Magnetoresistive oscillations in a doubly connected SFS interferometer with a ferromagnetic segment longer than the thermal coherence length

Yu N Chiang and O G Shevchenko

B Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of Ukraine, Kharkov, Ukraine

E-mail: chiang@ilt.kharkov.ua

Abstract. The conductance of ferromagnetic Ni samples of macroscopic length between F/S interfaces closed by a superconductor indium (an SNS system in the Andreev interferometer geometry) is investigated. The macroscopic size of the system makes it possible to measure directly the conductance of each of the elements of the branched Al circuit and to arrange conditions under which the contribution of side effects, reminiscent of the proximity effect, are minimal. The $\frac{hc}{2e}$ oscillations of the resistance with respect to magnetic field (the Aharonov–Bohm effect in disordered conductors), with an amplitude corresponding to the positive interference contribution to the resistance of an F/S interfacial region with a thickness of the order of the coherence length of the subgap excitations upon Andreev reflection in the presence of an exchange field typical for ferromagnetic materials (≈ 1 nm), are observed for the first time at lengths of the ferromagnetic segments exceeding the typical mesoscopic scale (≈ 1μm) by more than a factor of $10^3$.

Together with investigations of transport coherent phenomena in mesoscopic conductors, the use of macroscopic conductors for this same purpose is of alternative interest. This is due primarily to the possibility of eliminating the ambiguity in the estimated coherence length by using samples manifestly greater than any physically reasonable coherence length for metals. Furthermore, when one is investigating a branched system, in the case of macroscopic segment lengths one can measure their conductance directly. In mesoscopic branched systems the transport effects in the individual conductors are usually analyzed according to the behavior of the total conductance of the system, which represent a complex combination of the conductances of all its elements [1]. Of course, a macroscopic version of the experiment will require precision resolution of small effects.

An example of the results obtained from measurements of macroscopic samples are the results of direct four–contact measurements of the conductance of low–resistance (≈ $10^{-8}$ Ohm) wires of normal metals (Cu, Al, Ni) found in contact with a superconductor [2, 3], using high–resolution ($\leq 0.01\%$) potential difference measurement technique [4]. The change of the resistance of the wires, upon transition of the metal/superconductor (M/S) potential interfaces from the M/N to the M/S state was observed while potential interfaces were moved apart from each other to a distance of up to 1 mm, exceeding any possible coherence lengths in metals. This meant that the observed effect pertained not to the whole length of the wire, as could seem, but only to a limited part of it. From the character of the response in the conductance, the effect was the
direct opposite of the proximity effect. It was always manifested as an increase of the resistance \((R_{NS} > R_{NN})\) and was found to agree with the fundamental concepts of the theory \([5, 6]\). From this, in particular, it follows that the spatial scale of the proximity effect cannot be greater than that length.

Using the technique of precision measurements of small effects we investigated coherent effects in hybrid magnet/superconductor (SFS) systems with both conductors of much greater than mesoscopic length and Ni/In potential interfaces set a distance of 1 mm apart \([3]\). As in the case of nonmagnetic conductors, at the transition of the state of the interface \(F/N \rightarrow F/S\), the voltage between Ni/In potential interfaces increased every time.

The observation of the coherent effect in the SFS system settled the following question: Can effects sensitive to the phase of the order parameter in the superconductor be manifested in the conductance of ferromagnetic conductors of macroscopic size? The answer is yes.

Here we present the results of direct measurement of the conductance of two Ni conductors in a doubly connected SFS configuration (in the AI geometry). Nickel samples in the geometry shown in Fig. 1 were cut by the electrospark method from a single crystal with an elastic mean free path \(l_{el} \sim 1 \mu m\) \((RRR \approx 200)\). The technology used to fabricate the system, the F/S interfaces and the In superconducting bridges, and the technique of direct measurements of the individual segments of the system were the same as in \([3]\). The system was mounted in the end of a small lead shielded superconducting solenoid perpendicular to the direction of the field, which was calibrated beforehand by a field probe in the end of the solenoid. The elements of the measuring circuit and the system and solenoid were secondarily shielded by a superconducting shield. Under these conditions the instability of the field depended only on the instability of the solenoid supply current \(I_{sol}\). The absolute instability did not exceed \(\Delta I_{sol} = 5 \cdot 10^{-2} \mu A\) \((\Delta H = 5 \cdot 10^{-5} \text{ Oe})\) at any value of \(I_{sol}\). Measurements were made in the superconducting state of the In bridge for one of the samples at a temperature of 3.1 K and for the other at 3.2 K.

Fig. 2 shows the magnetic-field oscillations of the resistance of two samples in a doubly connected S/Ni/S configuration with different aperture areas, measured for the arrangement of the current and potential leads illustrated in Fig. 1. We present the results for two samples with

![Figure 1. Schematic view of the F/S system in the geometry of doubly connected "Andreev interferometer".](image)

![Figure 2. The \(hc/2e\) magnetic-field oscillations of the resistance of two ferromagnetic (Ni) conductors in AI–system Ni/In with an aperture area illustrated in Fig. 1 (dashed curve, left–hand scale, \(R_0 = 4.12938 \cdot 10^{-5} \Omega\)) and twice that area (solid curve, right–hand scale, \(R_0 = 3.09986 \cdot 10^{-6} \Omega\)).](image)
different steps in $H$ as typical results of several measurements, confirming the reproducibility of the period of the oscillations and its dependence on the aperture area of the interferometer.

The period of the resistive oscillations shown in Fig. 2, dashed curve, can be seen to be $\Delta H \approx (5/7) \cdot 10^{-4}$ Oe. It is observed, as follows from Fig. 1, at an interferometer aperture area $A \approx 3 \cdot 10^{-4}$ cm$^2$, measured from the midline of the segments and bridge. In a sample with twice the length of the sides of the interferometer and, hence, approximately twice the aperture area, the period of the oscillations turned out to be approximately half as large (solid curve in Fig. 2). From the values of the periods of the observed oscillations it follows that, to an accuracy of 20%, the periods are proportional to a quantum of magnetic flux $\Phi_0 = \hbar c/2e$ passing through the corresponding area $A$: $\Delta H \approx \Phi_0/A$. Here the relative amplitude of the oscillations for the two samples $\Delta R_{\text{max}}/R_L \approx 0.03\%$ and 0.01%, respectively, which corresponds to a relative value of the coherent effects measured independently in a configuration with open interfaces (see also [3]).

Obviously, the dependence of the conductance of the system on the magnetic flux means, in particular, that the conductance depends on the total length of the contour enclosing the magnetic flux. In our case this length actually corresponds to the macroscopic distances $L$ (the length of the dashed line in Fig. 1) between the Ni/S interfaces ($L \approx 0.7$ mm and $1.1$ mm, respectively, for the first and second samples). But oscillatory behavior of the conductance is possible if the phases of the electron wave functions are sensitive to the phase difference of the order parameter in the superconductor at the interfaces [7, 8]. Consequently, the memory of the order parameter in the superconductor at the interfaces [7, 8]. Consequently, the phase memory

$$L \sim L_\phi = \sqrt{D\tau_\phi} \gg \xi_T = \sqrt{\hbar D T}$$

($D$ is the diffusion coefficient, $\xi_T$ is the coherence length of the metal, over which the proximity effect vanishes, and $\tau_\phi$ is the dephasing time). In this regard it makes sense to make a qualitative estimate of the possible scale of $L_\phi$ for helium - temperature region. The value of the temperature contribution $\delta R_T$ to the resistance in this region in comparison with the residual resistance $R_0$ for metals with $l_{el} > 10$ $\mu$m ($D \sim 10^5$ cm$^2$/s) is usually of the order of $\delta R_T/R_0 \sim 10^{-3} - 10^{-4}$, and the electron-phonon relaxation time

$$\tau_{e-ph} \sim \frac{l_{el}}{v_F} \frac{1}{\delta R_T/R_0} \sim (10^{-7} - 10^{-8}) \text{ s},$$

while the electron-electron relaxation time $\tau_{e-e} \sim 10^{-8}$ s. Hence the possible phase breaking length at helium temperatures is $L_\phi = \sqrt{D\tau_\phi} \sim 0.3 - 1$ mm.

Under these conditions the nature of the observed oscillations is as follows. The electron–hole $e-h$ trajectories, arising in a doubly connected SFS system upon Andreev reflection, because of the Larmor curvature under the influence of the exchange field of the ferromagnet diverge to the trajectory thickness $\Lambda_B$ [3], i. e., lose coherence over a distance $\xi^* = \sqrt{2\lambda_B r_{\text{exch}}}$ from the interface [9] ($r_{\text{exch}}$ is the Larmor radius in the exchange field $H_{\text{exch}} \approx k_B T_c/\mu_B$ (for Ni $r_{\text{exch}} \approx 1$ $\mu$m); $T_c$, $k_B$, and $\mu_B$ are the Curie temperature, Boltzmann’s constant, and the Bohr magneton, respectively).

Since the trajectories of an e-h pair are spatially incoherent, their oscillatory contributions, proportional to the squares of the probability amplitudes, should combine additively:

$$|f_{h(i)}|^2 + |f_{e(k)}|^2 \sim \cos \phi_{e(k)} + \cos \phi_{h(i)} \sim \cos(\phi_0 + 2\pi \Phi/\Phi_0)$$

(1)

where $\phi_{e(k)}, \phi_{h(i)}$ are phase shifts for electrons and holes in the magnetic field (see, e. g., [10]); $\phi_0$ is the relative phase shift of the independent oscillations, equal to

$$\phi_0 = \frac{1}{2}(\phi_{0e} + \phi_{0h}) = \frac{\varepsilon_T}{\varepsilon_L} \frac{L_e + L_h}{2L}$$

(2)

where $\varepsilon_L = h v_F / L$, $\varepsilon_T = k_B T = \hbar D / \xi_T^2$. Hence it follows that any spatially separated $e$ and $h$ diffusion trajectories with $\phi_0 = 2\pi N$, where $N$ is an integer, can be phase coherent. Clearly this
requirement can be satisfied only by those trajectories whose midlines along the length coincide with the shortest distance \( L \) connecting the interfaces. In this case \( (L_0 + L_1)/2L \) is an integer \( m \), since \( L_{c(e,h)} \), \( L \sim l_{el} \) and \( (L_{c(e,h)}/L) = m(1 + \alpha) \), where \( \alpha \ll 1 \). Furthermore, \( (\varepsilon_T/\varepsilon_L)/2\pi \) is also an integer \( n \) to an accuracy of \( n(1 + \gamma) \), where \( \gamma \approx d/L \ll 1 \) (\( d \) is the transverse size of the interface). In sum, for all the trajectories considered

\[
\cos(\phi_0 + 2\pi \Phi/\Phi_0) \sim \cos(2\pi \Phi/\Phi_0). 
\]

This means that the contributions oscillatory in magnetic field from all the trajectories should have the same period. Taking into consideration the quasiclassical thickness of a trajectory, we find that the number of constructively interfering trajectories with different projections on the quantization area, those that must be taken into account, is of the order of \( l_{el}/\lambda_B \). However, the constructive interference of particles on these trajectories can be manifested only over the thickness of the segment \( \xi^* \), reckoned from the interface, where the particles of the e-h pairs are both phase- and spatially coherent. Accordingly, one can expect that the amplitude of the constructive oscillations will have a relative value of the order of

\[
\delta R^{c}/R_L \approx \xi^*/L \cdot \frac{l_{el}}{l^*_{el}} \sim \frac{l^*_{el}}{L} 
\]

\( (l^*_{el} \sim \lambda_B \ [3]) \), i. e., the same as the value of the effect measured with the superconducting bridge open. Our experiment confirms this completely: for the samples with the oscillations shown in Fig. 2, \( \delta R^{c}/R_L \approx 0.03\% \) and 0.01\%, respectively.

We note that in mesoscopic samples, as a rule, \( \xi^*/L \leq \xi^* \). In this case the contribution (4) can be comparable with the weak–localization correction (see, e. g., Ref. 11). If this is compared with the resistance of the whole segment in accordance with the rules of circuit theory, one obtains the same estimate as ours for the upper limit of the spatial scale for the proximity effect in the ferromagnets, which does not exceed the usual (singlet) scale for this effect (~1 nm).

In summary, we have investigated the conductance of two samples of ferromagnetic Ni of macroscopic length between F/S interfaces closed by a superconductor (indium) at helium temperatures. The configuration of the SFS system corresponded to the Andreev interferometer geometry. We have for the first time observed the \( hc/2e \) oscillations of the resistance in magnetic field in an Al with a ferromagnet segment of more than \( 10^3 \) times greater length than in mesoscopic structures. The oscillations observed in a disordered conductor of an SFS system of the order of 1 mm in length (the solid–state analog of the Aharonov–Bohm effect [12]) attests to a macroscopic scale of the diffusion dephasing length in sufficiently pure metals, including ferromagnetic ones, even at not too low helium temperatures.

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