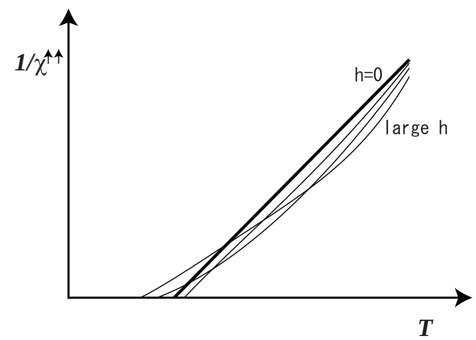


Fig. 2. A schematic $1/\chi^{\uparrow\uparrow}$ versus $T$ for various values of magnetic field. The bold line represents $h = 0$.

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