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Low temperature dephasing in irradiated metallic wires

Thibaut Capron[1], Yasuhiro Niimi[1], François Mallet[1], Yannick Baines[1], Dominique Mailly[2], Fang-Yuh Lo[3], Alexander Melnikov[3], Andreas D. Wieck[3], Laurent Saminadayar[1,†] and Christopher Bäuerle[1,†]

[1]*Institut Néel, CNRS and Université Joseph Fourier, B.P. 166, 38042 Grenoble, France*

[2]*Laboratoire de Photonique et Nanostructures, CNRS, route de Nozay, 91460 Marcoussis, France and*

[3]*Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität, Universitätsstraße 150, 44780 Bochum, Germany*

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We present phase coherence time measurements in quasi-one-dimensional Ag wires implanted with Ag^+ ions with an energy of $100\,keV$. The measurements have been carried out in the temperature range from $100\,mK$ up to $10\,K$; this has to be compared with the Kondo temperature of iron in silver, *i.e.* $T_K^{Ag/Fe} \approx 4\,K$, used in recent experiments on dephasing in Kondo systems[1,2]. We show that the phase coherence time is not affected by the implantation procedure, clearly proving that ion implantation process by itself *does not lead to any extra dephasing* at low temperature.

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The temperature dependence of the electronic phase coherence time in mesoscopic samples has been the subject of a heavy debate in recent years. This is due to the fact that the low temperature coherence time is related to the lifetime of the quasiparticles in a Fermi liquid, one of the main ingredients of Landau's Fermi Liquid theory. As the phase space available for electron diffusion (at the Fermi energy) crunches to zero at zero temperature, it sounds reasonable that the phase coherence time τ_ϕ of the electrons should diverge as the temperature T goes to zero. The frequent experimental observation of a saturating phase coherence time at low temperature in mesoscopic samples[3] has thus stimulated a lot of theoretical work in order to prove that it is intrinsic[4] or on the contrary related to extrinsic mechanisms[5–7]. Among several extrinsic mechanisms, the most obvious candidate is the diffusion by Kondo impurities.

Diffusion by magnetic impurities has been known for a long time to be an efficient mechanism for decoherence[8]. Comparison of experiment with theory has been difficult due to the absence of an adequate theory. In the past, the high ($T \gg T_K$), with T_K the Kondo temperature) and very low ($T \ll T_K$) temperature limit have been treated by theory[9]. Only very recently it has been possible to compare experimental results on the decoherence rate due to Kondo impurities with an exact theoretical calculation over all the temperature range from zero temperature to well above T_K. This important step has been made possible by the use of Numerical Renormalisation Group (NRG) technics by two different groups[12–15] and has led to a tremendous progress in the understanding of dephasing due to Kondo impurities. Indeed, recent experimental works[1,2,10,11] have confirmed the main features of the NRG calculation, using the Kondo systems Au/Fe and Ag/Fe. Due to the different Kondo temperatures of these two systems ($T_K^{Au/Fe} \sim 0.5K$; $T_K^{Ag/Fe} \sim 4K$), experiments could cover a temperature range extending from $\sim 5\,T_K$ down to $\sim 0.01\,T_K$. In almost the entire temperature range investigated, *the experiments have shown that the electron dephasing due to magnetic impurities is remarkably well described by a spin $S = 1/2$, single channel Kondo model.* This shows that magnetic impurities are perfectly screened when the temperature is lowered well below T_K.

Only at very low temperature $T \leq 0.1\,T_K$, small but significant deviations to the perfect $S = 1/2$ single channel Kondo model have been observed[1,2]. These deviations have been found to be proportional to the implanted magnetic impurity concentration. They must hence be due to the magnetic impurities themselves, or to the implantation process. It has been argued that they might be attributed to two levels systems created during the implantation of high energy ions: crystal defects would be created and some of them would be unstable. Such dynamical defects can indeed lead to decoherence even at very low temperature. On the other hand, it is well known that the Kondo temperature of a given system depends on the coupling constant between the magnetic ions and the conduction electrons; if some magnetic ions were in a position different than a lattice site, then this may lead to a Kondo effect with a different (and possibly much lower) Kondo temperature than the well known Kondo temperature of $4\,K$ of the bulk AgFe system. As these deviations are observed in the very low temperature regime where the Fermi liquid should be observed, it is of fundamental importance to understand whether these are due to the *magnetic* nature of the implanted ions or to the implantation process itself.

In this article, we present phase coherence time measurements in silver quantum wires implanted with silver ions in a temperature range from $10K \approx 4T_K^{Ag/Fe}$ down to $0.1K \approx 0.02\,T_K^{Ag/Fe}$. We show that no extra dephasing is observed when compared to the dephasing rate measured in the same but unimplanted sample. This rules out that the possibility of low temperature dephasing by dynamical two levels systems created during the implantation process and hence shows that the anomalous low temperature dephasing observed in references[1,2] is solely

due to the magnetic nature of the impurities.

Samples (see inset of figure 1) are fabricated on silicon substrate using electron beam lithography on polymethyl-methacrylate resist. No adhesion-layer has been used, and the silver has been evaporated in an electron gun evaporator from a 99.9999 % purity source. The electrical and geometrical parameters are summarized in table I.

Sample	l (μm)	R (Ω)	ρ ($\mu\Omega cm$)	D (cm^2/s)	dose ($ions/cm^2$)	n_s (ppm)
Ag_{Ag1}	270	1049	2.91	148	0	0
Ag_{Ag2}	310	1605	3.88	111	$2.5 \cdot 10^{13}$	70
Ag_{Ag3}	270	1549	4.30	100	$1.0 \cdot 10^{13}$	30

TABLE I: Sample characteristics: l, R, ρ, D and n_s correspond to the length, electrical resistance, resistivity, diffusion coefficient, and implanted Ag ion concentration, respectively. All samples have a width of $w = 150\,nm$ and thickness of $t = 50\,nm$. The diffusion constant has been calculated via equation $D = 1/3\, v_F\, l_e$, with v_F the Fermi velocity and l_e the mean free path.

All samples have been fabricated in a single evaporation run. Sample Ag_{Ag2} and samples Ag_{Ag3} have been ion implanted with Ag^+ ions at an energy of $100\,keV$ and a concentration $n_s = 70$ ppm and 30 ppm, while sample Ag_{Ag1} has been left unimplanted for reference.

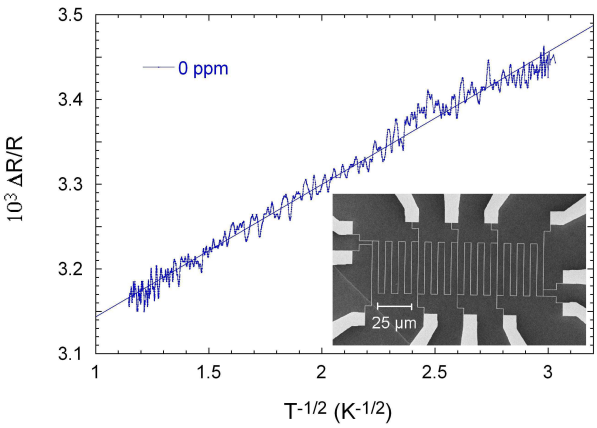

FIG. 1: Temperature dependence of the resistance at a field of B=540 mT, sufficient to suppress the weak localisation contribution. The solid line corresponds to a fit based on equation 1. The inset shows a scanning microscope micrograph of the sample.

Resistance measurements have been performed using a standard *ac* lock-in technique and a very low noise preamplifier ($0.4\,nV/\sqrt{Hz}$) situated at room temperature. At low temperature, the electrical resistance of a quasi one-dimensional wire is given by[16]:

$$R = R_0 + 0.782\,\lambda_\sigma\, R^2/R_K\, L_T/L \qquad (1)$$

where R_0 is the residual resistance, $L_T = \sqrt{\hbar D/k_B T}$ the thermal length and $R_K = h/e^2$; λ_σ a parameter which represents the strength of the screening of the interactions in the metal. Resistance of the sample Ag_{Ag1} as a function of $1/\sqrt{T}$ is depicted on figure 1: the experimental data follow nicely the theoretical prediction, proving that the electrons are indeed cooled down to the lowest temperature ($\sim 100\,mK$) of the experiment. From the fit to equation 1 we obtain a parameter $\lambda_\sigma = 3.77$, in relatively good agreement with the theoretical value $\lambda_\sigma^{theo} = 3.16$ as determined in previous measurements[8].

The phase coherence time is obtained by fitting the low field magnetoresistance to the standard weak localisation theory[18]. The magnetic field span is $\pm 4000\,G$ at temperatures above 1K and $\pm 400\,G$ at low temperatures. The spin-orbit length L_{so} is determined by fitting the magnetoresistance at high temperature and yields a value of $L_{so} = 330\,nm$. This value is then kept fixed for the entire fitting procedure and L_ϕ remains the only adjustable parameter.

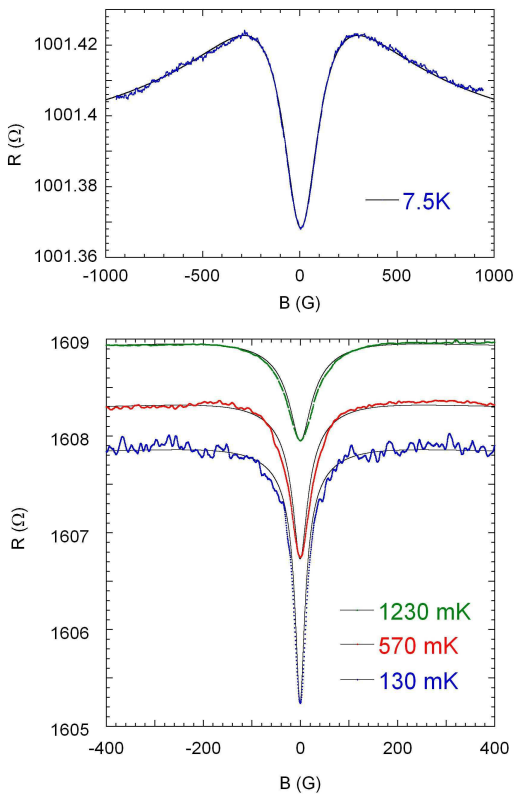

FIG. 2: Magnetoresistance of sample Ag_{Ag1} (top) and Ag_{Ag2} (bottom) for several temperatures. The data at high temperature (top) allows us to determine the spin-orbit length. The solid lines are fits to the standard weak localisation theory.

Several magnetoresistance curves for the unimplanted as well as implanted samples are displayed on figure 2. Agreement between experimental data and theoretical

fits is nearly perfect and allows us a reliable determination of the phase coherence length L_ϕ and subsequently of the phase coherence time *via* the relation $\tau_\phi = L_\phi^2/D$. For metallic wires containing no magnetic impurities, the phase coherence time is given by the formula:

$$\frac{1}{\tau_\phi} = \frac{1}{\tau_{e-e}} + \frac{1}{\tau_{e-ph}} \tag{2}$$

where

$$\frac{1}{\tau_{e-e}} = a_{theo}\, T^{2/3} = \left[\frac{\pi}{\sqrt{2}}\frac{R}{R_K}\frac{k_B}{\hbar}\frac{\sqrt{D}}{L}\right]^{2/3} T^{2/3} \tag{3}$$

corresponds to the Altshuler-Aronov-Khmelnitsky (AAK) expression for the electron-electron interaction term[16,17] and $1/\tau_{e-ph} = b\,T^3$ to the electron-phonon interaction term. From the fit of our data for the unimplanted sample, we obtain the experimental curve $\tau_\phi(T)$ depicted on figure 3 and experimental coefficients $a_{exp} = 0.56\,ns^{-1}K^{-2/3}$ and $b = 0.05\,ns^{-1}K^{-3}$. This has to be compared with the theoretical value $a_{theo} = 0.30\,ns^{-1}K^{-2/3}$. The agreement between the two values is quite good, although the experimentally observed dephasing time is obviously lower than the theoretically expected one. It must be stressed that this is quite a general feature of phase coherence time measurements obtained from weak localisation: even when the theoretical power law ($T^{2/3}$) is observed, the prefactor is always larger than the one expected from the standard AAK theory[8].

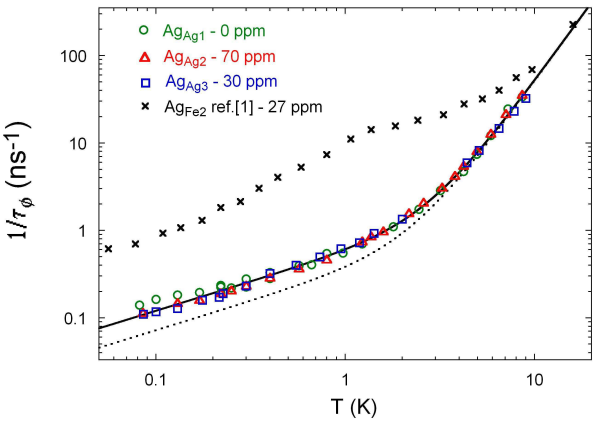

FIG. 3: Inverse of the phase coherence time as a function of temperature for samples Ag_{Ag1}, Ag_{Ag2} and Ag_{Ag3} as well as Ag_{Fe2} from ref.[1]. The solid line is the best fit to equation 2. The dotted line is the theoretical expectation for sample Ag_{Ag1}.

The same analysis can be made for the samples implanted with silver ions. The phase coherence time as a function of temperature is displayed on figure 3: within the error bars of our measurements, the experimental data follow nicely the theoretical expression of equation 2 with the same prefactors a_{exp} and b. More importantly, *the phase coherence time measured in the samples implanted with high energy silver ions has exactly the same value as in the unimplanted one.*

What can we infer from these findings? In very recent experimental works on dephasing in Kondo systems[1,2], it has been shown that the electronic phase coherence rate due to magnetic impurities γ_m is very well described by the $S = 1/2$, single channel Kondo model. In particular, the behavior of γ_m in a temperature range from above T_K down to $0.1\,T_K$ is extremely well described by the NRG calculations: this means that the physics of the screening process of the magnetic impurities by the surrounding conduction electrons is well captured by the theoretical model. At very low temperature, typically below $0.1\,T_K$, small but significant deviations from the theoretical predictions have been observed; these deviations are of importance, since they appear exactly in the temperature range for which one should recover the Fermi liquid behavior of the Kondo system. Different scenarii have been evoked to explain this anomalous behavior at very low temperature: first, it has been suggested that the disorder may lead to a distribution of the Kondo temperature over a certain temperature range[19], and as a consequence certain impurities may still be unscreened even well below $T/T_K^{Ag/Fe}$. Although plausible, the "weak" disorder present in our samples should lead to a very narrow distribution of the Kondo temperatures and therefore cannot account for the observed behavior.

Another and very plausible hypothesis is the creation of dynamical defects during the ion implantation process. Ion implantation is a relatively *violent* non-equilibrium process. During the random diffusion of the implanted ions, they create many defects along their trajectories inside the crystal. For instance, some silver atoms may be pushed away from their crystalline sites and may "oscillate" between two unstable positions. Such a dynamical two-levels systems (TLS) may be the origin of a very efficient mechanism for decoherence. As the characteristic energies of these two-levels systems should be widely distributed, they would lead to decoherence in a large temperature range.

To show that this scenario can be excluded, we represent in figure 4 the maximal contribution to dephasing of these hypothetical TLS. If there is an additional contribution to dephasing due to dynamical TLS, we can account for this by adding an additional term $(1/\tau_{TLS})$ in equation (2). In order to determine $\gamma_{TLS} \equiv (1/\tau_{TLS})$ we subtract the electron-electron contribution as well as the electron-phonon contribution, as indicated by the solid line in figure 3, exactly in the same way as has been done in reference[1] to obtain the magnetic decoherence rate. On the same figure we also plot the magnetic dephasing rate from recent experiments on AgFe quantum wires[1], as well as the NRG calculations for the spin 1/2, single channel model[13].

The maximum dephasing due to dynamical TLS lie more than an order of magnitude below the depasing rate

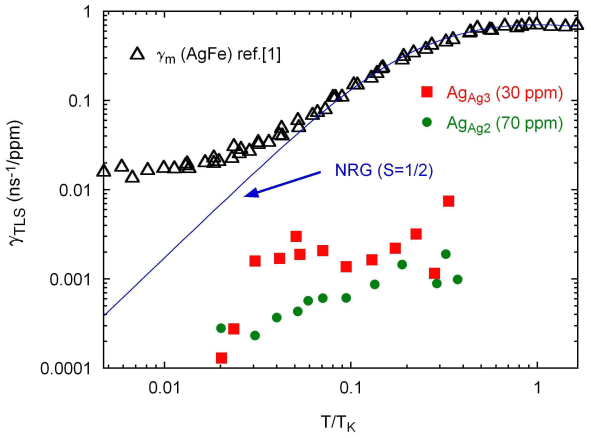

FIG. 4: Dephasing rate per implanted ion concentration of hypothetical TLS as a function of temperature. For comparison we also plot the magnetic dephasing rate of reference[1]. The solid line corresponds to the NRG data for spin 1/2 of reference[13]

γ_m obtained when Fe ions are implanted rather than Ag ions. In addition γ_{TLS} does not scale with the number of implanted Ag ions. It is therefore clear that our experiment definitely rules out this scenario and that the deviations from theoretical predictions observed in recent works can only originate from the magnetic nature of the implanted impurities.

In order to explain the experimentally observed deviations from the perfectly screened Kondo model one has to infer that a small fraction of the magnetic ions remains partially unscreened, even at the lowest temperature. The most probable scenario is that some of the implanted ions end up at a different lattice site or in an interstitial site inside the silver crystal compared to most of the implanted ions. The magnetic coupling with the conduction electrons of these magnetic ions would be different, and should lead to a much lower Kondo temperature. It is thus highly desirable to confirm this scenario by ab-initio calculations. Actually, from the magnetic decoherence rate observed at very low temperature, it can be estimated that a fraction of only 2 % of the impurities in such unconventional sites would be enough to produce the observed decoherence rate at very low temperature: this hypothesis sounds reasonable and may indeed explain the experimental data.

Finally we would like to point out that in a very recent theory a free magnetic moment phase is predicted for low dimensional disordered conductors[20]. When the magnetic coupling is small, local wave function correlations can leave some spins paramagnetic even at the lowest temperatures, and a finite dephasing rate at zero temperature would be expected. A quantitative analysis of such a scenario is in progress.

In conclusion we have measured the phase coherence time of silver quantum wires implanted with high energy silver ions. The phase coherence times measured in both the implanted and non-implanted wires exhibit the same temperature dependence, clearly proving that the implantation process by itself does not lead to any additional dephasing.

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† Mail to: `QuSpin@grenoble.cnrs.fr`

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