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Triplet superconductivity–spin vs. charge fluctuations and fermiology

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Abstract

Spin-triplet superconductivity, which is generally difficult to be realised as opposed to singlet, is theoretically discussed in terms of (i) dimensionality and fermiology, (ii) pairing interaction mediated by spin fluctuations vs. charge fluctuations, and (iii) single vs. multi-orbitals. We conclude that (i) two-dimensional (2D) systems are generally more favourable. Disconnected Fermi surfaces greatly help, since we can insert extra nodes, required for triplet pairs, in between the Fermi pockets. (ii) Charge fluctuations help, since they work constructively in the triplet channel. External magnetic fields can also give rise to a non-unitary pairing. (iii) Multi-orbital systems have a possibility of, e.g., a spin-triplet, orbital-singlet pair. These are conceived for materials design, along with applications to a quasi-2D Sr_2RuO_4 (for which we predict a time-reversal-broken triplet $p_{x+y} + ip_{x-y}$) and a quasi-1D $(TMTSF)_2PF_6$ (a triplet f predicted).

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1. Factors governing pairing symmetry and T_C

There has been an increasing fascination with spin-triplet pairing in the condensed matter physics, with a history dating back to the discovery of superfluid ^{3}He. One salient feature is that triplet superconductors are very rare: they have been found only in some heavy fermion compounds, organic metals, and more recently a ruthenate, Sr_2RuO_4. Theoretically, there is a good reason why this is so: in the electron mechanism of superconductivity the pairing interaction mediated by spin fluctuations is only $\frac{1}{3}$ in the triplet channel than in the singlet channel [1,2]. So any theory attempting to explain triplet pairing has to resolve this.

On the other hand, there is a growing realisation that the way in which the electron correlation effects such as magnetism and superconductivity appear is very sensitive to the underlying one-body band structure. We can even extend the idea to ‘‘fermiology in correlated electron systems’’ to explore the possibility of manipulating superconductivity and magnetism by choosing the shape of the Fermi surface [3]. Here we discuss how triplet pairing can be favoured from the viewpoints of (i) dimensionality and fermiology, (ii) spin-fluctuation mediated vs. charge-fluctuation mediated interactions and (iii) single- vs. multi-orbital systems.

2. Dimensionality and fermiology

2.1. Singlet vs. triplet waves in 2D vs. 3D

Arita et al. have examined typical 2D and 3D lattices with various band filling or t' [1] with the fluctuation exchange approximation (FLEX). The conclusion is

	2D	3D
singlet d	V	v
triplet p	×	×

The reason why 2D is more favourable than 3D may be traced back [1,2] to Éliashberg's equation, where the height and width of the region both in the frequency (ω) and

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momentum ($\boldsymbol{q}$) sectors over which the interaction is appreciable turn out to be similar between 2D and 3D. This means that their phase volume fraction is much greater in 2D. This agrees with the empirical fact that there are many layered superconductors (cuprates, Co compound, Hf compound, $CeCoIn_5$, etc). Why triplet p is weak even when ferromagnetic fluctuations dominate may be traced back primarily to the pairing interactions in the singlet channel and triplet channel (characterised by the $\boldsymbol{d}$-vector $\|\hat{z}$ or $\perp \hat{z}$),

$$V_{\text{singlet}}(\boldsymbol{q}) = +\frac{1}{2}\, V^{zz}_{\text{spin}}(\boldsymbol{q}) + V^{+-}_{\text{spin}}(\boldsymbol{q}),$$

$$V^{\boldsymbol{d}\|\hat{z}}_{\text{triplet}}(\boldsymbol{q}) = +\frac{1}{2}\, V^{zz}_{\text{spin}}(\boldsymbol{q}) - V^{+-}_{\text{spin}}(\boldsymbol{q}),$$

$$V^{\boldsymbol{d}\perp\hat{z}}_{\text{triplet}}(\boldsymbol{q}) = -\frac{1}{2}\, V^{zz}_{\text{spin}}(\boldsymbol{q}),$$

where $V^{zz}_{\text{spin}}(V^{+-}_{\text{spin}})$ is the longitudinal (transversal) spin-fluctuation-mediated interaction, and $\boldsymbol{q}$ is the momentum transfer. When the spin is isotropic ($V^{zz}_{\text{spin}} = V^{+-}_{\text{spin}}$) $|V_{\text{triplet}}| = (1/3)V_{\text{singlet}}$. Namely, the pairing interaction in the singlet channel, which can exploit all the three (two transverse [+−] as well as longitudinal) components, is three times as large as in the triplet channel.

2.2. *Why is T_C so low?—Higher T_C in "disconnected Fermi surfaces"*

T_C in the electron mechanism is very low, in that T_C, as estimated with FLEX [4] and more recently with DCA [5], is $T_C < 0.03t$, upper-bounded by a magnitude *two* orders smaller than the starting electronic energy scale, t. This is also the case with Uemura's experimental plot for T_C against T_F for all the known superconductors. Theoretically, there are good reasons why T_C is low: (a) the effective attraction mediated by the fluctuation is much smaller than the starting *repulsive* interaction. We can realise this when we recall that the laser-cooled Fermi gas was recently made superfluid, where T_C is as high as $\sim 0.1T_F$, but the interaction there is made attractive with Feschbach resonance. (b) Quasi-particles have finite lifetimes due to the self-energy correction arising from the electron correlation, and (c) pairing in repulsive systems has to be anisotropic with nodes in the gap function, and the nodes, which usually intersect the Fermi surface, act to greatly suppress T_C.

Recently, Kuroki and Arita [6] have proposed that we can overcome the difficulty (c) by considering *disconnected* Fermi surfaces, on which we can pierce the nodes in between the Fermi pockets. Each pocket is then fully gapped, with opposite signs across the pockets. $T_C \sim 0.08t$, almost an order of magnitude higher, is indeed estimated with FLEX in the disconnected cases. Other lattices (plaquette lattices [7], bond-alternating lattices in 3D [8]) have also been shown to have similar T_C. The mechanism works for triplet [9] as well. Examples for triplet are triangular and honeycomb lattices, and Kuroki et al. [10] have recently examined its relevance to the recently discovered Co compound superconductor, although complications such as multi-bands may be relevant in the compound [11].

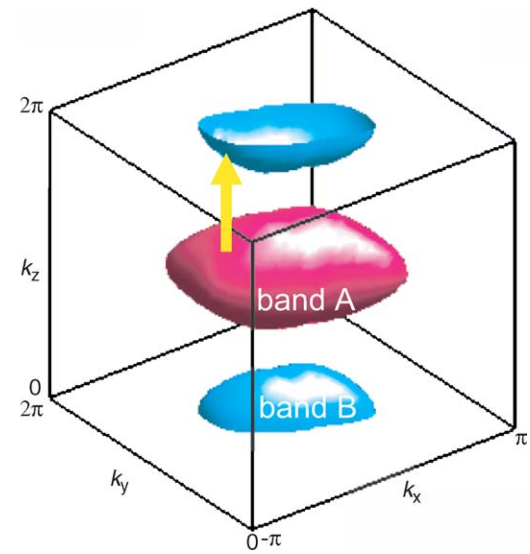

Fig. 1. Pairs, formed within each piece of the Fermi surface, can exploit interband pair scattering (arrows).

2.3. *Better the nesting, the better?*

In the above mechanism pairs are formed within each pocket, and they exploit the interband pair scattering processes (Fig. 1). A question then is: Better the nesting, the better? In the simply connected Fermi surfaces, the pairing arises from the intraband nesting, and we have suggested [12] that the better nesting does not necessarily imply the more enhanced pairing correlation. This applies to the interband nesting as well. A physical picture is that the Fermi surface, or the band dispersion to be more precise, must be such that the peak position, height and width in the spin susceptibility $\chi(\boldsymbol{q}, \omega)$ in both wave number and frequency sectors have to be right for the superconductivity to be optimised. Namely, the susceptibility peak has to be *blurred* with a width comparable to the size of the Fermi surface structure.

3. Spin- vs. charge-fluctuation mediated pairing

Even when the shape of the Fermi surface is right, we still have to overcome the difficulty of $|V_{\text{triplet}}| = (1/3)|V_{\text{singlet}}|$ for the triplet pairing to be stable. We can then note that the interaction contains not only V_{spin}, which is the main component for the Hubbard model with an on-site repulsion, but also the charge-fluctuation mediated pairing interaction, V_{charge}, which can become significant when the interaction extends beyond the on-site,