VOLUME 90, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 7 FEBRUARY 2003

Anomalous Temperature Dependence of the Dephasing Time in Mesoscopic Kondo Wires

Félicien Schopfer, Christopher Bäuerle, Wilfried Rabaud,* and Laurent Saminadayar
Centre de Recherches sur les Très Basses Températures, BP 166 X, 38042 Grenoble CEDEX 9, France

(Received 29 July 2002; published 3 February 2003)

We present measurements of the magnetoconductance of long and narrow quasi-one-dimensional gold wires containing magnetic iron impurities in a temperature range extending from 15 mK to 4.2 K. The dephasing rate extracted from the weak antilocalization shows a pronounced plateau in a temperature region of 300–800 mK, associated with the phase breaking due to the Kondo effect. Below the Kondo temperature, the dephasing rate decreases linearly with temperature, in contradiction with standard Fermi-liquid theory. Our data suggest that the formation of a spin glass due to the interactions between the magnetic moments is responsible for the observed anomalous temperature dependence.

DOI: 10.1103/PhysRevLett.90.056801 PACS numbers: 73.23.–b, 72.70.+m, 73.20.Fz, 75.20.Hr

The understanding of quantum coherence in metallic systems is one of the most important challenges in mesoscopic physics. This very fundamental problem addresses the "historic" question of the ground state of an electron gas at zero temperature [1] and is also relevant to the recent question of the possible realization of quantum computers. It is well known that the coupling of electrons to an environment is a very efficient source of decoherence. In metallic conductors, this coupling may be electron-electron interaction, electron-phonon interaction, or scattering by magnetic impurities. In the "standard" theory of metallic conductors [2], the dephasing rate, defined as $\gamma_\phi = 1/\tau_\phi$, where τ_ϕ is the dephasing time, is supposed to vanish at zero temperature, as both electron-electron and electron-phonon interactions go as simple power laws of the temperature T.

Recently, Mohanty *et al.* have suggested that the phase coherence time τ_ϕ saturates at low temperature, in contradiction with theoretical predictions [3]. Based on their own data on gold wires as well as several experiments of different groups, the authors claim that the observed saturation is universal. However, another experiment on pure silver and pure gold wires [4] shows that the standard theory is verified in these samples, while other experiments show that the low temperature behavior of the dephasing rate depends on the geometrical parameters of the sample [5]. It has been argued that the observed saturation of τ_ϕ may be due to inelastic coupling of the electrons to two-level systems [6]. On the other hand, an alternative and controversial interpretation of these experiments is that the observed saturation is indeed *intrinsic* and due to electron-electron interactions [7].

In this context, the understanding of the role of magnetic impurities is crucial. It is well known that in metals the interaction of conduction electrons with magnetic impurities gives rise to the Kondo effect [8]. The most widely studied consequence of this is the logarithmic increase of the resistivity of metals containing magnetic impurities below a certain temperature, the Kondo temperature T_K. The influence of Kondo impurities on the dephasing rate, on the other hand, is by far much less well understood: Although the scattering rate and the energy relaxation time have been addressed theoretically [9], it should be emphasized that these models are valid only strictly within the limit $T > T_K$. Below T_K, the interplay between the magnetic scattering and the screening of the magnetic impurities by the surrounding conduction electrons, the Kondo cloud, is certainly an important source for new physical phenomena. This points out the crucial need for new experiments relating the Kondo effect and the dephasing time at low temperatures.

In this Letter, we report on the temperature dependence of the magnetoresistance and resistivity of quasi-one-dimensional (1D) long and narrow Au/Fe Kondo wires down to 15 mK. We show that the dephasing rate due to Kondo impurities scattering exhibits a maximum around T_K. Below T_K, the dephasing rate continues to decrease, but does not follow the prediction of standard Fermi-liquid theory. We show that, in this new regime below T_K, the dephasing rate varies linearly with temperature and that the interactions between the magnetic moments are responsible for the observed anomalous temperature dependence.

The samples are fabricated on silicon substrate using electron beam lithography on polymethyl-methacrylate resist. The metal is deposited using a Joule evaporator and lift-off technique. A 1 nm thin titanium layer is evaporated prior to the gold evaporation in order to improve adhesion to the substrate. For the gold evaporation, we use two sources of 99.99% purity with different iron impurity concentrations. Since any chemical analysis is impossible on such small samples, we determine the actual iron impurity concentration via the resistance increase at low temperature due to the Kondo effect. Such a method has the advantage that we directly characterize the purity of the samples, which may be quite different from the purity of the sources. The Au/Fe Kondo system is chosen for the following reasons: Besides being one of the most extensively studied bulk Kondo systems, it has a Kondo temperature sufficiently low to ensure that electron dephasing

0031-9007/03/90(5)/056801(4)$20.00

TABLE I. Sample characteristics at 15 mK.

Sample	w (nm)	t (nm)	L (μm)	R (Ω)	D (cm^2/s)	l_e (nm)	l_T (μm)
A	150	45	450	4662	55.6	12.0	1.67
B	150	45	450	2236	115	24.9	2.42

is only weakly affected by electron-phonon scattering and sufficiently high to be able to perform measurements down to temperatures well below T_K. Gold as the host metal also avoids problems with surface oxidation: This has been verified by remeasuring the samples after six months of being exposed to air, and no measurable change has been observed. The characteristics of the two representative samples presented here are given in Table I. The dimensions of the samples are chosen such that they are quasi-1D with respect to both the phase-breaking length $l_\phi = \sqrt{D\tau_\phi}$ and the thermal length $l_T = \sqrt{\hbar D/k_B T}$, D being the diffusion constant, $D = 1/3 v_F\, l_e$.

All the measurements have been carried out using a standard ac resistance bridge with a current down to 2 nA for the lowest temperatures. Extreme care has been taken to filter external radio-frequency noise: π filters are placed at the top of the cryostat and electrical lines are made of high-loss coaxial cables [10], leading to an attenuation of 420 dB at 20 GHz. The phase coherence length l_ϕ is deduced from magnetoresistance measurements using standard weak localization theory [11], where we fix the spin orbit scattering length to 50 nm, determined at $T > 1$ K. The coherence time is then obtained from $\tau_\phi = l_\phi^2/D$. The temperature dependence of the phase coherence time as well as the electrical resistivity after subtraction of the electron-electron contribution for the two samples are displayed in Figs. 1 and 2. For the resistivity measurements, a magnetic field of 200 mT is applied to suppress weak localization. Both samples exhibit a logarithmic increase of the resistivity below 1 K, a clear signature of the Kondo effect [12]. The temperature dependence of the electrical resistivity is fitted using Hamann's law [13]: From these fits, we extract a Kondo temperature of 300 mK and an impurity concentration of 60 ppm and 15 ppm for sample A and sample B, respectively [14]. At very low temperature, the resistance starts to saturate and subsequently decreases: This behavior is associated with the freezing of the magnetic moments into a spin-glass state [15]. To our knowledge, this is the first time that a spin-glass transition is observed in such a diluted mesoscopic Kondo system where weak localization is accessible. The phase coherence time depends in a similar way on the temperature as the resistivity. The plateau observed for τ_ϕ in the temperature range between 300–800 mK is associated with the electron dephasing due to Kondo impurities [16,17]. At temperatures below T_K, τ_ϕ increases again: This is expected as soon as the magnetic impurities become screened by the surrounding conduction electrons and at low enough temperatures standard Fermi-liquid theory [18] should again describe the temperature dependence of τ_ϕ. However, at temperatures well below T_K, τ_ϕ saturates and the Fermi-liquid theory clearly does not describe our experimental data. We rule out heating effects for the observed saturation of τ_ϕ at low temperature for the following reasons: (i) We have carefully checked the dependence of the phase coherence time as a function of applied current and no heating effect has been observed for currents below 8 nA; (ii) the downturn of the resistance at the lowest temperatures, associated with the freezing of the magnetic impurities into a spin-glass, clearly shows that the electrons are cooled to these low temperatures; (iii) the temperature of the resistance maximum is consistent with data from the Au/Fe Kondo system [15].

An explanation of the observed saturation at low temperature of τ_ϕ, however presently very controversial, is

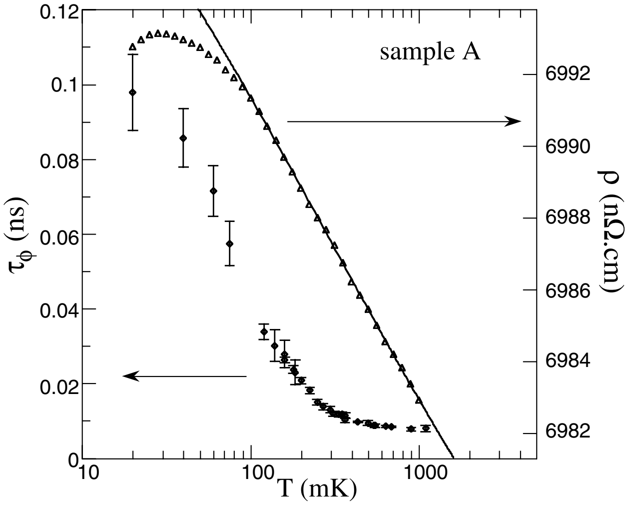

FIG. 1. Resistivity and phase coherence time as a function of temperature. The sample contains 60 ppm of Fe impurities.

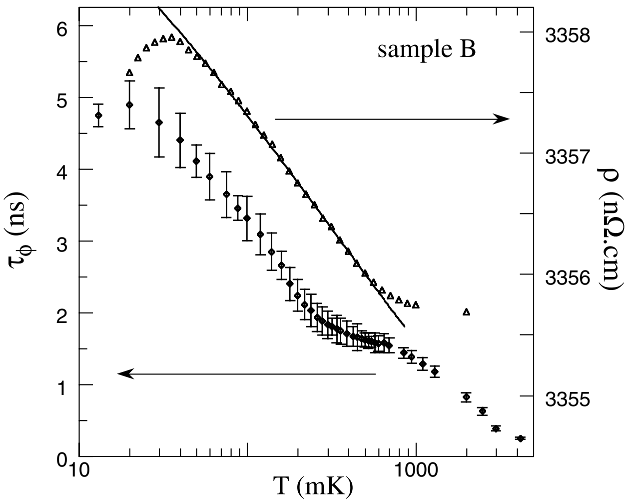

FIG. 2. Resistivity and phase coherence time as a function of temperature. The sample contains 15 ppm of Fe impurities.

the possible existence of zero temperature dephasing due to electron-electron interactions [7]. Following this model, it is interesting to plot γ_ϕ as a function of temperature on a linear scale as shown in Figs. 3 and 4: γ_ϕ varies linearly with temperature over the entire temperature range below T_K for both samples. In this respect, it is tempting to compare our data with the formula $\gamma_\phi = \gamma_{\phi_0} + \alpha T$ of Ref. [7]. From our measurements, we find $\gamma_{\phi_0} = 0.2\ \mathrm{ns}^{-1}$ and $\alpha = 0.7 \times 10^{-3}\ \mathrm{ns}^{-1}\,\mathrm{mK}^{-1}$ for sample B, whereas the theoretical values, using the geometrical parameters and the experimental value of γ_{ϕ_0} of our samples, are $0.7\ \mathrm{ns}^{-1}$ and $1.0 \times 10^{-3}\ \mathrm{ns}^{-1}\,\mathrm{mK}^{-1}$. The agreement found is reasonable. For sample A, the very high concentration of magnetic impurities, on the other hand, clearly disallows any comparison with such a model: In this case, the main decoherence mechanism is due to magnetic scattering, which is not included in this model. Only the γ_{ϕ_0} factor is meaningful, and we find an experimental value of $10\ \mathrm{ns}^{-1}$ versus a theoretical value of $7\ \mathrm{ns}^{-1}$.

It must be stressed that a complete description of our experimental data has to be done in the framework of the Kondo effect. To our knowledge, the problem of phase coherence in this regime at temperatures below T_K has not been addressed theoretically. Only the unitary limit, where the magnetic impurities are completely screened, can be described by Nozières Fermi-liquid theory [18]. Such a limit can be reached only if the impurity concentration is very low; otherwise, a spin-glass transition will occur and the unitary limit is never reached. The crucial question is then: How efficient are these partially screened magnetic impurities for dephasing? To get an insight into this question, let us try to separate the magnetic contribution from the total dephasing rate. The phase-breaking rate is given by $\gamma_\phi = 2\gamma_s + \gamma_{nm}$, where γ_s is the spin scattering rate and γ_{nm} the nonmagnetic scattering rate [17]. The spin scattering rate can then be obtained by subtracting γ_ϕ measured in samples containing no magnetic impurities. We assume a temperature dependence for γ_{nm} given by $\lambda T^{2/3} + \mu T^3$, which is justified from measurements on extremely pure gold wires [4]. Coefficient $\lambda = 0.8(0.6)\ \mathrm{ns}^{-1}\,\mathrm{K}^{-2/3}$ is calculated using the parameters of sample A (B) and coefficient $\mu = 0.04(0.04)\ \mathrm{ns}^{-1}\,\mathrm{K}^{-3}$ is obtained by fitting the data at high temperatures. It should be noted that the exact value of these parameters is not very crucial for the analysis. In Fig. 5, we plot the spin scattering rate obtained for samples A and B. Both samples exhibit a maximum of γ_s around T_K [16,17]. For sample B, γ_s decreases with a temperature dependence close to $T^{1/2}$ below the maximum [19,20], whereas for sample A, the maximum is shifted to higher temperatures and the slope of the subsequent decrease is steeper due to the higher impurity concentration [20]. In neither case the T^2 dependence of γ_s of Nozières Fermi-liquid theory [18] nor the $1/\ln^2(T_K/T)$ dependence for the incomplete screened case is observed [21].

At lower temperatures, the spin scattering rate saturates for both samples and is basically constant down to the lowest temperature. It is well known that RKKY interactions between magnetic impurities lead to the formation of a spin glass. Spin-spin correlations affect drastically the electronic spin scattering rate: Freezing of magnetic moments into a spin-glass state violates time reversal symmetry, hence leading to a very efficient dephasing mechanism. The change in the temperature dependence of γ_s can thus be associated with the appearance of spin-spin correlations between the magnetic impurities. This can also be seen from the resistivity curve: The departure from the logarithmic behavior appears approximately at the same temperature as the change in the temperature dependence of γ_s.

In fact, a constant spin scattering rate is expected for the spin freezing into a Heisenberg spin glass [22]. In this case a reduction of the scattering rate by a factor of $S/(S+1)$ compared with the free-magnetic moment

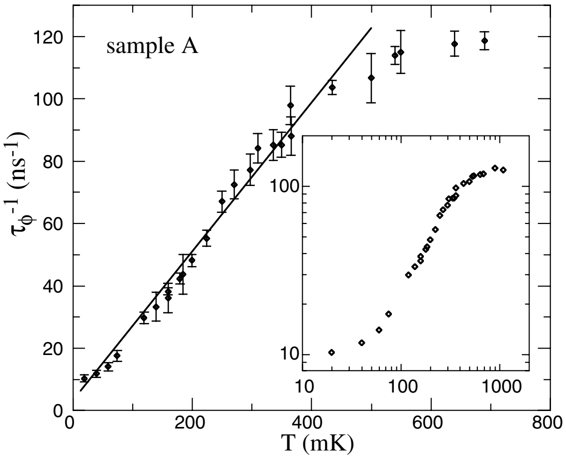

FIG. 3. Dephasing rate in the low temperature range: The straight line is a guide for the eyes. Inset: Dephasing rate over the entire temperature range on a log-log plot.

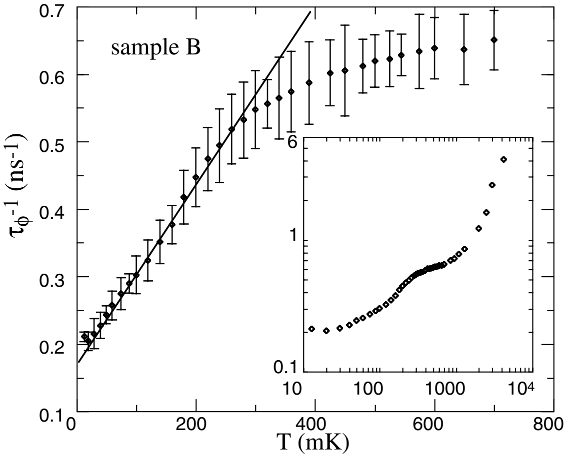

FIG. 4. Dephasing rate in the low temperature range: The straight line is a guide for the eyes. Inset: Dephasing rate over the whole temperature range on a log-log plot.

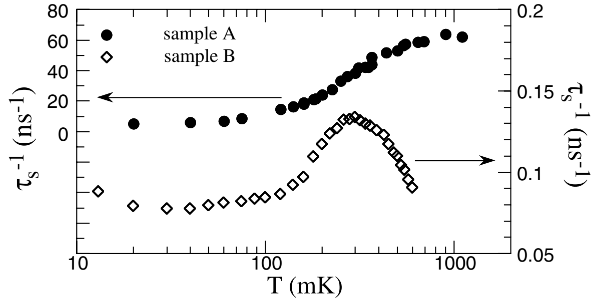

FIG. 5. Magnetic scattering rate for sample A and sample B obtained by subtraction of the standard dephasing rate from the data of the insets of Figs. 3 and 4.

system is predicted [22] in good agreement with sample B. The ratio obtained from the maximum of γ_s and its saturation value, however, varies strongly with the magnetic impurity concentration. This strong concentration dependence of both the reduction of the scattering rate and the saturation value suggests that the interplay between the Kondo effect and RKKY interactions is enhanced in samples with higher impurity concentration.

Our results clearly show that RKKY interactions, associated with the spin-glass freezing, lead to a constant spin scattering rate and, hence, yield a finite phase coherence time at very low temperatures in any system containing even a very small amount of magnetic impurities. The understanding of the electron dephasing in the temperature range below T_K is certainly a challenge for theory, but is probably the key point to interpret properly the experiments carried out on metals as they often contain magnetic impurities on the ppm level at best, with Kondo temperatures in the mK temperature range. Measurements at lower temperature on samples with very low concentration of impurities, well in the unitary limit, would also be of great interest. In this case all magnetic impurities are completely screened, and the standard Fermi-liquid behavior should be recovered. This would be the key test to discriminate between intrinsic dephasing and dephasing due to Kondo impurities.

In conclusion, we have measured the dephasing rate in quasi-1D gold wires containing iron impurities down to temperatures of 15 mK. Below the Kondo temperature, the dephasing rate varies linearly with temperature, clearly in contradiction with standard Fermi-liquid theory. Our measurements suggest that a constant spin scattering rate, associated with the formation of a spin-glass, is responsible for the observed saturation of the phase-breaking rate at low temperature.

We gratefully acknowledge L. Glazman, A. Zaikin, L. P. Lévy, O. Laborde, J. Souletie, P. Mohanthy, H. Pothier, A. Benoît, and F. Hekking for fruitful discussions. Samples have been made at NanoFab, CRTBT-CNRS. Part of this work has been performed at the "Ultra-Low Temperature Facility-University of Bayreuth" within a TMR project of the European Community (ERBFMGECT-950072). We are indebted to G. Eska, R. König, and I. Usherov-Marshak for their assistance.

---

*Present address: Department of Physics, University of Maryland, College Park, MD 20742-4111.

[1] D. Pines and P. Nozières, *The Theory of Quantum Liquids* (Benjamin, New York, 1966).
[2] B. L. Altshuler, A. G. Aronov, and D. E. Khemelnitskii, J. Phys. C **15**, 7367 (1982).
[3] P. Mohanty, E. M. Q. Jariwala, and R. A. Webb, Phys. Rev. Lett. **78**, 3366 (1997).
[4] F. Pierre, H. Pothier, D. Estève, M. H. Devoret, A. B. Gougam, and N. O. Birge, in *Kondo Effect and Dephasing in Low-Dimensional Metallic Systems*, edited by V. Chandrasekhar, C. van Haesendonck, and A. Zawadowski (Kluwer, Dordrecht, 2001), pp. 119–132.
[5] D. Natelson, R. L. Willett, K. W. West, and L. N. Pfeiffer, Phys. Rev. Lett. **86**, 1821 (2001).
[6] Y. Imry, H. Fukuyama, and P. Schwab, Europhys. Lett. **47**, 608 (1999); A. Zawadowski, J. van Delft, and D. C. Ralph, Phys. Rev. Lett. **83**, 2632 (1999); V. V. Afonin, J. Bergli, Y. M. Galperin, V. L. Gurevich, and V. I. Kozub, Phys. Rev. B **66**, 165326 (2002).
[7] D. S. Golubev and A. D. Zaikin, Phys. Rev. Lett. **81**, 1074 (1998); D. S. Golubev, A. D. Zaikin, and G. Schön, J. Low Temp. Phys. **126**, 1355 (2002).
[8] J. Kondo, Prog. Theor. Phys. **32**, 37 (1964).
[9] M. B. Maple, in *Magnetism V*, edited by G. T. Rado and H. Suhl (Academic, New York, 1973), Vol. V, p. 289; A. Kaminski and L. I. Glazman, Phys. Rev. Lett. **86**, 2400 (2001).
[10] A. Zorin, Rev. Sci. Instrum. **66**, 4296 (1995).
[11] S. Hikami, A. I. Larkin, and Y. Nagaoka, Prog. Theor. Phys. **63**, 707 (1980).
[12] V. Chandrasekhar, P. Santhanam, N. A. Penebre, R. A. Webb, H. Vloeberghs, C. Van Haesendonck, and Y. Bruynseraede, Phys. Rev. Lett. **72**, 2053 (1994).
[13] D. R. Hamann, Phys. Rev. **158**, 570 (1967).
[14] We use formula (4.3) of Ref. [13]. Note that the values for c given in the literature may vary by a factor of 2.
[15] O. Laborde and P. Radhakrishna, Solid State Commun. **9**, 701 (1971); G. Frossati, J. L. Tholence, D. Thoulouze, and R. Tournier, Physica (Amsterdam) **84B**, 33 (1976).
[16] R. P. Peters, G. Bergmann, and R. M. Mueller, Phys. Rev. Lett. **58**, 1964 (1987).
[17] C. van Haesendonck, J. Vranken, and Y. Bruynseraede, Phys. Rev. Lett. **58**, 1968 (1987).
[18] P. Nozières, J. Low Temp. Phys. **17**, 31 (1974).
[19] R. P. Peters, G. Bergmann, and R. M. Mueller, Phys. Rev. Lett. **60**, 1093 (1988).
[20] W. Wei, R. Rosenbaum, and G. Bergmann, Phys. Rev. B **39**, 4568 (1989).
[21] M. G. Vavilov and L. I. Glazman, cond-mat/0210507.
[22] W. Wei, G. Bergmann, and R. P. Peters, Phys. Rev. B **38**, 11751 (1988).