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LETTER TO THE EDITOR

Weak-localization-like effects in superconductor–ferromagnet–superconductor structures

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Abstract. We report measurements of the resistance as a function of temperature and magnetic field in structures containing a narrow (∼2 μm) ferromagnetic strip connecting two superconducting films. The low-field magnetoresistance has a general appearance similar to that expected for weak localization, but the magnitude is much too large to be accounted for in terms of this mechanism. In zero field the resistance exhibits behaviour well below the critical temperature of the superconductor which cannot be attributed to the usual proximity effect. Certain features of the results suggest that this behaviour may be associated with electron phase coherence.

Studies of electron transport in small structures have revealed a number of surprises in recent years [1]. Efforts in this area were initially concerned with normal-metal systems and phenomena such as weak localization [2] and the Aharonov–Bohm effect in multiply connected structures [3]. A key lesson from that work was the crucial importance of electron phase coherence. Recently much interest has focused on the behaviour of similar systems containing superconducting regions [4]. These so-called mesoscopic superconductors have been found to exhibit novel, and in some cases unexpected, behaviour. These include effects which have been attributed to coherent Andreev reflection, and also what appear to be greatly enhanced Aharonov–Bohm effects [5]. Most of the experiments in this area have employed multiply connected structures, such as rings, so that a magnetic field can be used to directly tune the Aharonov–Bohm phase via the flux through the structure [5, 6]. In this letter we describe experiments on a simpler type of superconducting–normal-metal structure, which avoids some of the complications that may arise in rings. We find several surprising results which suggest that the effects of electron phase coherence can indeed be greatly enhanced in such systems.

The structures that we have studied are shown schematically in the inset of figure 1. It is perhaps the simplest geometry for studying weak localization in thin films. A strip of normal metal a few μm wide and typically 10 μm long connects two much larger contact films. The contact films are superconductors; we used either In or Pb in our experiments. In order to minimize contributions of the proximity effect to our measurements, the normal metal was chosen to be Ni. The choice of a ferromagnet should eliminate, on the scale of interest here, any contribution of the proximity effect to the resistance of the structure (and its dependence on field) [7, 8].

The samples were patterned using several steps of optical lithography and lift-off, with the Ni films deposited first. The contact films were composed of either In or Pb. In both cases the superconducting film was deposited with the substrate cooled to 77 K. For the In we found that it was necessary to deposit a thin ∼300 Å layer of Cu between it and the Ni

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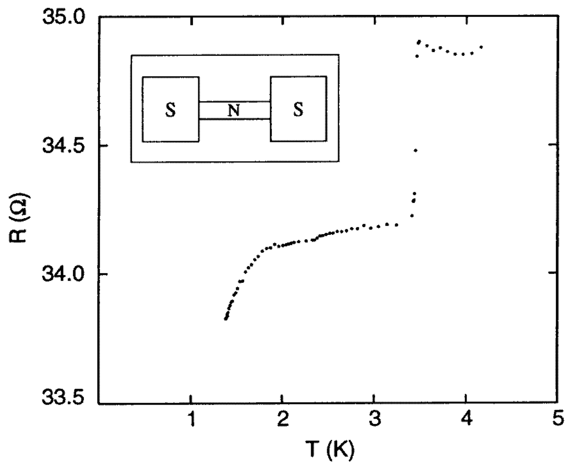

Figure 1. $R(T)$ in zero magnetic field for a Ni strip which was 2 μm wide, 8 μm long, and 300 Å thick. The contact regions were In films which were 1500 Å thick. The inset shows the sample geometry.

to prevent excessive contact resistances [9]. We found that this was not a problem for the samples involving Pb, but for comparison (to check if the Cu layer made any difference) we also made samples with Pb/Cu contact films. The results showed that the Cu did not have any effect on the behaviour. The Cu films were sputter deposited, while all of the other films were thermally evaporated. The measurements were made in a ^{4}He cryostat of standard design using dc techniques. Separate current and voltage leads were attached to each of the contact films; hence the measured resistance included a portion of the contact film from each end in series with the Ni strip.

Typical results for the temperature dependence of an In/Ni/In sample (i.e., a sample with two In contact films connected by a Ni strip) are shown in figure 1. The drop in R at ~3.4 K is due to the superconducting transition of the In films. As noted above, a portion of the contact film is effectively in series with the Ni strip at each end. We estimate this portion to be ~1 square of film at each end, and the observed drop in R at T_c is consistent with the measured sheet resistance of the contact films. A surprising aspect of these results is the rather strong temperature dependence below 3 K. From previous work on the proximity effect [7, 8] one would not expect to observe any change in R on this scale [10, 11]. The magnetoresistance, shown in figure 2, also reveals some surprising behaviour. The rapid variation of R at ~190 Oe is due to the superconducting transition of the In contact films. It is relatively abrupt, indicating that these films are fairly homogeneous. The surprising feature here is the very sharp dip in R near zero field. The extended range of field over which R is essentially constant, and which separates the dip at zero field from the changes at 190 Oe, suggests that the variation near zero field is not connected with the superconducting transition in the In, or with the proximity effect. The general shape of this dip is extremely reminiscent of the behaviour caused by weak localization in films such as Au [2, 12]. Indeed, we know of no other phenomena which produce a magnetoresistance having this functional form [13]. However, the magnitude of this dip is much too large to be explained by the conventional theory of weak localization. Roughly speaking, the theory predicts a conductance change no larger than e^2/h, but the dip in figure 2 is larger than this by two orders of magnitude. Moreover, if one insists on attributing the dip to weak localization then the width of the dip is proportional to L_ϕ^{-2}, where L_ϕ is the electron phase coherence length. A qualitative analysis of the results in figure 2 implies $L_\phi \sim 20\ \mu$m. This is implausibly large; for comparison, a Au film with a somewhat longer elastic mean free path would typically exhibit $L_\phi \sim 1$–$2\ \mu$m at the same temperature [12].

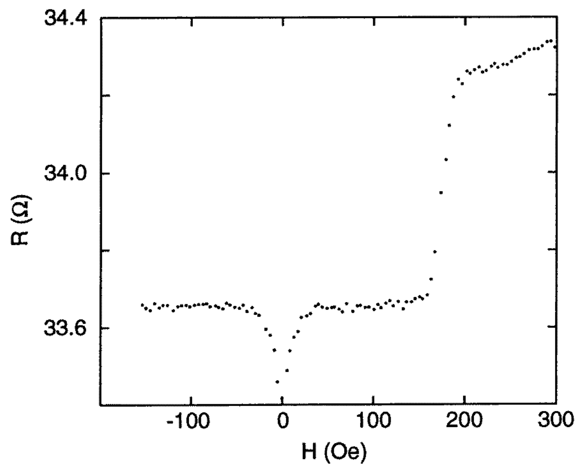

Figure 2. $R(H)$ at 1.4 K for the sample considered in figure 1. The field was perpendicular to the plane of the sample.

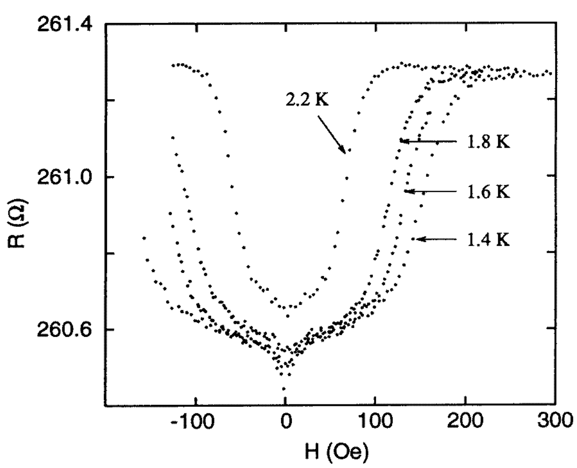

Figure 3. $R(H)$ at several temperatures for the sample considered in figure 1. The field was perpendicular to the plane of the sample.

The temperature dependence of the magnetoresistance is shown in figure 3. The narrow dip near $H = 0$ is seen to be extremely sensitive to temperature, and is vanishingly small (on this scale) above about 2.0 K. This suggests that it is not directly associated with the superconducting transition of the In contact films. However, comparing with the results for $R(T)$ in figure 1, it seems connected with the drop in R as the temperature is decreased.

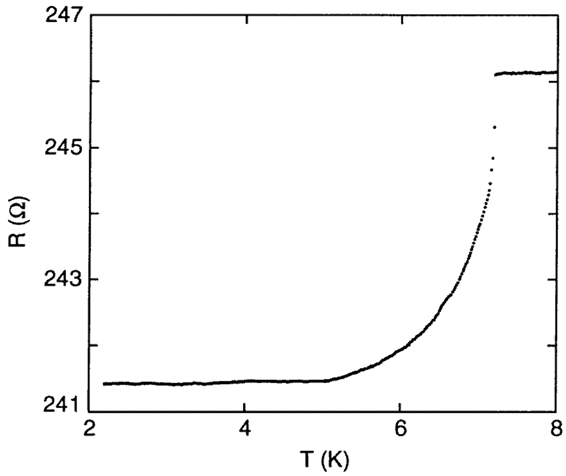

Figure 4. $R(T)$ for a Pb/Ni/Pb sample in zero field. The Ni strip was 2 μm wide, 7 μm long, and 300 Å thick. The contact regions were Pb films which were 1200 Å thick.

The results for Pb/Ni/Pb structures are similar in certain respects to those found with In contact films. Figure 4 shows results for the temperature dependence of R in zero field. While the functional form is different from that seen for the In/Ni/In sample (figure 1), here too we find a pronounced temperature dependence well below T_c. Figure 5 shows the magnetoresistance in both perpendicular and parallel fields for two Pb/Ni/Pb samples. In both cases we find a drop in R at high fields, which is associated with the superconducting transition in the contact films. This occurs at a higher field than with the In/Ni/In samples (figure 2), since the Pb contact films have a higher critical field. Near zero field we also observe a weak-localization-like dip, although the dip is much wider than with the In/Ni/In samples. Note also that the dip is broader for parallel than for perpendicular fields. This implies that it is the flux through the sample, rather than the field, that is important. This is an important feature of electron phase-coherent effects. However, if we insist on comparing this dip with what would be expected from weak localization, we again find that it is approximately two orders of magnitude larger than predicted.

The results for both the In/Ni/In and the Pb/Ni/Pb samples suggest that some sort of weak-localization- (WL-) like effect occurs in these structures. This conclusion is based on the *shape* of $R(H)$ near zero field, the rather small fields at which these dips occur, and the observation in figure 5 that it is the flux, rather than the field, that is important. We know of no other mechanism which leads to this distinctive form for $R(H)$, especially at such small fields. On the other hand, the magnitudes of the magnetoresistance dips are *much* larger than predicted by weak localization, and this makes an explanation in terms of WL problematic. The implausibly long phase coherence lengths inferred for the In/Ni/In samples are also very difficult to accept. It is interesting that some experiments on small superconducting–normal structures have been interpreted as being due to a greatly ‘enhanced’ WL-like effects [5, 14], and that such behaviour has also been predicted theoretically [15, 16, 17]. However, those experiments were performed (with one exception [18]) with normal metals such as Ag (i.e., nonferromagnets), and it has been suggested that the results may be due to the proximity effect [19]. Qualitatively, the results for our structures seem consistent with such an enhancement. Because we have used Ni for the normal metal, we would *not* expect our

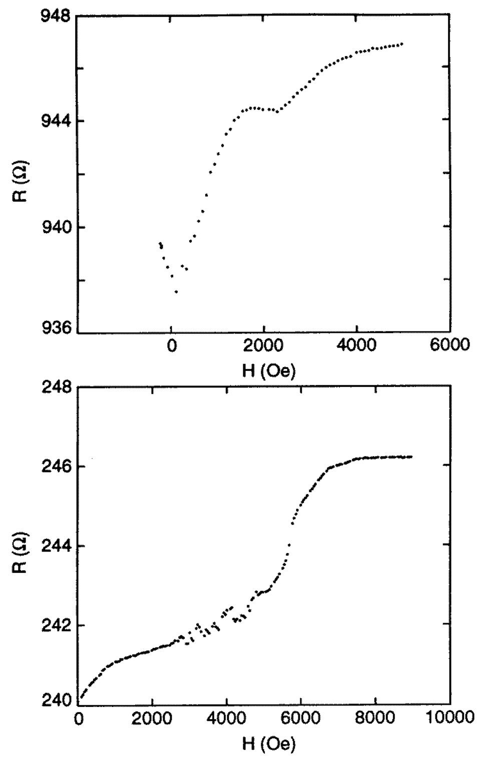

Figure 5. $R(H)$ for two Pb/Ni/Pb samples at 1.4 K. Top: $\boldsymbol{H}$ perpendicular to the plane of the film. The Ni strip was 1.5 μm wide, 21 μm long, and 200 Å thick. The contact regions were 1000 Å thick. Bottom: $\boldsymbol{H}$ parallel to the plane of the film, for the sample considered in figure 4.

results to be due to any sort of 'ordinary' proximity.

In summary, we have observed weak-localization-like effects in a very simple superconducting–normal-metal structure. However, the anomalies in $R(H)$ are two orders of magnitude larger than would be expected for conventional weak localization. The mechanism responsible for our results thus remains unclear.

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