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ELECTRON LOCALIZATION AND SUPERCONDUCTIVITY IN 2D METALS

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Abstract. The magnetic field and temperature dependence of the resistance of thin Al films and Cu/Pb proximity layers has been investigated at temperatures higher than the superconducting transition temperature. The results are explained in the framework of weak localization and electron-electron interaction in the presence of superconducting fluctuations in two-dimensional disordered systems.

I. Introduction

During the past few years much attention has been paid to the non-metallic conduction in two-dimensional (2D) systems. Measurements of the low temperature electrical resistance of thin metal films [1-5] revealed new effects in these disordered systems. The sheet resistance $R_\square$ increases logarithmically with decreasing temperature and is characterized by an anomalous behaviour at small magnetic fields.

These results have been analysed in terms of two mechanisms: i) weak localization (WL) due to the localized nature of the electronic states in disordered 2D systems which influences the mobility of the electrons [6]; ii) the impurity induced electron-electron interaction (EEI) giving rise to a decrease in the density of states near the Fermi-level and therefore an increase in the resistance [7]. The magnitude of the corrections to $R_\square(T)$ as predicted by both theories are quite similar and it is therefore very difficult to discriminate between either mechanism by simple resistance versus temperature measurements. The experiments are further complicated by the presence of spin-orbit coupling and magnetic impurity scattering which strongly influence or completely suppress WL and lead to new anomalous effects in the resistance [8].

The different magnetic field dependence of WL and EEI [8-10] enables however an independent determination of each contribution. The characteristic properties of localization can be determined in rather small fields while the magnetoresistance (MR) due to the electron-electron interaction is either negligible or only present in large fields. The MR measurement of thin metal-

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lic films provides also an interesting method for determining characteristic scattering times of the conduction electrons such as the inelastic life-time $\tau_i(T)$, the spin-orbit coupling time τ_{so} and the spin-flip scattering time τ_s.

Another interesting aspect of the interaction effects is the interplay between localization and various types of phase transitions. Among these, the superconducting phase transition has been discussed by Maekawa et al. [11] and the influence of superconducting fluctuations (SF) by Larkin [12]. One of the conclusions of Maekawa et al. is that the superconducting transition temperature T_c is reduced by strong impurity scattering. This result seems to be consistent with experimental reports that T_c in a thin film is reduced as $R_\square$ is increased [13]. According to Larkin the scattering of electrons by SF in 2D systems also modifies the MR in weak fields and allows the derivation of the absolute value and temperature dependence of i) the effective superconducting interaction between the electrons and ii) the inelastic scattering time. These predictions have recently been verified in superconducting Al-films [14,15].

In this paper results are presented of the temperature and magnetic field dependence of $R_\square$ in Al-films and Cu/Pb proximity layers. The data analysis is done at temperatures far above Tc and at very low fields in contrast to previous SF experiments [16].

After a brief description of the theoretical models in § 2, the experimental results will be given and discussed in § 3.

II. Theory

According to the localization theory [6] the temperature dependence of the sheet resistance $R_\square$ is given by:

$$\frac{\Delta R_\square(T)}{R_\square^2} = -(\alpha p)\frac{e^2}{2\pi^2\hbar}\ln(T/T_o) \qquad (1)$$

where $\Delta R_\square(T) = R_\square(T) - R_\square(T_o)$. The value of the parameter α depends on the relative magnitude of the various scattering times. In the absence of spin-orbit and spin-flip processes $(\tau_i \ll \tau_{so}, \tau_s)\alpha = 1, \alpha = 0$ for $\tau_s \ll \tau_i, \tau_{so}$ and $\alpha = -1/2$ if $\tau_{so} \ll \tau_i, \tau_s$. The prefactor p arises from the temperature dependence of the inelastic scattering time for which generally $\tau_i \propto T^{-p}$.

In the presence of SF the localization effect is substantially changed.

According to Larkin [12] the prefactor α becomes $\alpha - \beta(T)$, where $\beta(T)$ is the SF parameter which is directly related to the effective superconducting interaction $g(T)$. In the case of attraction, $\beta(T)$ increases with decreasing temperature and diverges logarithmically at $T = T_c$.

The electron interaction theory [7] predicts also a logarithmic divergence of the resistance given by:

$$\frac{\Delta R_\square(T)}{R_\square^2} = -(1 - F)\,\frac{e^2}{2\pi^2\hbar}\,\ln(T/T_o) \qquad (2)$$

where $0 < F < 1$ is a screening factor which depends on the electron concentration. For metal films like Cu and Al the factor $F \simeq 0.5$ which indicates that $(1-F) \simeq 0.5$ is smaller than the experimental value $\alpha p \simeq 1$ to 2 for weak localization.

Distinction between WL and EEI effects can be achieved by MR measurements. In low perpendicular fields ($H < 0.1$ T) localization is characterized by an anomalous MR. When spin-orbit and magnetic impurity scattering is included, localization theory [8] predicts:

$$\frac{\delta R_\square(H,T)}{R_\square^2} = -\frac{e^2}{2\pi^2\hbar}\left[\frac{3}{2} f(H/H_1) - \frac{1}{2} f(H/H_2)\right] \qquad (3)$$

where

$$H_1(T) = (\hbar/4eD)(1/\tau_i(T) + 2/3\,\tau_s + 4/3\,\tau_{so})$$

$$H_2(T) = (\hbar/4eD)(1/\tau_i(T) + 2/\tau_s)$$

and $\delta R(H,T) = R_\square(H,T) - R_\square(0,T)$, $f(x) = \psi(1/2 + 1/x) + \ln(x)\psi$ is the digamma function, D is the diffusion constant. In eq. (3), it is assumed that the elastic scattering time τ_e is much smaller than τ_i, τ_{so} and τ_s. When spin-orbit effects are small ($\tau_i \ll \tau_{so}$) then a negative MR shows up at very low fields.

If superconducting fluctuations are taken into account an additional positive and temperature dependent MR appears which rapidly increases when T_c is approached. According to Larkin [12]:

$$\frac{\delta R_\square(H,T)}{R_\square^2} = \frac{e^2}{2\pi^2\hbar}\,\beta(T) f(H/H_2) \qquad (4)$$

An analysis of the experimental MR-data using eq.(3) and eq. (4) enables to determine τ_{so}, τ_s, $\tau_i(T)$ and $\beta(T)$.

It should be noted that for $H < 0.1$ T and $\tau_i > \hbar/k_B T$ the orbital effect of the electron-electron interaction on the MR can be neglected [17]. For $0.1 \text{ T} < H < 1$ T both WL and EEI contribute to the MR; for $H > 1$ T a positive MR proportional to H^2 (normal MR) or ln(H)(interaction MR) is present.

Finally, the temperature dependence of $R_\square$ at $H > 1$ is given by [18]:

$$\frac{\Delta R_\square}{R_\square^2} = -(1 - F/4)\,\frac{e^2}{2\pi^2\hbar}\,\ln(T/T_o) \qquad (5)$$

This interaction produces also a logarithmic rise of $R_\square$ with decreasing T.

III. Experimental results and discussion

The samples used are thin Al films or Cu/Pb proximity layers deposited at room temperature on glass substrates ($P < 10^{-6}$ Torr). The four-terminal dc resistance measurements were carried out on strips whose size (4.00 x 0.235 mm^2) was defined by photolytographic techniques [3].

We have measured $R_\square(T)$ and $R_\square(H,T)$ of Al films with thicknesses $d_{Al} \simeq 10$-20 nm and $1\ \Omega/\square < R_\square < 60\ \Omega/\square$. Fig. 1a shows the superconducting transition ($T_c = 1.82$ K) of a typical Al sample with R (4.2 K) = 8.15 $\Omega/\square$ and $d_{Al} = 9.5$ nm. The sharpness of this transition proves that the Al film is homogeneous on a scale determined by the superconducting coherence length ξ_{Al}, which is essential to perform a detailed comparison with the theoretical predictions. Due to SF the normal resistance value is only reached at $T \simeq 2T_c$. The fluctuation conductivity as well as its field dependence in the region $T_c < T < 2T_c$ has been studied intensively in dirty Al films [16]. We note that at $T > 2T_c$ (see expanded scale) there is still a finite fluctuation conductivity. This can be explained by the Maki-Thompson term which dominates the fluctuation conductivity far above T_c. The inflexion point observed around T = 10 K is due to the scattering by thermal phonons. A detailed comparison of $R_\square(T)$ with theory is therefore very difficult. Moreover additional mechanisms may cause a temperature dependent electron scattering. It was already pointed out that a strong perpendicular magnetic field completely destroys WL and SF effects. We nevertheless observe (see Fig. 1b) that at $H > 1$ T the resistance increases logarithmically with decreasing temperature. This is probably due to the presence of EEI at high fields

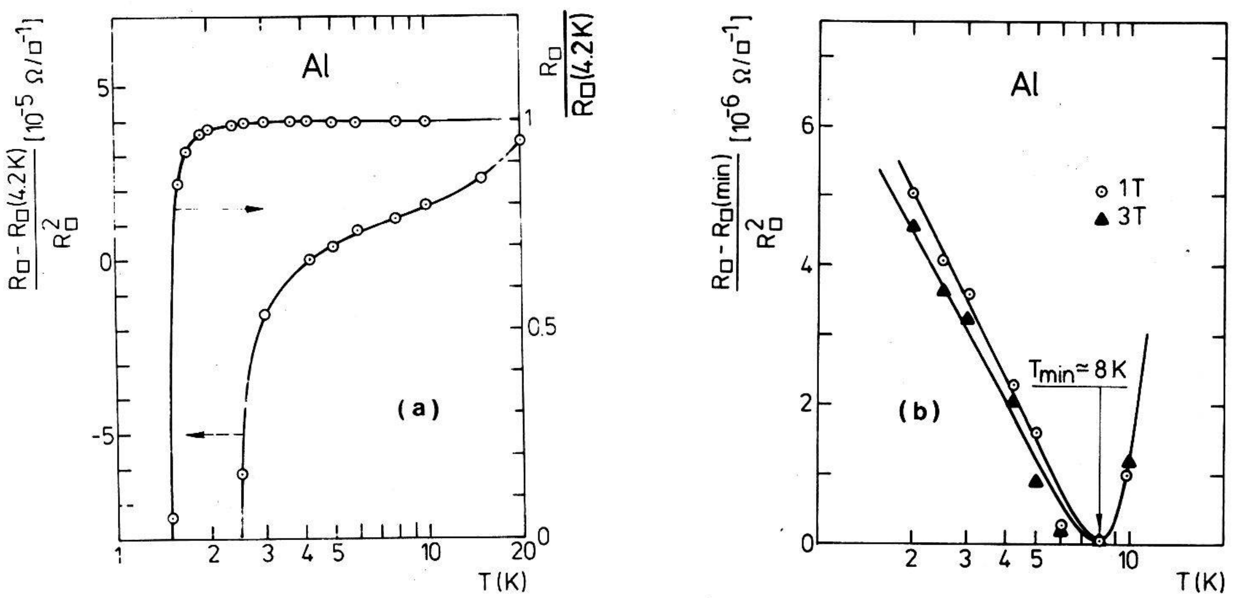

Figure 1: Normalized resistance vs temperature for an Al-film (d_{Al} = 9,5 nm, $R_{\square}$ = 8.15 $\Omega/\square$) at H = 0 (a) and H > 1 T (b)

as predicted by eq. (5).The experimentally observed slope of $R_{\square}$ versus T is in good agreement with theory if we assume that the screening factor $F \simeq 0.41$ for the Al film (free electron model $F \simeq 0.47$). We also studied the SF effect in Cu/Pb proximity systems. When d_{Cu} = 11 nm is kept constant, the strength of the superconducting order can be varied by changing the Pb thickness. Although the superconducting Pb film has an island-like structure, the proximity system may have a superconducting transition behaviour comparable to the one found in Al films. Moreover, the T_c for Cu/Pb films in the Cooper-limit is a unique function of the thickness ratio d_{Cu}/d_{Pb} [19]. A typical transition for a Cu/Pb layer with $d_{Pb} \simeq 7$ nm is shown in Fig. 2a. The temperature dependence of $R_{\square}$ above T_c = 1.6 K is similar to the one observed for Al films, including the inflexion point arount T = 10 K. When the mean thickness of the Pb film is decreased towards $d_{Pb} \simeq 6$ nm, a more complicated $R_{\square}(T)$-behaviour is observed (fig. 2b). The Cooper-limit model [19] predicts $T_c \simeq 1.4$ K, a value not confirmed by the data shown in fig. 2b (T_c < 0.5 K). A detailed analysis of R (T) above T ≃ 3 K (see fig. 2b) reveals a much broader transition than for the thicker Pb layer. This may be due to inhomogeneities on a scale defined by the superconducting coherence length. The maximum in the $R_{\square}$ versus T curve can qualitativelly be explained using the SF theory of Larkin: we have $\alpha - \beta(T) < 0$ for $T < T_{max}$ (SF dominate) and $\alpha - \beta(T) > 0$ for $T > T_{max}$ (WL dominates), while $\alpha \simeq \beta(T)$ for T ≃ 3.7 K.

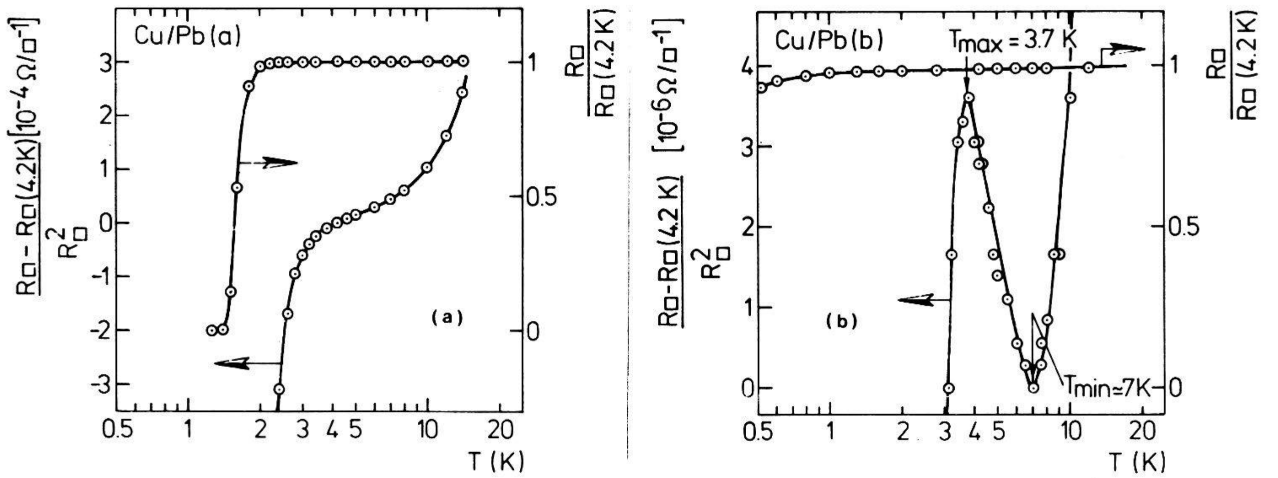

Figure 2: Normalized resistance vs temperature for Cu/Pb layers with (a) $R_{\square}$ = 12.4 Ω/□, $d_{Cu} \simeq$ 11 nm and $d_{Pb} \simeq$ 7 nm and (b) $R_{\square}$ = 10.3 Ω/□, $d_{Cu} \simeq$ 11 nm and $d_{Pb} \simeq$ 6 nm

The inflexion at T ≃ 7 K is again caused by phonon scattering.

Fig. 3 shows the $R_{\square}$ versus H curves at different temperatures for the 9.5 nm thick Al film. The full lines represent a theoretical fit using the sum of eq. 3 and eq. 4. Since Larkin assumes a field independent β-value a good agreement is only obtained at H $\lesssim 5.10^{-3}$ T. The temperature dependence of the experimental β-value (Fig. 5) is in very good agreement with Larkin's theory if the experimental T_c is used. The calculated τ_i follows approximately a T^{-2} power law (see insert of fig. 5). The MR data for the Cu/Pb(b) layer with d_{Pb} = 6 nm is shown in fig. 4. The agreement between theory (full curve) and experiment is good up to H ≃ 0.1 T, indicating a field independent β-value. The evaluated β(T) deviates however from Larkin's theoretical curve as shown in fig. 5. It should be noted that the experimental MR-data for the Cu/Pb system can only be fitted if a value for $T_c \simeq$ 1.4 K is used which is not in agreement with the $R_{\square}$(T)-measurement (T_c < 0.5 K). A possible explanation is that the superconducting order in the Cu/Pb system changes due to the fact that the mutual distance between the Pb islands is greater then the superconducting coherence length ($\propto l_{el}^{1/2}$). The temperature dependence of τ_i (insert fig. 5) does not follow at T^{-p} power law, indicating a complex inelastic scattering mechanism in the Cu/Pb system. Finally, the MR data yielded a value for $\tau_{so} \simeq 3.5 \times 10^{-13}$ sec, which is much smaller than the value $\tau_{so} \simeq 10^{-11} - 10^{-12}$ sec for pure Cu-films [5]. The enhancement of τ_{so} may be produced by the heavy Pb layer.

More experiments are required to analyse quantitatively the importance

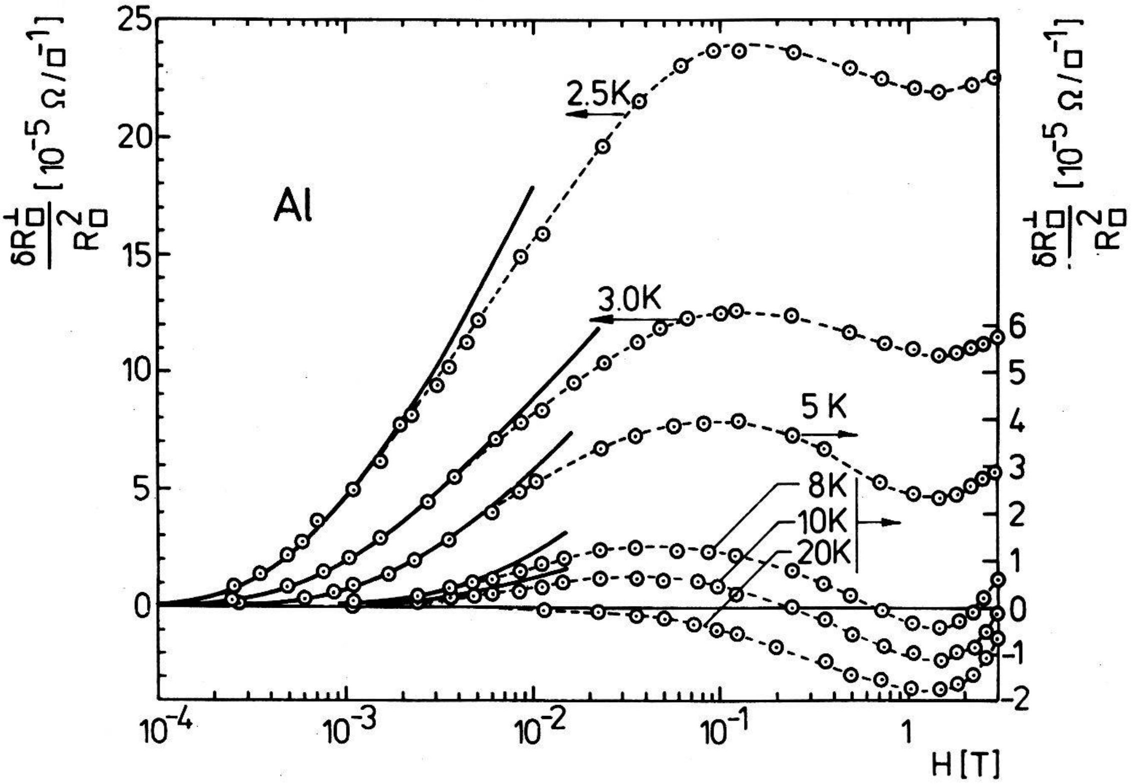

Figure 3: Magnetoresistance curves for the Al film with $R_{\square}$ = 8.15 Ω/□ at different temperatures. The full lines are calculated using eq. (3) and (4).

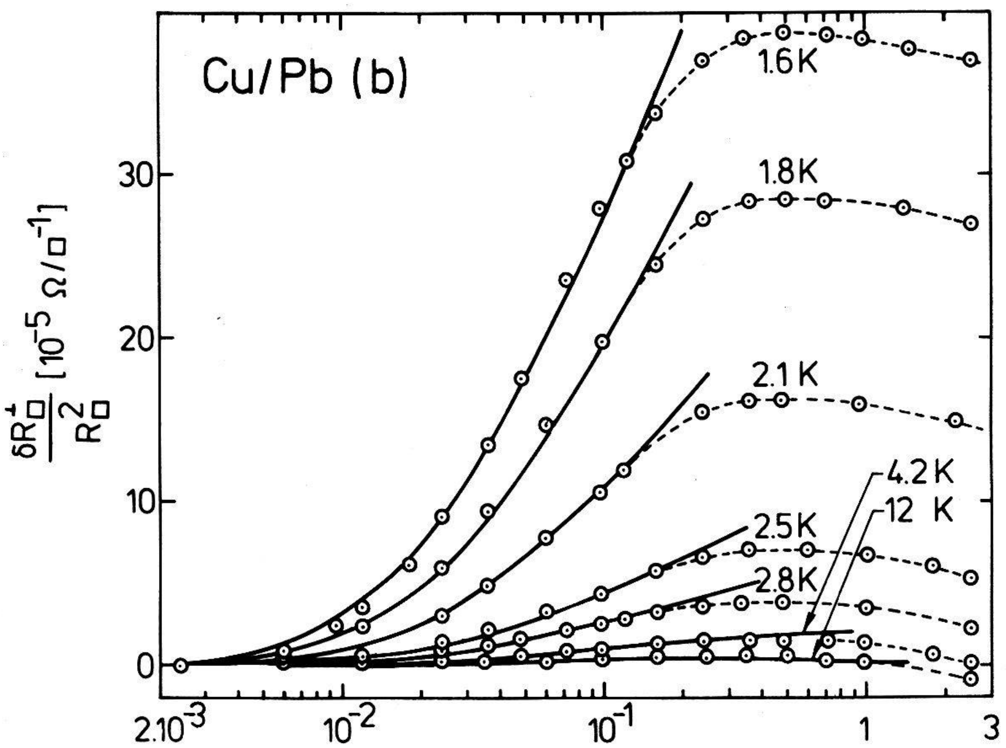

Figure 4: Experimental and theoretical magnetoresistance for the Cu/Pb (b) layer at different temperatures.

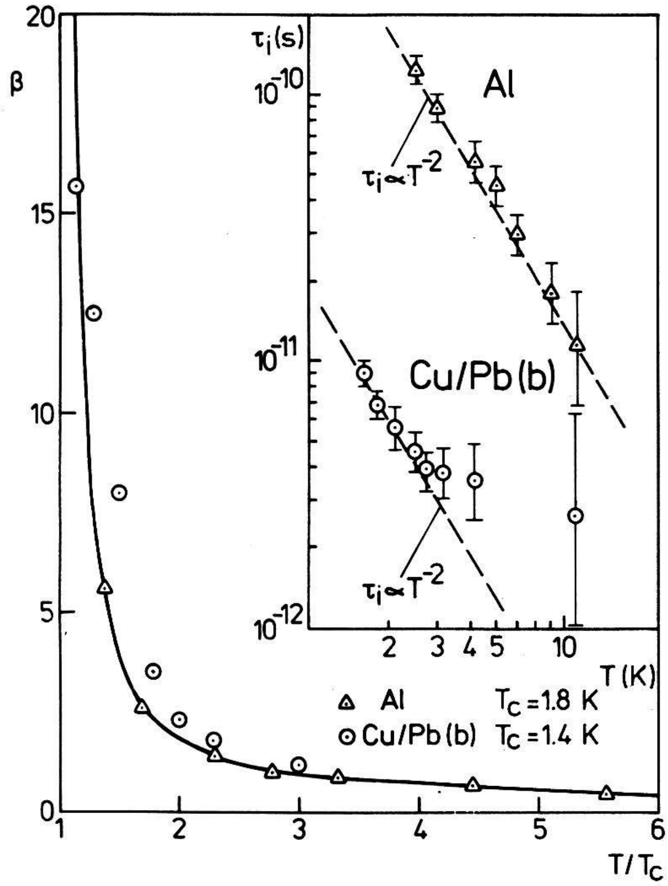

Figure 5: Temperature dependence of the superconducting fluctuation parameter β for the Al and Cu/Pb(b) samples. The solid line is calculated with the the theory of Larkin. The insert shows the $\tau_i(T)$ dependence.

of the different interaction mechanisms present in superconducting proximity systems. How all these effects depend on $R_\square$ also requires further study.

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