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Proximity effect of the superconducting states between two superconductors of different parity

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ABSTRACT

The theoretical study of the mutual proximity of the superconducting states between two superconductors of different parity led to the conclusion that their order parameters might suppress each other strongly. A superconductor with an attractive triplet channel is not likely to be attractive in any singlet channel and vice versa.

INTRODUCTION

[1] considered an arrangement in which a thin film (thickness a) of an s-wave superconductor is placed on a bulk heavy-fermion superconductors (fig. 1).

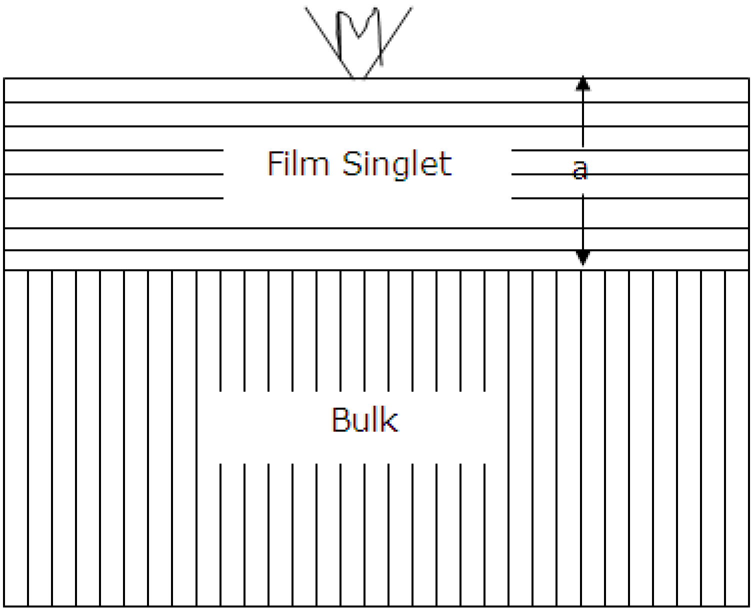


Fig. 1. Arrangement for the experiment study of the proximity effect between an unconventional bulk superconductor and a conventional s-wave superconducting film (Millis, 1985).

The bulk critical temperature (T_c^o) of the s-wave superconductor is suppressed to be smaller that that of the bulk heavy-fermion superconductor (T_c^b). The measurement of the superconducting order parameter on the film surface (point M) opposite to the interface by a tunnelling effect gives information about the parity of the superconducting state of the bulk material. This arrangement can easily be studied as a one-dimensional problem in the Ginzburg-Landau approach. The behaviour of the system is mainly determined by the boundary conditions of the interface.

If the bulk superconductor has s-wave symmetry, it will also induce a finite, detectable superconducting order parameter in the film via the proximity effect. Immediately below the bulk transition temperature T_c^b, the film order parameter behaves as

$$[\eta_{film}\,(T)] \sim [\eta_{bulk}\,(T)]/\xi_{bulk}\,(T) \sim (1 - T/T_c^{b})^{3/2}$$

that is, as a "driven" order parameter. Below (T_c^o) the order parameter η_{film} "has its own life" and is then essentially proportional to $(1 - T/T_c^o)^{1/2}$

In the case of an odd-parity (triplet) superconductor in the bulk, it is assumed that a driven s-wave order parameter in the film is absent or only very small, because the effect of a magnetically active interface, which is able to convert even and odd-parity states, is considered to be negligibly small in this picture. Therefore the effective boundary condition for a thin film would have the form

$$a,\ \eta_{film}\,[{}^{1}/_{b}\ \eta_{film}]_{interface} = 0, \qquad 1.1$$

acting suppressively for η_{film} at the interface. The extra-polation length b is determined by the tunnelling and reflection properties of the interface and by the properties of the bulk superconductor (the effective coherence length of the s-wave order parameter in the bulk, e.t.c).

With this boundary condition the transition temperature of a film of thickness a is reduced compared to $T^o{}_c$, as may be easily calculated in the Ginzburg-Landau formulation,

$$T_c = T_c\,[1 - \frac{\xi_0^2}{a^2}\,r(b/a)], \qquad 1.2$$

where ξ_o as the zero temperature coherence length of the film superconductor ($\alpha\, L^{1/2}$ for the dirty limit, where L is equal to the mean free path of the film) and r a function of the ratio b/a with r $\rightarrow \pi/2$ for b << a. For temperatures larger than T_c the s-wave order parameter detected at the M would essentially be zero. From these two qualitatively different behaviours one could distinguish experimentally whether even-or-odd-parity superconductivity were present in the bulk superconductor

THEORETICAL CONSIDERATION AND CALCULATION

By Variation of the free energy with these interface terms, boundary conditions are found which couple the order parameters of the two sides. As an example we consider the consideration $G_1 = G_2 = D_{4h}$ and $\Gamma^{(1)} = \Gamma_5^-$, $\Gamma^{(2)} = \Gamma_5^+$ with the general form of the free energy

$$F = \int d^3r\,[f_{(1)} * f_{sf(1)}^{(n1)} + f_{(2)} * f_{sf(2)}^{(n2)} + f_{coupling}\,(n_1, n_2)] \qquad 1.3$$

where f_{sf} are the surface terms in each side of the interface.

$$f_{coupling} = [T^*T(n_{1y}\,\eta_1^{(1)*} - n_{1x}\,\eta_2^{(1)*})\,n_{2z} \times (n_{2x}\,\eta_1^{(2)} + n_{2y}\,\eta_2^{(2)}) + c.c]_{interface} \qquad 1.4$$

Before performing the variation of F, it is convenient to diagonalize the bilinear surface terms $f_{sf(1)}$ and $f_{sf(2)}$. For simplicity we fix $n_1 = (1, 0, 0)$, leaving the basis in (1) unchanged, where n_2 will be arbitrary, with

$$\eta_1^{(2)} = n_{2x}\,\eta_1^{(1)} + n_{2y}\,\eta_2^{(2)}/\sqrt{n_{2x}^2 + n_{2y}^2} \qquad 1.5$$

and

$$\eta_2^{(2)} = (-n_{2y}\,\eta_1^{(2)} + n_{2x}\,\eta_2^{(2)}/\sqrt{n_{2x}^2 + n_{2y}^2} \qquad 1.6$$

In the new basis the variation of F with respect to $\eta_1^{(1)}$ leads to the boundary conditions

$$\delta_x\,\eta_1^{(1)} = \frac{1}{b_1^{(1)}}\,\eta_1^{(1)},$$

$$\delta_x\,\eta_1^{(1)} = \frac{-T^*T}{2k_2^{(1)}}\,n_2\sqrt{n_{2x}^2 + n_{2y}^2} \qquad 1.7$$

$$n_2 \,.\, \nabla\eta_1^{(2)} = \frac{1}{b_1^{(2)}(n_2)}\,\eta_1^{(2)} + \frac{T^*T}{2k_2^{(2)}}\,n_{2z}\sqrt{n_{2x}^2 + n_{2y}^2}\quad \eta_2^{(1)} \qquad 1.8$$

$$n_2 \,.\, \nabla\eta_2^{(2)} = \frac{1}{b_2^{(2)}(n_2)}\,\eta_2^{(2)} \qquad 1.9$$

All equations are restricted to the interface. The gradients are taken with respect to the basis of the crystal lattice (1) and (2), respectively. Terms containing the extrapolation lengths $b_j^{(1)}$ describe the reflection property of the interface, while the others describe the transfer property [K(n_2) is a combination of coefficients in $K_i^{(2)}$ in the free energy $f_{(2)}$ depending on n_2]. These terms exhibit their physical interpretation if we introduce the order parameter in terms $n_1^{(1)}$ =[$n_1^{(1)}$ expi $\varnothing_1$ (1) separate them into real and imaginary parts. From the first two equations [connected with side (1)] we explain

$$(T^*T = |T|^2 e^{i\varnothing 1})$$

$$\delta_x\,|\eta_1^{(1)}| = \frac{1}{b_j^{(1)}}\,|\eta_1^{(1)}|,$$

$$\delta_x\,|\eta_2^{(1)}| = \frac{-|T|^2}{2k_2^{(1)}}\,n_{2z}\sqrt{n_{2x}^2 + n_{2y}^2}\;|\eta_2^{(1)}| \times \cos[\varnothing_1 + \varnothing_1(2) - \varnothing_2(1)] \qquad 1.10$$

$$|\eta_1^{(1)}|\,\delta_x\,(1) = 0,$$

$$|\eta_1^{(1)}|\,\delta_x\varnothing_1(1) = \frac{-|T|^2}{2k_2^{(1)}}\,n_{2x}\sqrt{n_{2x}^2 + n_{2y}^2}\;|\eta_1^{(2)}| \times \sin[\varnothing_1 + \varnothing_1(2) - \varnothing_2(1)] \qquad 1.11$$

The other two equations lead to similar expressions as boundary conditions belonging to side (2). The imaginary part (the third and fourth equation of equation 1.10 can be combined into an expression for the current density at the interface,

$$j = \frac{e}{c}[k_1|\eta_1^{(1)}|^2\delta_x\varnothing_1(1) + k_2|\eta_2^{(1)}|^2\delta_x\varnothing_2(1)] - \frac{e}{2c}|T|^2 n_{2z}\sqrt{n_{2x}^2 + n_{2y}^2}$$

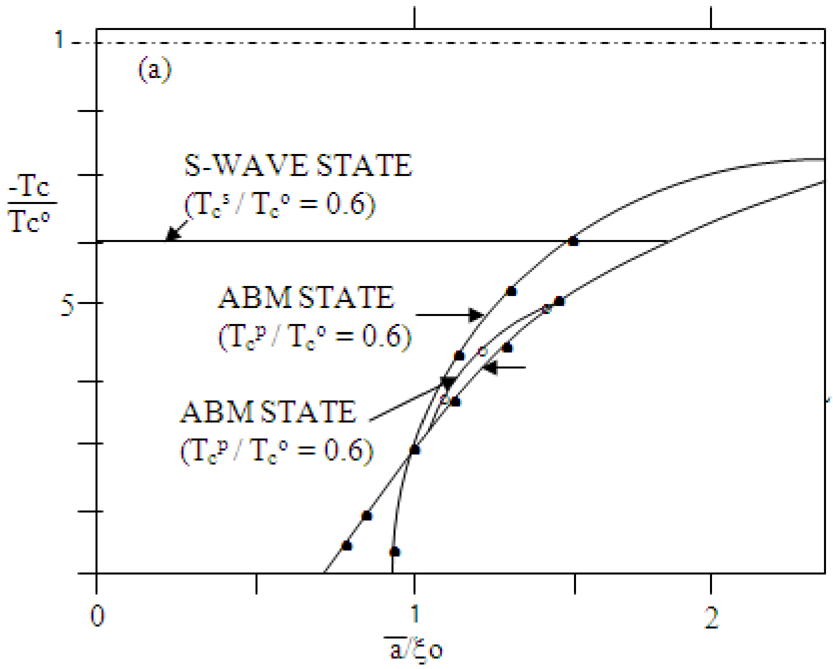
$$|\eta_2^{(2)}||\eta_2^{(1)}| \times \sin[\varnothing_1 + \varnothing_1(2) - \varnothing_2(1)] \qquad 1.12$$

The real part [the first and second equations of equation 1.10 is the effective boundary condition for the superconductor on side (1). Solving the Ginzburg-landau equations and these interface equations of both sides self-consistently, as a one-dimensional problem, we obtain the characteristics of the current j versus the phase difference at the interface. In that calculation it has to be taken into account that the order parameter in the bulk region is also suppressed by a finite current density. In general, for good coupled (ID) superconductors, the characteristics deviate considerably from the simple form

$$j = j_m \sin(\varnothing_1 + \Delta\varnothing) \text{ [3].}$$

RESULTS AND DISCUSSION

According to equation (1.2), a similar arrangement was studied by [2]. Taking the opposite approach, they assumed $T_c^o \geq T_c^b$, and calculated the effective transition temperature of the film (at the point M) in the presence of different bulk phases. They found a significant difference in the film transition temperature depending on whether singlet or triplet superconductivity was present in the bulk. Their result for the temperature –a- phase diagram is plotted in fig 2(a) for a clean and in fig 2(b) for a dirty film [by renormalization of the film thickness rate T of the interface (a = a/T)]. It is remarkable that the reduction of the s-wave superconductivity of the film by a triplet bulk superconductor is quantitatively almost the same as by a normal (non-superconducting) metal. Thus their effective extrapolation length (Equation 1.1) has to be almost equal.



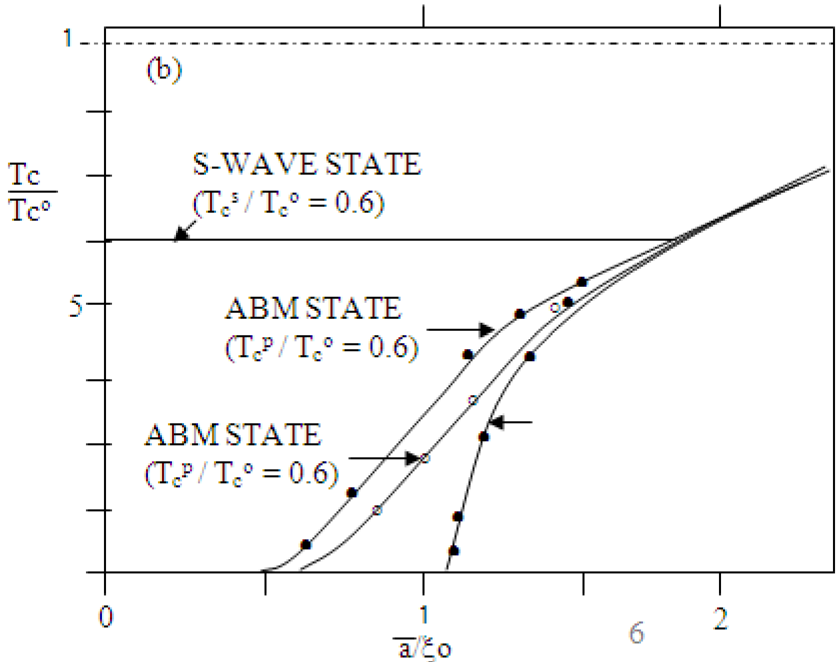


Fig. 2. Critical temperature T_c of clean and dirty films (thickness a) in proximity contact with various bulk materials (different types of p-wave superconductors, normal-metals and s-wave superconductors with smaller T_c^s). The critical temperature is defined by the vanishing of the s-wave order parameter in the film. T_c^o and T_c^p are the unperturbed transition parameter in the film and p-wave superconductor, respectively; ξ_o is the coherence length of the s-wave superconductor and a= a/(1 – R) is an adjusted thickness which includes the effect of reflections at the interface: (a) clean thin film (b) a dirty film. From Ashauer, Kieslemann, and Rainer, 1986

CONCLUSION

Obviously, for an experiment, good films of a thickness a of the order ξ_oT or smaller are required, where ξ_o is the coherence length of the s-wave superconductor. Therefore a large mass mismatih, mentioned initially, could suppress T strongly, so that this experiment is rather difficult to realize with heavy-fermian superconductor.

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