Possible diminution of impurity pair breaking for triplet pairing superconductivity in two-dimensional or quasi-two-dimensional, weakly localized, nearly magnetic systems

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We propose a conjecture according to which, as a consequence of weak localization in two-dimensional, nearly magnetic itinerant paramagnets, the pair-breaking parameter due to normal impurity scattering, in triplet pairing superconductivity, may be reduced at low enough temperature. It might then, in principle, become easier to observe triplet pairing superconductivity in dirty two-dimensional or quasi-two-dimensional metals, than in three-dimensional ones; thus some recently observed puzzling superconductive behaviors should be reexamined.

Localization in disordered two-dimensional (2D) systems has recently received a lot of interest.[1] In the present note, we make an extensive use of some results obtained by one of us[2] in the weakly localized regime, i.e., when the system is still metallic, to examine the problem of triplet pairing superconductivity in nearly magnetic itinerant systems,[3] as such systems, especially in confined geometries,[4] have already been proposed to be favorable candidates for the observation of triplet pairing superconductivity.

It appeared, from Ref. 2, that the contribution of electron scattering on normal impurities, together with the one of electron-electron mutual interactions yields a $\ln T$ correction to the conductivity transport relaxation rate, in a.u.,

$$\frac{1}{\tau_{\rm tr}}=\frac{1}{\tau_0}\left[1+\frac{g}{2\pi\epsilon_F\tau_0}\ln\frac{1}{4\pi\tau_0 T}\right]. \quad (1)$$

ϵ_F is the Fermi energy, τ_0 is due to s-wave impurity scattering and contributes to the residual resistivity at 0 K, T is the temperature. Moreover, if τ_ϵ is the relaxation time due to inelastic scattering, Ref. 2 assumed that

$$\frac{1}{\tau_\epsilon} << T << \frac{1}{\tau_0} << \epsilon_F. \quad (2)$$

g is a combination of dimensionless mutual interactions:

$$g=g_1+g_2-2(g_3+g_4) \quad (3)$$

entering through four types of self-energy corrections to the fermion propagators and due to mutual interactions as shown in Fig. 2 of Ref. 2. Impurity scattering was treated to infinite order both in the particle-hole and the particle-particle channels. The g_i included contributions to the first order in the various interactions in Ref. 2, but were, later, extended[5] to include interaction contributions to all orders.

The subsequent effect on BCS type, singlet pairing, superconductivity was examined,[6] as well as the pair-breaking parameter for that same type of superconductivity, in the presence of inelastic scattering[7] for weak disorder (note that the case of strong disorder has also been recently examined[8]): disorder tends to suppress BCS type superconductivity. In contrast, in the present note, we address ourselves to the problem of p wave or triplet pairing superconductivity in dirty nearly magnetic itinerant fermion systems in two dimensions or quasi-two dimensions.

We first recall some general features of the pure systems of itinerant strongly interacting fermions in three dimensions (3D) (Ref. 3) and 2D.[9] As well known, these systems consist in sets of itinerant fermions of characteristic energy ϵ_F, interacting through a phenomenological strong, instantaneous, contact repulsion I among opposite spins, of the order of ϵ_F, so that, when $\bar{I}=IN(\epsilon_F)\sim I/\epsilon_F$ is smaller than, but close to, 1, the system approaches a magnetic instability at $T=0$ [$N(\epsilon_F)$ is the density of states at the Fermi level]. On the other hand it has been shown that the strong spin fluctuations, "paramagnons," present when $\bar{I}$ is close to 1, and which renormalize all properties of these systems, altogether prevent[10(a)] s-wave type, normal BCS superconductivity (since the overall effective interaction among opposite spins happens to be repulsive), but, in contrast, do favor[10(b)] p-wave type, triplet pairing superconductivity (due to the effective interaction being attractive among parallel spins). Triplet pairing superfluidity has been observed,[11] we recall, in liquid He^3, which can be obtained ultrapure. However, it is much more difficult, if not impossible, to get rid of impurities in metals and thus p-wave superconductivity has been, so far, hard to detect in metals because, it was argued,[12] that it is easily destroyed by normal impurities scattering as efficiently as s-wave BCS superconductivity is destroyed by magnetic impurities; more precisely, Ref. 12 showed that the pair-breaking parameter in triplet pairing superconductivity is just the transport relaxation rate $1/\tau_{\rm tr}$. Therefore if a mechanism happens to reduce $1/\tau_{\rm tr}$ or possibly make it vanishing, then triplet pairing superconductivity may have a better chance to be detectable.

We now come back to Refs. 2 and 5, where $\ln T$ corrections to the transport relaxation rate were computed, taking into account weak disorder as well as mutual interactions. These ones were computed to infinite order in Ref. 5 and read

$$g_1-2g_3=\bar{I}^{-1}\ln[(1-\bar{I}^2)^{-1}]-(4/\bar{I})\ln[(1-\bar{I})^{-1}]+4$$
$$=-(3/\bar{I})\ln[(1-\bar{I})^{-1}]+4+\bar{I}^{-1}\ln[(1+\bar{I})^{-1}],$$
$$g_2=2g_4=-\bar{I}\left(1+\bar{I}\ln\frac{1.13\omega_0}{T}\right)^{-1}, \tag{4}$$

where ω_0 is the cutoff defined in Ref. 5. Here, for convenience, we have used the notation $\bar{I}$ instead of $F/2$ of Ref. 5, in order to deal with the case of a nearly magnetic system where the fermion interaction I plays the role of the potential interaction of Ref. 5. From (4) it is clear that when $\bar{I}$ is close to 1 (and of course positive), the main contribution to (3) is

$$g\simeq-(3/\bar{I})\ln[(1-\bar{I})^{-1}]=-3\ln S\ , \tag{5}$$

where $S=(1-\bar{I})^{-1}>>1$ is the Stoner enhancement of the nearly magnetic system. Therefore in that case

$$g \text{ is negative and } |g|>>1. \tag{6}$$

As a consequence, the transport relaxation rate $1/\tau_{tr}$ reads

$$\frac{1}{\tau_{tr}}\propto\frac{1}{\tau_0}\left[1-\frac{3\ln S}{2\pi\epsilon_F\tau_0}\ln\left(\frac{1}{4\pi\tau_0T}\right)\right], \tag{7}$$

with:

$$S>>1\ . \tag{8}$$

Therefore $1/\tau_{tr}$ is reduced when T decreases, and thus, according to Ref. 12 recalled above, the pair-breaking parameter for triplet pairing superconductivity is reduced. Under such conditions, and although weak localization is unfavorable to singlet pairing superconductivity,[6,7] it would, in contrast, favor triplet pairing superconductivity in the presence of strong paramagnons. Thus appears more realistic the previous proposal[4] that when nearly magnetic systems are in confined geometries where S is larger, triplet pairing superconductivity ought to be more easily observable. After writing, (7), it would be tempting to evaluate at which temperature $1/\tau_{tr}$ would vanish. At this stage, one must be careful that the original formula in Ref. 2 was obtained in perturbation; in (7), for large enough S, even if $(\epsilon_F\tau_0)^{-1}$ is $<<1$, one may have the competing product of both, [i.e., $(\ln S)(\epsilon_F\tau_0)^{-1}$], to exceed 1 and the perturbational result[7] may loose its validity. However, similar difficulties occurred in the well-known Kondo problem and equivalent means to deal with them could be examined. To put (7) equal to zero would not give the temperature where $1/\tau_{tr}$ vanishes, but rather, the equivalent of the Kondo temperature, below which the perturbational result (7) loses its validity. Nevertheless for adequate values of S, and this is the essential point of the present note, the pair-breaking parameter for triplet pairing superconductivity, measured by $1/\tau_{tr}$ may be weakened by weak localization in nearly magnetic 2D systems, and possibly, as well, in quasi-2D such systems.

Experimentally,[13] a few metallic compounds have been recently shown to behave like nearly magnetic Fermi liquids at low T, with a strong Pauli susceptibility, a strong value of the linear T coefficient in the specific heat .... But, at lower temperatures, these systems become superconductors, at T_c. The nearly magnetic character above T_c, *a priori*, prevents BCS superconductivity. On the other hand, triplet pairing superconductivity was discarded by the experimentalists as well, since these systems easily contain a certain amount of impurities. However, the structure of these systems is often highly anisotropic: for instance $CeCu_2Si_2$ can be said to exhibit a "weak 2D character."[14] Uniaxial pressure may reinforce the 2D character in order to check the possible consequences, but is, altogether, difficult to apply to such brittle compounds. Therefore from the experimental point of view, at present, the question whether the observed superconductivity is BCS or triplet pairing type is not solved.

However, if our conjecture appears to be correct and if it may hold, not only for 2D, but also for quasi-2D, or strongly anisotropic 3D systems, then, in nearly magnetic such metals or metallic compounds, impurities will no longer act as preventing triplet pairing superconductivity. Nevertheless, for practical purposes and actual comparison with experiments, it remains to calculate the superconducting temperature T_c under the same conditions and to examine whether or not it can be reached experimentally. Such a study is currently investigated by the authors.

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