Probing the electron-electron interaction in a diffusive gold wire using a controllable Josephson junction

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We have studied the critical current of a diffusive superconductor - normal metal - superconductor (SNS) Josephson junction as a function of the electron energy distribution in the normal region. This was realized in a 4 terminal device, in which a mesoscopic gold wire between two electron reservoirs is coupled in its center to two superconducting electrodes. By varying the length of the wire and applying a voltage over it we are able to control the electron distribution function in the center of the wire, which forms the normal region of the SNS junction. The observed voltage and temperature dependence are in good agreement with the existing theory on diffusive SNS junctions, except for low energies. However, an electron-electron interaction time \( \tau_0 = 10 \text{ ps} \) was found, which is three orders of magnitude faster than expected from theory.

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The study of electron-electron interaction in metals has attracted considerable attention recently. One of the reasons is an experiment performed by Pothier et al. \[1\] in which the electron distribution function in a mesoscopic wire connected to large electron reservoirs was measured using a superconducting tunnel junction. The shape of the distribution function depends, at low temperatures, on the effective electron-electron interaction experienced by the electrons, and the voltage \( V_c \) applied over the reservoirs. If the wire is short, the electrons will keep their energy while traversing the wire, and the distribution function will show a double step structure, with a separation between the steps of \( eV_c \). If the wire is much longer, so that the diffusion time \( \tau_D \) through the wire strongly exceeds the electron-electron interaction time \( \tau_0 \), then a local thermal equilibrium of the electron system will be regained with an effective temperature \( T_{\text{eff}} \), depending on \( eV_c \). The electron interaction time constant \( \tau_0 \) obtained from these experiments yields, assuming a local two particle interaction, \( \tau_0 \approx 1 \text{ ns} \) for copper, which is two orders of magnitudes faster than expected from theory \[3\].

On the other hand, it is in principle also possible to use a diffusive superconductor - normal metal - superconductor junction as a probe to study electron-electron interaction effects in a mesoscopic wire. The prediction is that \( I_c R_n \) product (critical current times normal state resistance) of such a SNS junction is very sensitive to the exact electron distribution function \[3\]. In this Letter we report experiments in which we studied the critical current of a SNS junction as a function of the electron distribution. This was realized using the device shown in Fig. 1. A diffusive gold wire (control channel) between two very large electron reservoirs is coupled to two niobium electrodes by means of a cross shaped extension in the center of the wire. We study two different device geometries, which differ only in the length of the control channel. We made 3 devices with a short control channel, \( L_{\text{control}} = 1 \mu\text{m} \), and two devices with a long control channel, \( L_{\text{control}} = 9 \mu\text{m} \). The behaviour of identical devices was similar, we therefore present only two devices in the remainder of the text: Device 1, with a short control channel and device 2 with a long control channel.

The devices are made by means of e-beam lithography using a double layer of PMMA resist and a subsequent lift-off process on top of a thermally oxidised Si wafer. The 100 nm wide control channel is evaporated first, which consists of 40 nm of gold on top of 5 nm
Ti, which was used to improve adhesion. Subsequently 70 nm of niobium was sputter deposited after an in-situ argon etching of the gold contacts to ensure a high interface transparency. In a last step the very thick (475 nm) gold reservoirs were deposited. The size of the reservoirs is in the order of a millimeter because they should also act as effective cooling fins to prevent unwanted electron heating \( [1] \). The gold has a diffusion coefficient of 0.020 m²/s which results in an estimated diffusion time through the channel of \( \tau_D = 50 \) ps. and 4 ns. for device 1 (\( L_{\text{control}} = 1 \mu m \)) and 2 (\( L_{\text{control}} = 9 \mu m \)) respectively. The SNS junctions all have a normal state resistance of 2.1 Ω, and a separation of the niobium electrodes of 375 nm.

In the experiment we measured the current-voltage (I-V) characteristics of the SNS junction as a function of both the voltage \( V_c \) applied over the control channel as well as the bath temperature \( T_B \). In the first case the bath temperature is kept at 100 mK to obtain a very sharp electron distribution function in the reservoirs. RC filtering at room temperature and copper powder filtering at the bath temperature are used in all measurements to reduce external noise and hence, unintentional heating of the electrons. From these measurements we obtained the critical current. In Fig. \( [2] \) we show the results. The voltage dependence of device 1, as shown in the bottom panel of the figure, shows the transition to a \( \pi \)-junction at control voltages \( V_c > 0.5 \) meV, similar to previous experiments \( [6] \). However, the maximum supercurrent in the \( \pi \)-state is much smaller than expected when assuming a perfect step distribution function. The top panel of Fig. \( [2] \) shows the results obtained in the limit of a thermal distribution function: The filled circles and squares represent the temperature dependence of the \( I_c R_n \) product of device 1 and 2 respectively. The empty squares represent the behaviour of the critical current of device 2 as a function of \( V_c \), expressed in terms of the effective temperature \( T_{\text{eff}} \), assuming a perfect thermalisation of the electrons in the wire \( [7] \). The effective electron temperature in the center of the control channel can now be calculated using the Wiedemann-Franz law \( [1] \):

\[
T_{\text{eff}} = \sqrt{T_B^2 + (a \cdot V)^2}
\]

with \( a = 3.2 \) K/mV. All curves show the expected monotonic decrease in \( I_c \) with increased temperature \( [8] \), and at higher temperatures all curves lay essentially on top of each other, with the exception that \( I_c R_n \) vs. \( T_{\text{eff}} \) (open squares) is somewhat larger than \( I_c R_n \) vs. \( T_B \) (solid squares) at higher temperatures. This indicates that \( T_{\text{eff}} \) increases slower with increasing \( V_c \) than expected, which is probably due to the onset of electron-phonon interactions at higher electron energies \( [9] \). This leads to an extra cooling of the electrons, and thus to a larger supercurrent. A very striking difference between both devices, which is counterintuitive and seems to be in disagreement with theoretical predictions \( [8] \), arises at low temperatures, \( T < 800 \) mK: device 1, with the lowest control channel length, and thus the strongest coupling to the normal reservoirs, shows a much higher \( I_c R_n \)-product (87 µeV), than device 2 (\( I_c R_n = 56 \) µeV), whereas one would expect a reduction in supercurrent with increased coupling to a normal reservoir. This observation is consistent with a previous experiment, which yielded an even higher \( I_c R_n \)-product for a system with an even stronger coupling to the normal reservoirs \( [7] \).

The next step in the analysis is to compare the data to the existing theory on diffusive SNS junctions. This theory predicts that supercurrent will be carried by a supercurrent carrying density of states, \( \text{Im}(J(\epsilon)) \), which can be calculated using the quasi-classical Green’s function theory \( [6] \). The positive and negative parts of the supercurrent carrying density of states, as shown in of Fig. \( [8] \), represent, at a given phase difference \( \pi/2 \), energy dependent contributions to the supercurrent in the positive and negative direction. The critical supercurrent now depends strongly on the occupation of this continuum of states, and thus on the electron distribution function in the normal region, and can be calculated according to

\[ I_c R_n \text{ as a function of temperature and voltage for both devices. The top panel shows the temperature dependence of device 1 (circles) and device 2 (filled squares), and the voltage dependence of device 2 (open squares) expressed in units of } T_{\text{eff}}. \text{ The bottom shows the voltage dependence of device 1. The best fits to the theory are given by the solid lines, assuming a distribution function as shown in the insets.} \]
where \( \text{Im}J(\epsilon) \) is the supercurrent carrying density of states and \( f(\epsilon) \) the electron distribution function. The transition to a \( \pi \)-junction in case of a perfect step function can be understood from this, for in this case the distribution function will be exactly 0.5 over a region \( eV_{c} \) around the Fermi energy, resulting in a zero contribution to the supercurrent over this energy range. At a large enough value of \( V_{c} \), its magnitude depending on \( E_{th} \), all positive contributions to the supercurrent will be blocked, which obviously changes the direction of the supercurrent.

\[
I_{c}R_{N} = \int_{-\infty}^{\infty} \frac{\partial}{\partial \epsilon}[1 - 2f(\epsilon)]\text{Im}(J(\epsilon))
\]

(2)

The results of the fits are shown by the solid lines in Fig. 2 in which the maximum value of the \( I_{c}R_{n} \)-product of device 1 was used as normalisation constant. The inset shows the distribution functions (in units of \( E/eV_{c} \)) in the limit where \( kT/eV_{c} \) of the reservoirs is constant. We found a value of the Thouless energy given by \( E_{th} \approx 21 \text{ meV} \), which is in good agreement with the expected \( I_{c}R_{n} \)-product of a diffusive SNS junction, \( \frac{I_{c}R_{n}}{E_{th}} = \pi \) [13], as well as the value reported in [3] for the cross geometry discussed here, \( \frac{I_{c}R_{n}}{E_{th}} = 5 \). The effective Nb electrode separation using this value of \( E_{th} \) is \( l=800\text{nm} \), which is in between the minimum Nb separation and the maximum extent of the gold under the Nb. It is clear from Fig. 3 that the agreement between the experiment and the calculations is excellent, apart from the low voltage region of device 2 discussed previously. However, from the insets is also clear that the shape of the distribution functions indicates a significant electron-electron interaction: The distribution function has a Fermi-Dirac shape in the case of device 2, which was expected, but it is also very rounded already in the case of device 1. This strong rounding is responsible for the small magnitude of the supercurrent in the \( \pi \) state. The interaction time constant \( \tau_{0} \) obtained from this analysis is device independent, and given by \( \tau_{0} \approx 10 \text{ ps} \). We have found that choosing a larger relaxation time constant in combination with another normalisation constant or another value of \( E_{th} \) does not yield reasonable and consistent fits for both devices. Moreover, the dependence of the \( I_{c}R_{n} \)-product on the control voltage is extremely sensitive to the effective electron relaxation in the control channel, \( \tau_{D}/\tau_{0} \), and thus on the exact shape of the distribution function, as shown at the bottom of Fig. 4. Here the calculated distribution function as well as the resulting \( I_{c}R_{n} \) - \( V_{c} \) behaviour is plotted for 5 different distribution functions, using five different ratio’s of \( \tau_{0}/\tau_{D} \). It is clear that even small deviations from a thermal distribution function (curve b) results in a quite strong difference in the voltage dependence of the \( I_{c}R_{n} \)-product, even leading to the transition to a \( \pi \)-junction at relatively rounded distribution functions (curve c).

Up till now we have based our analysis on the assumption that \( \text{Im}(J(\epsilon)) \) is correct. However, the small values of the \( \pi \) supercurrent could in principle also be explained assuming a perfect step distribution function if the nega-
tive contributions to the supercurrent of $\text{Im}(J(\epsilon))$ would be smaller. This assumption yields the fit of the $I_c R_n$ vs. $V_c$ data of device 1 as shown in panel A of Fig. 4. However, if this form of $\text{Im}(J(\epsilon))$ is used to calculate the temperature behaviour, we get a strong disagreement between measurements and theory, as shown in panel B. We therefore conclude that the theory which describes the supercurrent as a function of the distribution function is in principle correct, except at low energies, for it fails to predict the difference in $I_c R_n$-product between the devices at low temperatures.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{The two top figures show a theoretical fit to both the voltage and temperature dependence of device 2, assuming a perfect step distribution function and, as a result, smaller negative contributions in $\text{Im}(J(\epsilon))$. The bottom figure shows the strong dependence of the $I_c R_n$ vs. $V_c$ behaviour on the effective electron-electron interaction in the control channel, $\tau_0/\tau_D$. The inset shows the corresponding distribution functions. $\tau_0/\tau_D$: a) 0, b) 0.1 c) 0.2 d) 0.4 e) 1.}
\end{figure}

On the other hand, the value of $\tau_0$ implies an upper bound for the quasiparticle lifetime, valid over the energy range of these experiments (0.01 - 1.8 meV), given by $\tau(E) < \tau_0/\ln(E/0.01 \text{ meV})$. This yields a maximum quasiparticle lifetime, at $E=0.01 \text{ meV}$, given by $\tau_{e-e} \sim 10$ ps. However, the electron out scattering time can be calculated using the existing theory on electron-electron interactions in a diffusive 1D wire, according to [2-4]:

$$\tau_{e-e}(E) = \sqrt{2 \pi n_0 S} \sqrt{\frac{\hbar D}{E}}$$

with $n_0$ the density of states around the Fermi level, and $S$ the area cross section of the wire. However, this yields, using $n_0=1.9 \cdot 10^{28} \text{ m}^{-3}\text{eV}^{-1}$, $\tau_{e-e}(0.01 \text{ meV})=80$ ns, a difference of three orders of magnitude with our result. We note that experiments on similar wires using superconducting tunnel junctions [16] give a a value of $\tau_0$ 1 ns and 0.1 ns for copper and gold respectively. The difference between our data and these measurements can be explained by the fact that we used a thin Ti adhesion layer (which has a very fast phase relaxation at low temperatures, caused by electron-electron interaction [13]). Alternatively the strong coupling between the niobium and the gold in the junction might influence the electron interaction. However, the difference with the existing theory [4] is more than 3 orders of magnitude, which can hardly be explained using such arguments. Very recently [17] the experimental procedure of Ref. [10] to obtain the electron distribution was questioned, as well as the method discussed here [13]. The prediction is that the shot noise in the control channel associated with the non-equilibrium distribution function yields a smearing of the density of states in the superconducting electrodes, resulting in a supercurrent reduction. Our observations are not in agreement with the predicted [18] behaviour of $I_c$ vs. $V_c$ (see bottom panel of Fig. 2). Also, assuming the theoretical value $T_0 \approx 80$ ns would result in a transition to a $\pi$-state of device 2 as well, which we did not observe in the experiment.

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