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Quantum coherence and magnetic scattering

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Abstract: The time τ_ϕ over which an electron can maintain its phase coherence at low temperatures is of fundamental importance in mesoscopic systems. The observability of many phenomena, such as the Aharonov Bohm effect, the universal conductance fluctuations, the weak localisation correction to the conductance, persistent current in ringstructures and many more rely on a long enough phase coherence time. In disordered conductors and within the standard Fermi liquid picture, the phase coherence time is expected to diverge at zero temperature. However, most experiments show a saturating phase coherence time at low temperatures. This *saturation* has often been attributed to the presence of a small amount of magnetic impurities giving rise to the so-called Kondo effect. In this paper, we present a brief review of recent advances, both experimental and theoretical, in the understanding of dephasing by magnetic impurities in the framework of the Kondo effect.

Keywords: Quantum coherence, Kondo effect, Fermi liquids, quantum wires, weak localisation

Biographical notes: Laurent Saminadayar is a professor at the Université Joseph Fourier and **Christopher Bäuerle** is senior scientist at the French National Center for Scientific Research (CNRS). Together, they have founded a research group devoted to the study of quantum (spin) transport in nanoscale devices at the Néel Institute, Grenoble, France. Their work concerns quantum coherence in Kondo systems and spin glasses, Kondo effect in semiconductor nanostructures and more recently spin based quantum bits and nanomechanics. The group has good expertise in very low temperature physics under high magnetic field, ultra-low noise transport measurements and micro-SQUID magnetometry.

Pascal Degiovanni is CNRS researcher at the École Normale Supérieure of Lyon, in the condensed matter theory group. He has worked in decoherence problems in superconducting qubits, cavity QED and Luttinger liquids. He is now working on the development of quantum optics formalism for electrons. His expertise includes field theory methods in condensed matter physics as well as dissipative quantum dynamics.

1 Introduction

Quantum coherence in mesoscopic systems is one of the major issues in modern condensed matter physics as it is intimately linked to the field of quantum information. The interaction of solid state qubits with environmental degrees of freedom strongly affects the fidelity of the qubit, and the subsequent decoherence is the main limitation to the actual efficiency of such a device. More fundamentally, the quantum coherence of an electron in a mesoscopic system is also directly related to the lifetime of a quasiparticle in Landau's theory of Fermi liquids. In that sense, electronic quantum coherence itself can be used as a test of this notion of quasiparticles.

Finally, decoherence can also be exploited as an extremely sensitive probe of interactions between system and environment. A good example is the interaction between a localised magnetic impurity and the delocalised conduction electron in a metal, well known as the Kondo effect [1]. This effect has been studied *via* resistivity measurements for more than eight decades [2]. Only recently, however, it has been shown, that the measurement of the quantum coherence is a much more sensitive probe to investigate the microcopic mechanism which governs the Kondo effect as compared to the more traditional measurements such as resistivity, susceptibility, etc.

Let us also point out that the problem of quantum coherence in mesoscopic physics has been subject of a heavy and controversial debate over the last decade, in the context of what could be called the "zero temperature dephasing question". Ten years after, there seems still no definitive answer to the question of whether decoherence in metals at very low temperature is actually intrinsic or extrinsic. In metallic systems, however, for which most of the experiments have been performed up to date, the observed saturation of the phase coherence time has usually been linked to dephasing by Kondo impurities [3].

In the following, we will present a brief review of recent advances, both experimental and theoretical, in the understanding of the dephasing at low temperatures and in particular in relation with magnetic impurities. We start with a short review of the historical approach to the Kondo problem mainly in relation with decoherence measurements. We then outline briefly the basic theoretical concepts of decoherence followed by a summary of recent advances and achievements in the field of decoherence in relation with magnetic impurities. In the last section, we summarise recent decoherence experiments carried out in semiconductor heterostructures where the effect on disorder has been investigated.

2 Early experiments on quantum coherence in mesoscopic systems

Mesoscopic systems are macroscopic quantum objects in the sense that they are a) macroscopic (*i.e.* there typical size is much larger than any microscopic dimension) and b) quantum objects in the sense that electrons in such conductors behave quantum mechanically. The notion of quantum coherence is thus at the heart of the mesocopic physics itself. There are several ways to measure the phase coherence length L_ϕ in mesoscopic devices: the most commonly used is the zero field magnetoconductance usually referred to as *weak localisation* of electrons. An alternative method consists in measuring the universal conductance fluctuations (UCF) as a function of the magnetic field. The main advantage of the second technique, otherwise much less straightforward, is that the universal conductance fluctuations do exist at *any* magnetic field; this property is important to discriminate between magnetic/non magnetic dephasing.

In the "early" days of mesoscopic physics, the measurement of the phase coherence time τ_ϕ was essentially used to characterise a given material before using it for interference experiments. In these pioneering measurements, it was very often observed that the phase coherence time do saturate at very low temperature, and the presence of residual magnetic impurities was invoked to explain this saturation.

To the best of our knowledge, the first paper mentioning explicitely the dephasing by magnetic impurities is due to Pannetier and co-workers in 1985 [4,5,6]. In this work, the authors put a lot of effort in obtaining very large phase coherence length; but at low temperature, they observed a systematic saturation of τ_ϕ. The solution to the problem (at least to significantly increase L_ϕ) was to thermally anneal the samples. Such an annealing process oxidizes the magnetic impurities, suppressing decoherence due to magnetic diffusion and hence increases the phase coherence length. Shortly after, the pioneering works by van Haesendonck *et al.* [7] and Peters *et al.* [8] addressed the problem of the phase coherence time in the presence of magnetic impurities. Both groups observed a maximum of dephasing around the Kondo temperature. Naturally, these experiments were extended to the low temperature regime in order to explore the ground state of the Kondo system. However, in the experimental system chosen (AuFe), the Kondo temperature T_K is quite low (typically below 1 K), and the experimental setup did not allow to observe the "zero" temperature limit of the Kondo problem. Instead, a very slow temperature dependence of the magnetic contribution to the dephasing rate has been found below T_K [9]. This puzzle has remained unresolved for almost 20 years, mainly due to absence of theoretical predictions in the temperature range around T_K. In connection to the saturation problem, Kondo decoherence has recently gained new interest. In a recent experimental study [10], a very curious linear temperature dependence of τ_ϕ below the Kondo temperature has been observed in AuFe quantum wires which again seemed to have contradicted the Fermi liquid prediction. In this context, it seemed obvious that a deeper understanding of the magnetic decoherence and new experiments were needed to capture the physics of magnetic dephasing in the low temperature limit. In the following, we summarise recent advances and achievement in the field of decoherence at low temperature in relation with decoherence due to magnetic impurities.

3 Decoherence and Kondo effect: basic theoretical concepts

The Kondo effect of magnetic impurities in non-magnetic metals, e.g. Mn, Fe or Co in Cu, Ag or Au, first manifested itself [2] in the early 1930's as an anomalous rise in resistivity with decreasing temperature, leading to a resistivity minimum. In 1964 Kondo explained this effect [1] as resulting from an antiferromagnetic exchange coupling between the spins of localised magnetic impurities and delocalised conduction electrons. In the ensuing years, the Kondo effect has become a paradigm for the interplay between localised and delocalised degrees of freedom and today is one of the best-studied problems in condensed matter physics.

So why should one still be interested in studying this problem? Actually it is surprising that even after 70 years of the dawn of Kondo physics there is still no quantitative understanding of this effect: for many dilute magnetic alloys it remains unclear what the real value of spin the magnetic impurity has. Examples are Fe impurities in Au and Ag, the former being the very first magnetic alloy known to exhibit an anomalous resistivity minimum [2].

Kondo systems are usually studied by transport properties. Magnetic impurities affect these in two different ways. Besides causing the afore-mentioned resistivity anomaly, they also make an anomalous contribution γ_m (T) to the electronic phase decoherence rate γ_ϕ (T) =1/τ_ϕ (T) measured in weak (anti)localisation: an itinerant electron which spin-flip-scatters off a magnetic impurity leaves a mark in the environment and thereby suffers decoherence. Here, the dephasing rate γ_ϕ is defined as the time required for an electron infinitesimally close to the Fermi surface to loose its phase coherence.

The weak localisation correction to the conductivity is then expressed in term of the decay of the single particle phase $\langle e^{i\phi(t)} \rangle_T$ [11]:

$$(\delta g)(T) \approx -2s \int P_0(t) \langle e^{i\phi(t)} \rangle_T \frac{dt}{\tau_D}$$

Assuming exponential decay of this phase $\langle e^{i\phi(t)} \rangle_T \propto e^{-t/\tau_\varphi(t)}$ the weak localisation correction is then directly related to the dephasing time. Any inelastic scattering will contribute to the dephasing time: at low temperatures, the dominant mechanisms are electron-electron (e-e) interactions as well as inelastic scattering from magnetic impurities.

This e-e interaction contribution to the dephasing has been at the center of a controversy since 1997. The standard theory [12,13] for dephasing predicts a diverging dephasing time at vanishing temperature whereas an alternative theory proposed by Golubev and Zaikin predicts a saturation of the dephasing time at low temperatures [14,15,16,17,18]. The actual behavior of the single electron dephasing time at very low temperature is precisely the afore mentioned “zero temperature dephasing question”. Saturation of the dephasing time down to absolute zero raises the question of the breakdown of the Fermi liquid theory and, as such, is of basic importance for our understanding of metallic conductors.

Concerning the scattering from magnetic impurities, checking model predictions for weak localisation as well as for the Kondo resistivity anomaly against experimental observations over several decades in temperature can thus be used as a highly sensitive probe of the actual form of the effective exchange coupling.

In the regime of dilute impurities, the Kondo model deals with the exchange coupling between a single quantum spin and conduction electrons. The model is based on the celebrated Kondo Hamiltonian written here for a spin S impurity and a single conduction band:

$$H_K = \sum_{\sigma,k} \varepsilon(k) c_\sigma^+(k) c_\sigma(k) + J \sum_a S^a \sum_{\sigma,\sigma'} \psi_{\sigma'}(0) \sigma^a_{\sigma'\sigma} \psi_\sigma(0)$$

where S^a denotes the quantum spin impurity and the $\psi_\sigma(x)$ the fermion field of electrons of spin σ. The first term represents the kinetic energy for electrons with dispersion relation $\varepsilon(\sigma)$. The second term which is the Kondo interaction basically tends, in the antiferromagnetic regime J>0, to induce a screening of the impurity spin by the conduction electrons. In the case of S = ½, at very large coupling J, a single electron forms a singlet with the impurity spin. Because of the Pauli principle, nearby electrons tend to anti-align with the electron spins and in fact, a cloud of electrons with polarization oscillating over a length scale k_F develops. This "Kondo cloud" has a size ξ_K which defines the Kondo energy scale $k_BT_K = hv_F/\xi_K$. Electrons with very high energy $\varepsilon >> k_BT_K$ only see an unscreened spin and their coupling to the impurity can be treated perturbatively. On the other hand, electrons with very low energy $\varepsilon < k_BT_K$ effectively see a screened impurity and perturbation theory breaks down in this regime.

Because of the coupling between electrons and the quantum impurity, the many body state formed by a single electron excitation of well defined momentum p above a filled Fermi sea is no longer an eigenstate of this Hamiltonian. It evolves in time, leading to the production of a complicated many body state involving potentially electron/hole pairs. Indeed, decoherence arises because of the imprint left by a single electron on the spin degrees of freedom (spin flip) but it also occurs because of the alteration of the many body state of the electron fluid arising from the creation of electron/hole pairs, even in the absence of impurity spin flip.

The relaxation time $\tau_{in}(p)$ for an electron of momentum p is related to the inelastic cross section $1/\tau_{in} = n_{imp} v_F \sigma_{in}(p)$ where n_{imp} denotes the density of magnetic impurities. The whole problem is thus to evaluate the inelastic scattering rate for any momentum, or equivalently for any energy ε above the Fermi surface.

This program has been completed by Zárand *et al.* [19] using the powerful numerical renormalization group (NRG) method. Indeed, analytical methods were not able to go beyond the limiting regimes of the Kondo effects which are $\varepsilon >> k_BT_K$ (high energy) and the limiting case of $\varepsilon << k_BT_K$.

At high energies, the impurity spin is weakly screened and perturbation theory can be applied to obtain estimates of scattering. It shows that, for high enough energies, almost all processes are inelastic thus leading to an inelastic time:

$$\frac{1}{\tau_{in}} = \frac{\pi n_{imp}}{2\rho} \frac{S(S+1)}{\ln^2(\varepsilon / k_B T_K)}$$

where ρ is the density of states (DOS) at the Fermi energy. In the deep infrared (IR) regime, for the single channel Kondo model, the almost perfectly screened impurity mostly acts as an elastic scatterer of the conduction electrons. This is the Fermi liquid regime of Nozières [20]: $\sigma_{in}(\varepsilon) \to 0$ for $\varepsilon \to 0$. Detailed calculations based on an effective Fermi liquid description close to the IR fixed point show that $\sigma_{in}(\varepsilon) \propto \varepsilon^2$ [20] at low energy. But, as NRG calculations have shown, this is only valid in the deep infrared regime $\varepsilon \leq 0.05 T_K$. The intermediate regime and indeed the whole scaling form of the inelastic cross section has remained an open problem up to the recent work based on NRG.

The method consists in relating the single particle scattering amplitude to conduction electron Green's functions using the reduction formulae. Then, the interacting electronic Green function can be expressed using for example the equations of motion, in terms of a local Green function that involves the quantum spin and the electronic operator. The NRG technique can then be used to numerically evaluate this local Green function and subsequently derive the inelastic scattering rate for all values of the energy (see Fig. 3 in [19]).

The same method can also be used to discuss the case of the over-screened Kondo model where the number of channels k exceeds the number required to perfectly screen the quantum impurity. The two channel S=1/2 Kondo model models this situation and exhibits a non-Fermi liquid behaviour whose IR properties have been studied using conformal field theory methods by Affleck & Ludwig [21,22]. In the present case, the NRG method provides a complete estimate of total, elastic and inelastic scattering rates showing in particular that, at vanishing energy $\sigma_{el} = \sigma_{in} = \sigma_{tot}/2$ does not vanish. This results from the vanishing of the scattering amplitude in the s channel at the Fermi surface, thus reflecting the non-Fermi liquid nature of the electron fluid first suggested by Nozières and Blandin [23]

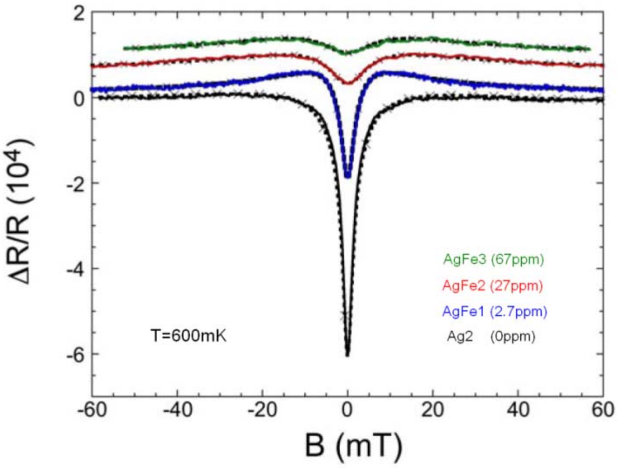
Extension of the method to finite temperatures and including disorder has been achieved by Micklitz *et al.* [24]. The dependence in external magnetic field can also be obtained [25]. A complete review of the NRG methods and its applications has recently been written by Bulla, Costi and Pruschke [26].

4 Universal scaling of the Kondo dephasing

When exploring quantum coherence in any physical system at low temperatures one is faced with many extrinsic sources which can lead to decoherence. In addition, in all "natural" materials one always has to worry about inclusion of magnetic particles. Indeed, with present conventional chemical analysis methods like state of the art secondary ion mass spectroscopy (SIMS) one can hardly resolve a magnetic impurity ion concentration of less than one part-per million (ppm) especially in structures of sub-micron size which are employed for the study of quantum coherence. As it turns out, the most sensitive tool to determine the actual magnetic impurity concentration are indeed phase sensitive measurements, which can resolve a magnetic impurity level well below the ppm level.

To study decoherence, a very common and powerful tool is the measurement of weak localisation. This is illustrated in Figure 1 where we display the magnetoresistance of several silver quantum wires which have been implanted with iron impurities of various concentrations.

Figure 1 Magnetoresistance of several silver quantum wires containing different concentrations of iron impurities (from top to bottom: (green) 67 ppm; (red) 27 ppm; (blue) 2.7 ppm and (black) 0ppm). All data are taken at a temperature of 600 mK. The dip in the resistance is due to quantum interference usually referred to as "weak anti-localisation".

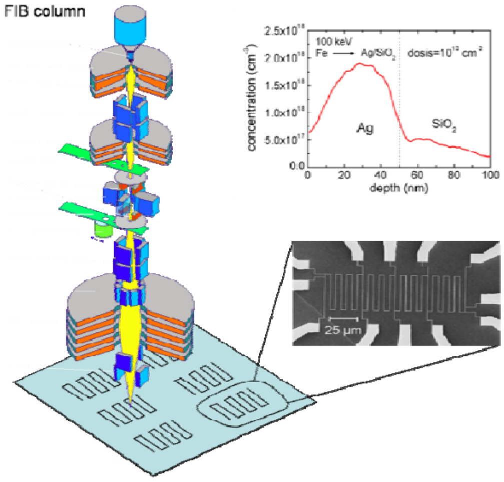


The data for all samples are taken at a temperature of 600 mK. For all samples one observes a pronounced dip in the magnetoresistance around zero field which is due to quantum interference phenomena and usually referred to as weak anti-localisation [11,12]. For the quantum wire Ag2 which contains no magnetic impurities this weak antilocalisation is maximal and accounts for a very large coherence time. For the sample AgFe1, which contains only 2.7 ppm of magnetic impurities one observes already an important reduction of the resistance minimum: inelastic spin flip scattering induced by the magnetic impurities reduces the coherence time and consequently leads to a reduction of the weak antilocalisation. Increasing the magnetic impurity concentration decreases further the minimum as clearly seen in figure 1. The rapid decrease of the minimum by adding a very small amount of magnetic impurities clearly shows the sensitivity of this method for the detection of magnetic impurity concentrations on the ppm level.

To study the influence of magnetic impurities like Fe, Co, Mn, etc. on decoherence one has to prepare samples where at least one dimension is smaller than the phase coherence length of the electron L_ϕ in this specific material. A second requirement is a very good control on the magnetic impurity concentration since the magnetic impurity level should be on the order of one part per million. If the impurity concentration is too high, interactions between the magnetic impurities may arise and the physics is altered [10]. It should be stressed that the screening length for the magnetic impurities (roughly the size of the Kondo cloud) scales as $1/T_K$: choosing a system with a relatively "high" Kondo temperature thus allows to deal with a "pure" Kondo system with no spin-glass like transition. In the early experiments the magnetic impurity concentration was obtained by mixing a very pure metallic source with a source containing the magnetic impurities with the desired ratio. For concentrations on the ppm level, this is not very easy to realise as the pure metal may already contain a tiny proportion of intrinsic magnetic impurities. Another approach was to “sandwhich” an atomically thin layer of magnetic impurities between two pure metallic films [8]. This, however, has the disadvantage that the magnetic impurities are not uniformly distributed in the sample.

For a much better control of the magnetic impurity concentration we have developed together with the group of A. Wieck at the University of Bochum an original technique where magnetic ions are implanted with a focussed ion beam (FIB) microscope. This has the advantage that we perfectly control the impurity concentration as well as the magnetic impurity distribution inside the sample, but more importantly we can implant different impurity concentrations in samples on the same wafer, which are all identical. This allows us to study the concentration dependence and also gives us the possibility to compare the results with non-implanted samples.

Figure 2 Ion implantation scheme: several metallic quantum wires (bottom right image) are evaporated onto a single Si wafer. The FIB column is then placed on one of the samples and an ion implantation (Fe) with a given ion concentration is performed. The FIB is then moved towards another sample and the implantation is repeated with another ion concentration (change of exposure time). The top right graph shows the ion distribution in a metallic silver wire of thickness of 50 nm using an implantation energy of 100 keV.



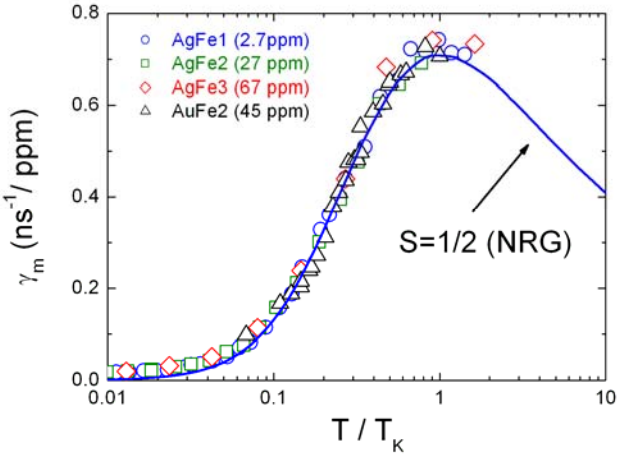
The experimental set-up of the implantation procedure is shown in figure 2. A focussed ion beam is placed onto a silicon wafer where many identical metallic quantum wires have been evaporated. By moving the FIB across the wafer we can implant the samples with the desired impurity concentration. The energy of the implanted ions is adjusted such that the peak of the Gaussian distribution is located in the middle of the thickness of the wire as shown in the top right graph of figure 2.

Such measurements have been pioneered in very thin metallic films (thickness smaller than L_ϕ) by van Haesendonck et *al.* [7] and by Peters et *al.* [8]. Both groups have been able to measure the Kondo maximum of the dephasing rate due to the scattering of magnetic impurities in thin metallic films. This maximum arises from the antiferromagnetic coupling of the localised magnetic impurities to the itinerant conduction electrons and reaches its maximum at the Kondo temperature T_K where spin flip induced decoherence is maximal.

Naturally, these measurements have then been extended to temperatures below T_K to investigate the ground state of the Kondo problem. In this limit $T << T_K$, Fermi liquid theory predicts a T^2 dependence of the inelastic scattering rate [20]. The early experiments, on the other hand failed to observe this regime [27].

An exact calculation of the inelastic scattering time in Kondo metals using Wilson's Numerical Renormalisation Group (NRG) approach [19] could finally resolve this puzzle. Calculations showed that in a limited temperature range, in particular for $0.1\ T_K < T < T_K$, the inelastic scattering rate due to magnetic impurities is linear in T, indeed consistent with the experimental findings [10,28]. Only for temperatures below $0.1\ T_K$, the temperature dependence is expected to be proportional to T^2. This temperature regime has been explored experimentally only very recently [29,30] and we will present here a short overview of the very recent achievements in the understanding of decoherence due to magnetic impurities.

Figure 3 Dephasing rate per magnetic impurity as a function of reduced temperature for the Kondo systems AgFe and AuFe having significantly different Kondo temperatures. The solid blue line corresponds to the NRG data for the spin ½, single channel model of ref. [24].



In figure 3 we show recent data of the dephasing rate per magnetic impurities as a function of reduced temperature (T/T_K) for two different Kondo systems (AuFe and AgFe) having different Kondo temperatures [29]. All data collapse on a *universal curve* which is indeed expected for a Kondo system. In addition, the temperature dependence is extremely well described by the spin $S = ½$, single channel model [24] as represented by the solid blue line. This is quite remarkable in the sense that the underlying theoretical model is a spin ½ single channel model, whereas the real spin of iron is *not* ½.

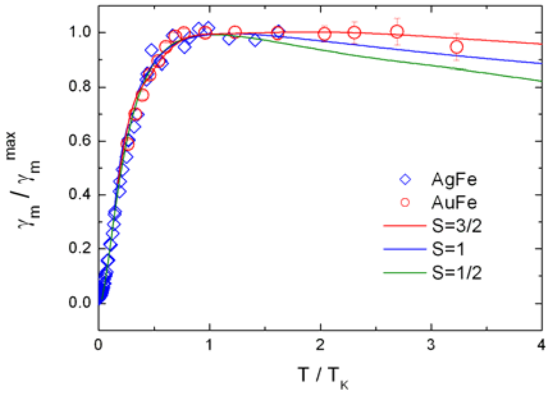
The good agreement with the spin ½ single channel model originates from the fact that the low temperature behaviour ($T < T_K$) is described by a perfect screening [31]. If the number of the conduction channels n_c matches the number of multiples of impurity spin ½ (e.g. n_c=1 and S = ½; n_c=2 and S= 1 and so on), the impurity spin can be perfectly screened at low temperatures and for such cases the Fermi liquid regime is reached in the low temperature limit ($T << T_K$) which is characterised by a T^2 temperature dependence.

We have seen that the spin ½ model describes remarkably well the temperature dependence of the decoherence time, especially in the temperature range below the Kondo temperatures. However when compared to other measurements like resistance variations or magnetoresistance measurements on field scales much larger than T_K several discrepancies are revealed. For instance, different values of the Kondo temperature are extracted when analysing different physical quantities with the S=½ model [32]. This clearly shows that the S=1/2 model is not sufficient and let us conclude that the underlying model to describe the Kondo system AgFe is most probably a fully screened model, however involving more than one channel and a spin larger than ½.

In a collaborative effort with theorists, we have very recently been able to finally reveal the real value of the spin of iron in noble metals like gold and silver, the former being the very first Kondo system to be discovered. This has been achieved by developing an effective low-energy Kondo-type model which yields a realistic description of the relevant multiple bands, spin and orbital degrees of freedom and comparing them to phase sensitive transport measurements. From this model we were able to calculate the resistivity $\rho(T)$ and decoherence rate $\gamma_m(T)$ due to magnetic impurities for three fully screened Kondo models, with $n_c = 2S = 1$, 2 and 3, using Wilson's numerical renormalization group (NRG) approach. A more detailed description of the theoretical approach can be found in ref. [31].

A comparison of the experimentally measured decoherence rate of two different Kondo systems Ag/Fe and Au/Fe and the theoretical calculations for various fully screened Kondo models are shown in figure 4. We can see that all fully screened models for S = ½, 1 and 3/2, as indicated by the continuous coloured lines, show relatively similar temperature dependence below the Kondo temperature. In the low temperature regime it is therefore not possible to distinguish between different fully screened models. At temperatures higher than T_K, however, the theoretical predictions differ and the best agreement between theory and experiment is obtained for $n_c=3$. In addition, when analysing the resistivity data with the theoretical predictions for the fully screened models we finally resolve the discrepancy between the Kondo temperatures when extracted from these two different quantities. Indeed, we find that only for the 3 channel, S= 3/2 model the Kondo temperatures extracted from resistivity measurements as well as decoherence measurements coincide, in particular ($T_K^{AuFe} = 1.3$ K; $T_K^{AgFe} = 5.1$ K), giving us very good confidence that the spin of iron is S = 3/2.

Figure 4: Dephasing rate per magnetic impurity as a function of reduced temperature for the Kondo systems AgFe and AuFe. The solid lines corresponds to the NRG data for various fully screened Kondo models from ref. [31]



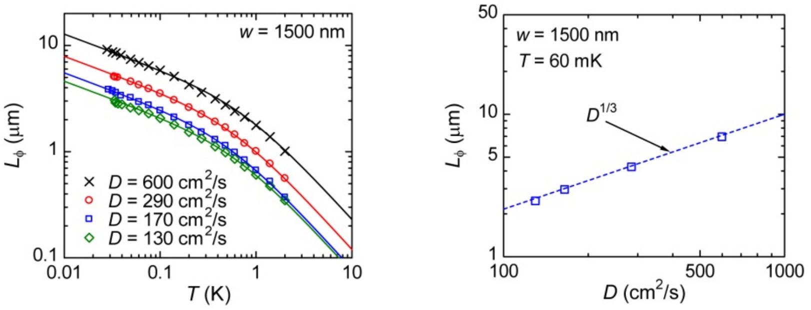
Another approach to investigate the influence of magnetic impurities on the electron coherence involves phase coherent measurements under strong magnetic fields [25,33,34]. In this case, one can suppress the effect of magnetic impurities by applying a sufficiently high magnetic field in order to fully polarise the magnetic impurity spins, and therefore study temperature dependence of phase coherence time without contribution from magnetic impurity spins. Because of the required high fields on the order of teslas, low-field weak localisation measurements cannot be used to extract the phase coherence time. However, measurements of Aharonov Bohm (AB) oscillations and universal conduction fluctuations (UCF) are possible. Pioneering work on both, UCF and AB oscillations in quasi-1D quantum conductors containing a small amount of magnetic impurities (down to 40ppm) has been performed by Benoît and coworkers in 1988 [35,36] and more recently by Pierre et al. [37] and Mohanty et al. [38]. In such measurements the amplitude of the AB (UCF) oscillations are measured as a function of magnetic field. For this purpose, a relatively large field span of several oscillation periods (AB) or correlation fields (UCF) has to be covered to get a reliable value of UCF/AB amplitude at a given magnetic field [37]. It turns out, however, that such measurement are not sensitive enough to determine with precision the temperature dependence of τ_ϕ or reveal the actual spin of the magnetic impurities.

The field dependence can also be probed by measuring the classical magnetoresistance at fields much larger than the Kondo temperature [30,39]. Such measurement should also allow us to extract the actual spin of the magnetic impurities. This work is presently under way and should give further proof that the spin 3/2, 3 channel model is indeed the correct one to describe the interaction of iron impurities with the conduction electrons in noble metals like gold and silver.

5 Decoherence and disorder

As we have pointed out in the introduction, our decoherence measurements in mesoscopic wires related with magnetic impurities have been motivated by the "saturation problem" and has finally led to a very good understanding of decoherence induced by magnetic impurities. The initial goal, however, was to give an answer to the "saturation problem". This has also been attempted theoretically as well as experimentally by several other groups by addressing different extrinsic mechanisms for the low temperature saturation such as the presence of dynamical two level systems [40,41], size dependent decoherence [42], the presence of a small amount of magnetic impurities [3,10,37], radio frequency assisted dephasing [43] and so forth. All these works have shown that various effects can lead to decoherence at very low temperatures, but none of them has been able to clearly rule out the validity of the GZ theory. It is clear that a measurement of the temperature dependence of the phase coherence time τ_ϕ cannot by itself discriminate between intrinsic and extrinsic decoherence [44]: an extremely small amount of magnetic impurities may always explain the observed saturation of τ_ϕ [28,29,44]. In this respect, the question of whether the phase coherence time of electrons in metals does or does not saturate at zero (or at least very low) temperature cannot be answered by such measurements.

Figure 5 Left: phase coherence length as a function of temperature for mesosocopic wires etched into a GaAs/GaAlAs semiconductor heterostructure with various diffusion constants. The solid lines correspond to a combination of a $T^{-1/3}$ dependence at low temperatures and a T^{-1} dependence at high temperatures [48]. Right: phase coherence length taken at 60mK and plotted as a function of diffusion coefficient. The dotted line corresponds to a $D^{1/3}$ power law.



An important ingredient in the theories about decoherence is the disorder dependence, or in other words, the dependence of the decoherence time on the diffusion coefficient *D*. Some attempts to measure this dependence have been realised in metallic systems [45,46], but in this case it is very difficult to vary *D* in a controlled way over a wide range. Another study has been performed on two dimensional electron systems [47], however, in that work the phase coherence time was already saturating in their cleanest samples at relatively high temperatures. To perform such kind of experiments an extremely good control of the intrinsic disorder of the sample is necessary. Such a control can indeed be achieved with the implantation technique we have developed for our studies on decoherence in relation with magnetic impurities. When applying this technique to semiconductor mesoscopic wires made from GaAl/GaAlAs heterostructures we are able to change the intrinsic disorder in an extremely controlled way by implanting

Ga-ions into a two-dimensional electron gas (2DEG). By varying the Ga-ion concentration, we have been able to measure the decoherence in mesoscopic wires made form a semiconductor heterostructure by changing the diffusion coefficient over more than 2 orders of magnitude [48].

The temperature dependence of the phase coherence length L_ϕ is depicted in figure 5 (left) for samples with diffusion coefficients ranging from 130 cm^2/s up to 600 cm^2/s. For all our data the temperature dependence is very well described a $T^{-1/3}$ temperature dependence in the very low temperature regime due to electron-electron interaction as expected within the AAK theory. Taking the phase coherence length at a given temperature (here T = 60 mK) we can then extract the diffusion dependence as shown in figure 5b. Our data show a $D^{1/3}$ power law dependence as indicated by the dotted line. Such a D dependence is indeed expected within the AAK theory.

It is important to note that for all data no apparent saturation of the phase coherence length is observed down to a temperature of 30 mK. This seems to be in contradiction with the theory of GZ. In their case a strong D^α dependence ($\alpha>1$) of the zero temperature saturation time is expected. As our samples do not show any saturation down to the lowest temperatures this would mean that either the theory is inconsistent with our data or that the zero temperature saturation occurs at much lower temperatures for *all* diffusion coefficients investigated. The latter, however, is in our opinion very unlikely since in metallic systems the *apparent* saturation of the decoherence time for similar diffusion coefficient occurs at much higher temperatures.

6 Conclusions

What have we learned from all this story? It is clear that the controversy about the low-temperature saturation in mesoscopic wires has lead to some interesting "side-effects". It has been recognised that magnetic impurities do play a predominant role in the low temperature decoherence of metallic systems. Weak localisation measurements turned out to be sensitive to a tiny fraction of magnetic impurities, well below the ppm level, and it is this extreme sensitivity which has consequently been exploited to get a much deeper understanding of the Kondo effect in metals. Simultaneous advances in theory has finally led to a quantitative understanding of the Kondo effect in metals.

From weak localisation measurement on silver wires containing a very well controlled concentration of magnetic iron impurities, we have been able to measure the *universal* dephasing time caused by magnetic impurities. This universal curve has been compared with exact theoretical predictions [24]: the agreement has been found to be very close to the fully screened Kondo model for spin ½ for temperatures below T_K.

A more realistic description of iron impurities in the noble metals gold and silver has been recently derived [31]. When comparing this model to our experimental data we find that a fully screened S=3/2 three-channel model yields a coherent picture of the decoherence rate as well as the electrical resistivity of the classical Kondo system AuFe (as well as AgFe) and finally solves a fundamental problem which has been around for more than 70 years.

Concerning the saturation problem we have shown that in extremely clean semiconductor mesoscopic wires no saturation of the decoherence time is observed in the low temperature regime within a large range of diffusion coefficients. These observations hopefully close the debate on zero temperature decoherence.

Nevertheless, it doesn't close theoretical and experimental studies of electronic decoherence. Beyond the magnetic field dependence of Kondo impurity decoherence, a better understanding of interactions is required. An in depth study of electron relaxation has been conducted in diffusive wires [3] and these data were well interpreted by a Boltzmann equation treatment. Experiment in progress by Pierre et al. studies the energy relaxation of electrons propagating along edge channels of a 2DEG in the integer quantum regime [49]. Experimental results suggest a rapid destruction of the quasi particle whose relaxation cannot be described within the standard Boltzmann equation approach. Studying energy relaxation of electrons in edge states appears as a promising line of research for exploring electron decoherence scenarios in a situation dominated by Coulomb interactions and without any disorder.

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