Proximity effects of a thin film of unconventional superconductor in contact with a magnetic substrate

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Abstract

We suggest some new experiments that might be used to distinguish between states of various representations of unconventional superconductivity. In particular we investigate pair-breaking effects for various models of the order parameter in the thin films in contact with a magnetic substrate. The effect of a magnetic field on a thin film is qualitatively different for even- and odd-parity superconductors, depending strongly on the orientation of the field relative to that of the order parameter (and therefore to the crystallographic orientation), with the superconductivity entirely suppressed for some special orientations.

Identification of the superconducting state for a non-s-wave superconductor has been a challenge to both the theorists and the experimentalists [1]. Take for example UPt$_3$; although the existence of multiple superconducting phases in UPt$_3$ [2] argues strongly in favor of unconventional superconductivity, and in particular an order parameter belonging to one of the two-dimensional representations [3], which state is actually realized continues to be a subject of debate (for a summary, see, for example, ref. 4). Some earlier work favors the singlet $E_{\text{g}}$ representation, but it has been argued that the upper critical field anisotropy is only consistent with the triplet $E_{\text{u}}$ representation [4].

Thus new experiments that distinguish between the various candidates, and in particular its spin structure, are needed to identify uniquely the order parameter. We thus investigate the pair-breaking effects for various models of superconducting order parameter in thin films in contact with a magnetic substrate, which can be either ferromagnetic or paramagnetic and subject to an external field. The effect of a magnetic substrate is qualitatively different for different states and depends strongly on the orientation of the field relative to that of the order parameter and therefore to the crystallographic orientation because of strong spin–orbit locking.

We consider a superconducting film of thickness $d$ sandwiched between a magnetic insulator and a perfectly reflecting non-magnetic surface. This geometry has been used in tunneling measurements [5] and considered theoretically for conventional superconductors [6]. For tunneling experiments the oxide barrier is weakly transparent, but to a good approximation we may assume that it is perfectly reflecting. The surface is also assumed to be smooth. The thickness $d$ of the film is assumed small in comparison with the coherence length, so that the order parameter can be taken as a constant throughout the film. In this paper we use the same model to study the proximity effect on unconventional superconducting thin film in contact with a magnetic insulator.

We shall concentrate on the superconducting states appropriate to UPt$_3$ where the symmetry group of the normal state is the hexagonal group. The states can be classified into pseudo-spin singlets or triplets. We shall only discuss the two-dimensional representations, which are the most probable candidates for UPt$_3$. For convenience we list them in Table 1.

Our calculation is based on the quasi-classical theory, and follows the notation in the review by Serene and Rainer [7].

We expand the quasi-classical Green function as a constant term plus a linear term in $s$, the position coordinate normal to the plane of the film:

$$g(\hat{p}, s; \epsilon_n) = g_0(\hat{p}, \epsilon_n) + (s - d)g_1(\hat{p}, \epsilon_n)$$  \hspace{1cm} (1)
where \( d \) is the thickness of the film, \( s = 0 \) at the magnetic surface and \( s = d \) at the perfectly reflecting plane. \( g \) satisfies the boundary condition \((s = d)\)

\[
g_0(\hat{p}) = g_0(\hat{p}),
\]

(2)

here \( \hat{p} \) is the specularly reflected partner of \( \hat{p} \). This requires, in the case where the surface is also a plane of reflection symmetry,

\[
A(\tau) = A(\tau)
\]

i.e. any order parameter component proportional to an odd power of momentum normal to the surface is totally suppressed.

The zeroth-order Green function \( g_0 \) is found to satisfy

\[
\{ [M(\hat{p} - \alpha \hat{\mu} \cdot \hat{\Sigma}, g_0(\hat{p})] - i \frac{\tan(\theta/2)}{2} \}
\]

\[
\times \{ [M(\hat{p}), \hat{g}_0(\hat{p})] - \hat{\mu} \cdot \hat{\Sigma} \} = 0
\]

(4)

In eqn. (4) \( \Sigma_1 = \sigma_1, \Sigma_2 = \sigma_2 \tau_1 \) and \( \Sigma_3 = \sigma_3 \). \( \sigma \) and \( \tau \) are the Pauli matrices in spin and particle–hole spaces respectively, \( \alpha \hat{p} = (\nu \hat{p} \cdot \hat{\sigma})/2d \tan(\theta/2) \), \( M(\hat{p}) = \nu \hat{p} \tau_1 - \hat{J}(\hat{p}) \) and \( \Theta \) is the spin rotation angle that parameterizes the scattering matrix \( S = \exp(-i(\Theta/2) \mu \cdot \sigma) \) for a quasi-particle scattering off the magnetic substrate. This \( S \) matrix describes the rotation of the spin of a quasi-particle as a result of its tunneling into the classically forbidden region and its interacting with the internal field (along \( \hat{\mu} \)) of the magnetic substrate.

The first term in eqn. (4) is similar to the transport equation for an applied external field along \( \hat{\mu} \). In fact the form of the solution to eqn. (4) is identical in these two cases, i.e. the second term in eqn. (4) is identically zero when we substitute the solution for \( g_0 \). Thus one of the physical effects of the magnetic substrate and the coherence of the superconductor is to provide a spatially homogeneous but momentum-dependent magnetic field in the superconducting film. If the Cooper pairs are spin-singlet, then this magnetic field, which favors an unequal population of spins, is a pair breaker [8]. In a spin-triplet superconductor with spin–orbit locking its effect is highly anisotropic. The effect of a magnetic field is conveniently discussed in terms of the \( d \) vector, which we denote by \( D(\hat{p}) \). One has equal-spin pairs (ESPs) (\([\uparrow \uparrow] \) and \([\downarrow \downarrow] \)) for any quantization axis perpendicular to \( D(\hat{p}) \) (both its real and its imaginary parts if it is complex) and opposite-spin pairs (OSPs) for a quantization axis parallel to \( D(\hat{p}) \). A magnetic field along the ESP directions has no difficulty in polarizing the system and therefore is not a pair breaker. However, a magnetic field along the OSP direction is a pair breaker as in the case of an \( s \)-wave superconductor [9].

In general the spin-mixing angle \( \Theta \) depends on the direction of the momentum [6]. Here we shall take it to be a constant for simplicity (but \( x \) is still momentum dependent). In this case it is convenient to introduce a dimensionless pair-breaking parameter \( \rho \):

\[
\rho = \frac{\xi_0}{2d} \tan \left( \frac{\theta}{2} \right)
\]

(5)

where \( \xi_0 = \nu \hat{p} / 2\pi T_{c0} \) is the coherence length and \( T_{c0} \) is the bulk transition temperature.

The transition temperature for the film can be obtained from the self-consistent Bardeen–Cooper–Schrieffer gap equation, once we solve for \( g_0 \). We have checked that the transition between the superconducting states and the normal state is always second order. This is to be contrasted with the behavior of a small crystal under a uniform applied external field, where, in the cases with magnetic suppression, the transitions are always first order (except for the \( E_{2u} \) representation) [10].

Figures 1 and 2 show the calculated transition temperatures for cases where the \( \hat{\epsilon} \)-axis is in the plane of the film with \( \hat{\mu} \) also in the plane but parallel and perpendicular to \( \hat{\epsilon} \) respectively. In both cases the \( E_{2u} \) order parameter is completely suppressed by surface scattering. The effect of surface magnetic pair breaking on \( T_c \) is identical for the two \( E_{1g} \) and \( E_{2u} \) singlet order parameters, as one would expect. However, the behavior of \( T_c \) for an \( E_{1u} \) superconductor is completely different in the two cases, being unaffected when \( \hat{\mu} \) is parallel to \( \hat{\epsilon} \) but suppressed when \( \hat{\mu} \) is parallel to \( \hat{\epsilon} \) (note that \( D \) is parallel to \( \hat{\epsilon} \) for all \( \hat{p} \) in this representation). Figure 3 shows the transition temperature for the case where the \( \hat{\epsilon} \)-axis is along the normal to the film and \( \hat{\mu} \) is in the plane. For this case there is no magnetic pair breaking for an \( E_{1u} \) order parameter. However, the \( E_{1g} \) state is suppressed entirely by the boundary, but an \( E_{2u} \) order
amounts to momentum-dependent magnetic fields which are strongest for momentum directions near the normal to the film; thus, in the orientations with magnetic pair breaking, the effect is strongest when the maximum of the gaps are along the normal to the film (e.g. compare the results for \( E_{2g} \) in the three cases above).

In conclusion we point out that the proximity effect of a magnetic substrate on a superconducting film strongly depends on the superconducting state and the relative orientations of the internal field and order parameter. These effects can in principle be used to distinguish between the possible order parameters of unconventional superconductors.

Details of this work will be published elsewhere [10].

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