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Electron Decoherence by a Single Spin

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Recently it has been suggested that the ubiquitous saturation of electron dephasing time at low temperatures could be due to an extremely small number of magnetic impurities—even as small as a single magnetic spin. However, extensive data from a series of recent experiments at both low and high magnetic fields clearly indicate the contrary. At high magnetic fields, the spins, irrespective of their number or concentration, freeze along the field, and the electron dephasing time is determined only by mechanisms that do not involve magnetic impurities. This dephasing time measured via conductance fluctuations still saturates at low temperatures, unequivocally suggesting that the saturation is not due to a mechanism that involves magnetic impurities at any level.

KEYWORDS: Kondo effect, dephasing, decoherence, magnetic impurities, single-spin dynamics

1. Search for a new mechanism

Decoherence of a quantum system requires an environment to which it is coupled. A new mechanism of decoherence inevitably requires a new environment and its appropriate interaction with the quantum system. In low-dimensional disordered conductors, there are only a few types of degrees of freedom: charge and spin of the electron, phonon, localized spin from magnetic impurities, pseudo-spin or two-level system of fluctuating atoms, and nuclear spin. The interaction of an electron with any of these degrees of freedom results in decoherence. The sources of decoherence depend on the system or sample being studied, and their material composition.

In the same vein, one could also enumerate additional mechanisms of decoherence depending on the measurement process or the laboratory environment in which the experiment is carried out. Examples are external high-frequency noise sources giving rise to high-frequency photons, non-equilibrium or non-linear processes resulting from the measurement current or loss of thermal contact between the interfering electron and the cryostat, and any other outside sources of noise such as cosmic particles, gravitons etc.

Whether internal or external—i.e whether sample- or material-dependent or measurement-dependent—all the mechanisms can be easily discerned by their magnitude and dependencies on various experimental parameters such as temperature, magnetic field, size etc. On the theoretical side, comparison of the decoherence time by a certain mechanism to the experimental data requires an unambiguos and well-developed calculation of decoherence time. All the afore-mentioned mechanisms have been shown to be irrelevant to the experimental data of electron decoherence time in low-dimensional disordered conductors at low temperatures[1)] with the sole exception of the mechanism of electron-electron interaction, which is still under discussion and debate. Theoretical controversies aside, there has been an intense search for yet another mechanism which would both qualitatively and quantitatively explain the vast amount of experimental data, within the conventional Fermi liquid framework of metals, disordered or otherwise.

It has been recently suggested that there is yet another mechanism, involving *an arbitrarily small number* of magnetic impurities in the mostly pure, metallic conductors.[3)] This mechanism involves an indirect interaction between electrons mediated by the magnetic impurity spins. A simple estimate shows that in order to obtain the level of decoherence (with a temperature-independent decoherence time τ_ϕ 1 ns), the pure conductor needs to contain an extremely small concentration of magnetic impurities. The most fascinating—and obviously, experimentally intriguing—fact is that the required concentration for a typical sample in the nano scale translates to a single magnetic spin in the entire phase-coherent volume or even the entire sample.

The importance of single-spin effects requires no motivation, considering the recent outburst of theoretical and experimental efforts in spintronics and quantum information processing based on single-spin qubits. Here we focus on the mechanism of electron decoherence by a single magnetic-impurity spin and whether or not it explains the low temperature dependence of the decoherence time.

A proper account of this mechanism in the sole context of decoherence is the subject of this paper.

2. Electron-electron interaction mediated by magnetic impurities

Recently, Kaminski and Glazman have proposed a theory of electron energy transfer as a mechanism for enhanced energy relaxation and dephasing.[3)] The mechanism involves indirect electron-electron interaction mediated by a magnetic-impurity spin, and the spin interacts with the electrons according to the standard Kondo picture. In essence, the magnetic spin provides another channel for energy transfer between the electrons, if temperature is too low (or zero) to provide sufficient energy to the electrons to scatter inelastically and hence undergo dephasing.

However, in the conventional picture electrons are pro-

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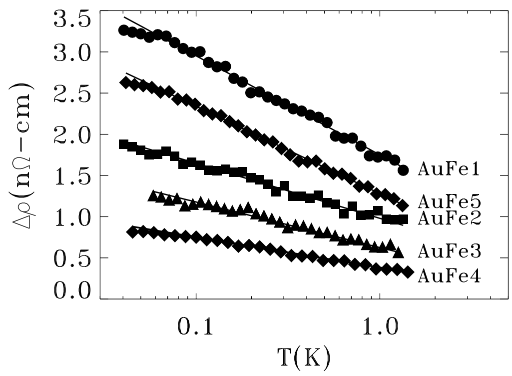

Fig. 1. Kondo resistivity for five disordered quasi-1d AuFe wires showing the expected logarithmic form, $\Delta\rho(T) = a - b\ln(T)$, in spite of the presence of disorder. The concentration of iron (Fe) impurities is $\sim$ 11,7,6,3, and 10 ppm for the samples AuFe1 through Aufe2. Sample details are given in ref.[5]

hibited from scattering at low temperatures, as the temperature precisely determines the number of final states for a given electron to scatter into. Additional considerations following the Pauli exclusion principle add further constraints on the phase space for scattering. How would one obtain a large scattering of the electron, involving the loss of energy or phase memory? Whether the conductor is absolutely pure or whether it contains a small number of magnetic impurities, the scattering rate is still suppressed because of the simple phase space argument. The details of low temperature decoherence of pure electron-electron interaction is the subject of ongoing debates, and we will not discuss it here.[1] We will instead focus on this second type of electron-electron interaction involving a magnetic impurity spin.

An additional degree of freedom–the spin–comes into play in the electron wave function in the presence of magnetic impurities inside the metallic system. Electrons inside a host metal interact with the spin of a magnetic impurity ion. At high temperatures, the interaction is defined by the magnetic scattering rate introduced by the spin-flip scattering of the electron by the impurity spin. The scattering process is further modified if the temperature is lowered below a characteristic temperature, known as the Kondo temperature T_K, and determined by the host material and the type of the magnetic impurity. The electron spin—as a part of the electron cloud–tends to screen the impurity spin. At even lower temperatures, the spin is completely screened, and therefore it becomes irrelevant as a scattering source. This state is the Kondo singlet state. However, the Fermi-liquid description of the vanishing scattering rate for the electron in the host-metal plus the magnetic-impurity system still remains valid. At high temperatures $T \gg T_K$, described by the magnetic scattering, and very low temperatures $T \ll T_K$, the Fermi liquid description is valid. This is because the magnetic scattering rate $1/\tau_s$ varies as $1/T^2$, vanishing at zero temperature.[?] And at low temperatures the Kondo singlet state is a well-defined Fermi-liquid ground state.[?] The crossover is described by various interpolation theories, such as the Suhl-Nagaoka description. In summary, the normal interaction between the electrons in equilibrium conditions leads to Fermi liquid picture of vanishing scattering rate for decoherence, whether or not their interaction is mediated by a magnetic-impurity spin.

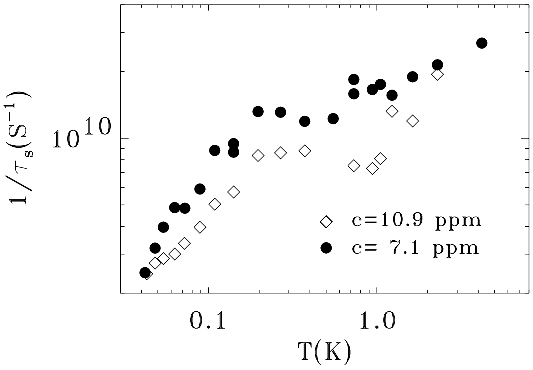

Fig. 2. Spin scattering time for samples Aufe1 (bottom) and Aufe2 (top) described in Fig. 1. The peaks around 0.2 and 0.3 K correspond to the respective Kondo temperatures of the two samples, described by the Suhl-Nagaoka expression with the respective Kondo temperatures (ref.[5]

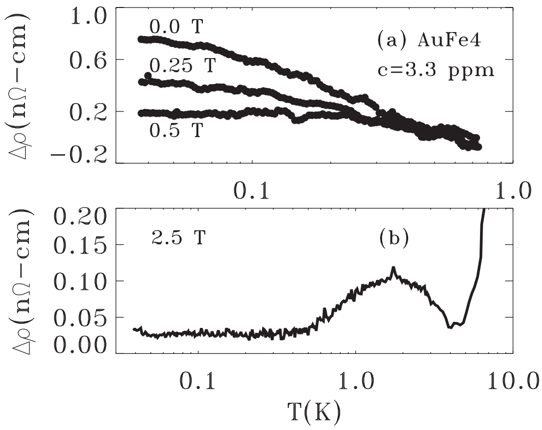

Fig. 3. The Kondo resistivity saturates as the field increases. The peak in (b) shows the competition between the two energy scales, magnetic field and temperature.

The ingenious proposal of Kaminski and Glazman is to replace temperature by another energy scale, which facilitates the electron-electron interaction via the magnetic-impurity spin. If this energy is larger than the temperature, it would allow electron scattering, previously prohibited on the grounds of phase-space argument. And the scattering rate would be dependent on this energy rather than on the temperature, resulting in a temperature independent scattering rate. If this is the case, the large scattering processes, governing energy relaxation, or dephasing, could be understood, by merely identifying such a source.

A number of such sources could be relevant in the experimental situation: bias voltage or current used in the transport-measurement configuration eV, Zeeman energy in presence of an external magnetic field $g\mu B$, and energy from the external high-frequency photons $\hbar\omega$. This energy replaces k_BT, and one obtains instead of a temperature dependence in the scattering rate a similar dependence on the appropriate parameter such as the bias voltage V or the magnetic field B or the frequency of the photon ω. The essential point is that the process is necessarily *nonequilibrium.*

The external energy has to be comparable to or larger than the energy required in each collison process. If this energy is much smaller than $E \ll k_BT$, then one naturally retrieves the normal magnetic scattering, and the corresponding Fermi liquid behavior. If $E \gg k_BT$, then the electron is in a nonequilibrium state, and the Glazman-Kaminski mechanism becomes dominant over the conventional magnetic-scattering mechanism.

The anomalously-large energy relaxation rates observed in recent nonequilibrium measurements have been successfully explained by the Glazman theory.

For a detailed explanation of the physical process of the mechanism, we refer to the original paper[3)] and other companion papers.[6–8)]

3. Assumptions and theoretical results

The proposed mechanism of electron-electron interaction mediated by magnetic impurities works under a series of assumptions, of which the nonequilibrium condition is the most important. Otherwise, the electron behaves according to the conventional electron-electron interaction or normal Kondo scattering, oberying in both cases the Fermi liquid picture of diverging dephasing time with decreasing temperature.

This mechanism suppresses weak localization and conductance fluctuations. Recently, explicit expressions have been derived to describe the suppression of these interference effects in quasi-1D systems.[8)] In the following we describe some of the essential assumptions and the results of the theory.

3.1 Two temperature ranges

The Kondo temperature marks two definite temperature ranges, relevant to the mechanism. The effect is valid only at $T > T_K$ as the spin needs to be completely or partially free to be able to mediate energy exchange between electrons. Qualitatively, the temperature dependence of the decoherence rate, if dominated by this particular mechanism, should show strong suppression and saturation at higher temperatures, down to T_K. Below T_K the spin gets screened out by the electron cloud, forming the Kondo singlet state with the electrons. The mechanism therefore vanishes at low temperatures $T < T_K$, and the Fermi liquid picture is again valid. The dephasing rate should then show the diverging form with the decreasing temperature in this regime.

3.2 Energy relaxation for $E > T_K$

If the energy transfer E is larger than the Kondo temperature T_K, then the kernel K for the corresponding collision integral in the kinetic equation for the distribution function is found to be $K \propto J/E^2$, where J is the collision integral. The collision-integral kernel in the experimentally-relevant regime $E < eV$ is found to have the form: $K(E) = \frac{\hbar}{\tau_0 E^2}$. Further assuming that the smearing of the Fermi level by eV is larger than k_BT and larger than the energies of the colliding electrons, an expression for the kernel in the regime $eV \gg k_BT_K$ is found:

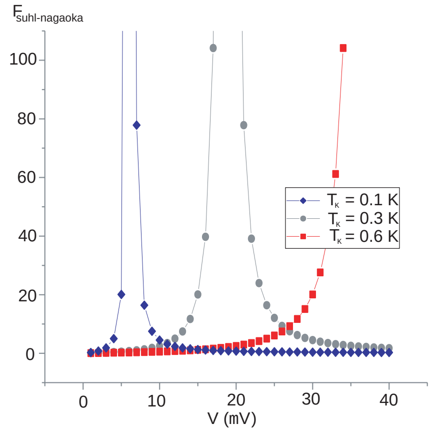

Fig. 4. Dependence of the Suhl-Nagaoka function on the bias voltage for three different Kondo temperatures. Note that a change in the bias voltage by an order of magnitude, from 1 μV to 10 μV, results in an order of magnitude change in the Suhl-Nagaoka function and hence in $\tau_{\phi 0}$.

$$K(E) = \frac{\pi}{2}\frac{n}{\nu}S(S+1)[ln(eV/k_BT_K)]^{-4}\frac{1}{E^2}. \qquad (1)$$

If $eV < (k_BT, k_BT_K)$, then the scattering rate reduces to the Fermi liquid form.

3.3 Dephasing rate for $E > k_BT_K$

The dephasing rate is given in a form similar to the standard Suhl-Nagaoka expression. In the nonequilibrium case, the dephasing rate is dominated by the magnetic scattering due to spin-flip processes with a spin-flip rate given by:

$$\frac{1}{\tau_s} = \frac{c}{2\pi\hbar N(E_F)}\frac{\pi^2 S(S+1)}{\pi^2 S(S+1) + ln^2(eV/k_BT_K)}. \qquad (2)$$

The temperature-independent dephasing rate for $eV > (k_BT, k_BT_K)$ can be expressed as

$$\frac{1}{\tau_{\phi 0}} \simeq \pi^2 S(S+1) ln^{-2}(eV/k_BT_K). \qquad (3)$$

Once again, if $eV < k_BT$, then k_BT replaces eV, giving the standard Suhl-Nagaoka result.

3.4 Low magnetic field

All the interference measurements are done in presence of a finite magnetic field. The Zeeman splitting of the conduction electron states affects the interference correction. In a series of recent papers various limits of the magnetic field have been studied in detail.[6,7)] However, it is essential to note that in all these limits the spin is partially polarized, and the conduction electron state assumes a partial or full Zeeman splitting. At low magnetic fields, $g\mu B$ replaces eV in the above expressions. The crossover regime has been recently studied in ref[7] and the two extreme limits have been studied in ref.[6]

3.5 *High magnetic field*

If the field is so strong that the spin is completely polarized along the field there will be no spin-flip, and the mechanism vanishes. The magnetic impurity merely operates as a local point-like disorder, and makes negligible contribution to the conventional transport quantities in disordered systems.

3.6 *Dependence on bias voltage or current*

The temperature independence primarily comes from an energy scale larger than the temperature—for example eV or $\hbar\omega$ or $g\mu B$. In the case of bias-dominated nonequilibrium scattering, there is a well-defined dependence of dephasing time on the bias voltage or current:

$$\frac{1}{\tau_{\phi 0}} \propto \frac{1}{ln^2(eV/k_B T_K)} \equiv F_{Suhl-Nagaoka}. \quad (4)$$

Since $F_{Suhl-Nagaoka}$ is a rapidly-varying function of the bias voltage, it serves as a definitive check to verify whether the dephasing rate is indeed primarily determined by the mechanism being discussed here.

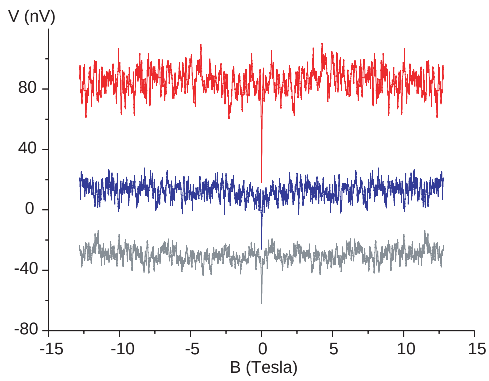

Fig. 5. Magnetoresistance of three quasi-1D gold wires over a field range of ± 15 tesla. At low fields, a dip in the resistance is observed due to the weak anti-localization. Antilocalization instead of localization is observed in gold samples because of strong spin-orbit scattering. The fluctuations at higher fields are the reproducible conductance fluctuations. We show the the voltage in the y-axis rather than the resistance change. The dimensions of the three samples are the following: 18 nm thick, 30 nm wide and 20 μm long. The resistance of the three samples are 2390 Ω, 2886 Ω and 3115 Ω.

3.7 *Electron-electron interaction to conductivity*

Electron-electron interaction or the Altshuler-Aronov correction to the conductivity in normal metals appears due to the modification of the Coulomb interaction by the introduction of nonmagnetic impurities or disorder. Mgnetic impurity spins do not give a substantial contribution to the corrections to the Coulomb interaction because of the lack of translation invariance. Therefore, the effect of the Glazman-Kaminski mechanism is not expected to be observable in the measurement of electron interaction correction. In quasi-one-dimensional disordered metallic wires, the form of the electron-electron interaction correction $\Delta\rho_{ee} \propto 1/\sqrt{T}$ remains practically unchanged in presence of a very small number of magnetic impurities.

3.8 *Estimation of impurity concentration*

Let us estimate the concentration and the number of magnetic impurity spins in a prototype quasi-1D wire, assuming that all the necessary conditions for the proposed mechanism are met. In fact, almost none of the conditions, including the nonequilibrium assumption, are satisfied. Nevertheless, it is important for the rest of the analysis to proceed with a definitive number. (The self contradiction in the following analysis is necessary to understand the original data[4] in the framework of the proposed mechanism.)

We choose the parameters for a typical sample given in ref.[4] We assume iron (Fe) to be the dominant magnetic impurity in gold with a Kondo temperature T_K of 0.3 Kelvin. In order to obtain a saturation time of $\sim$ 4 ns with a bias voltage of $10\mu V$, one would require on the order of 1 ppb (part per billion) impurity concentration.

The typical spectroscopic detection sensitivity for impurity ions in a (bulk) sample is $\sim$ 1 ppm. The suggestion that 1 ppb of magnetic impurity ions will be sufficient in yielding the saturation makes it experimentally impossible to do a direct and controlled check.

Now let us consider the concetration level of 1 ppb and evaluate the number of impurities in a given quasi-1D wire. For the experiments to be discussed in the next section, let us evaluate the number in a 4-micron-long quasi-1D wire with a rectangular cross section of 20 nm x 30 nm. A concentration of 1 ppb translates to a total of 0.15 magnetic-impurity ions out of 150 million gold ions. Since a fraction of an ion does not make much sense, we will assume that the requirement for the proposed mechanism is to have only one magnetic impurity ion in the entire sample.

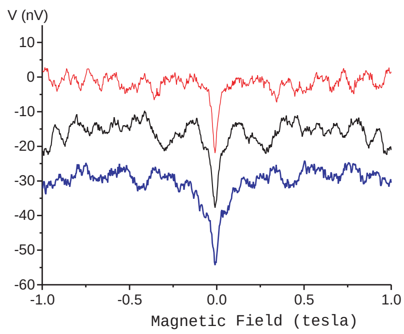

Fig. 6. Both conductance fluctuations and weak localization contributions are shown within a field span of 1 tesla. These samples are short compared to the earlier weak-localization samples so that the conductance fluctuations will not average out.

4. Experiments at high fields

It is extremely difficult to ion implant a single ion into a nanoscale structure to perform the kind of controlled measurements reported in ref.[5] In other fields such as spintronics and spin-based quantum computation, the holy grail is to detect, control and manipulate a single spin. For the purpose of determining whether or not the proposed mechanism is the dominant mechanism in causing the saturation of decoherence time, we have performed a different set of experiments. In the following, we report the results of our experiments in which the mechanism was purposefully switched off by applying a very large magnetic field. The magnetic-impurity spin, irrespective of its number or concentration, aligns along the magnetic field (on the order of tesla and larger). Once the spin freezes, it becomes irrelevant to the transport properties.

Our goal is to measure decoherence time with conductance fluctuations at high magnetic fields. Since the proposed mechanism is not present at high fields, the conventional Fermi liquid behavior is expected to be recovered. If we observe a saturation in the decoherence time, commensurate with the saturation observed in low-field measurements, then it is certain that the saturation effect is not due to any magnetic-impurity-based mechanism.

Figures 5 and 6 display the magnetoresistance traces for three quasi-1D gold wires, fabricated from gold with a purity of 99.99995ensure the high quality and reproducibility of these wires. The sample length of 20 μm is designed to be roughly 5 L_ϕs long at a temperature of 40 mK. The reason is to observe both weak localization and conductance fluctuations in the same sample, albeit in different field ranges, to allow a comparison of decoherence times obtained by two methods. It would also allow to address a theoretically relevant issue: Is the decoherence time from electron-electron interaction same for both conductance fluctuations and weak localization? Since our main focus is to study the temperature dependence of τ_ϕ at high fields in the context of the Glazman mechanism, the comparison between weak localization and conductance fluctuations will be discussed elsewhere.

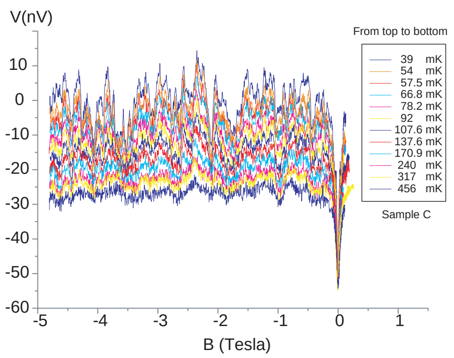

Fig. 7. Temperature dependence of the conductance fluctuations as well as weak localization within a field span of 5 tesla.

Fluctuations are defined in terms of their statistical properties: moments and cumulants. Each moment of conductance fluctuations is well-described in the standard theory of Universal Conductance Fluctuations.[9] The mean or average, which basically gives the baseline about which the fluctuations occur, is the classical conductance with a temperature dependence given by the electron-electron interaction correction to the conductivity. Figure 8 shows the temperature dependence of the mean in one of the samples, obtained by averaging the fluctuations outside the window of $\pm$ 1 tesla. The temperature dependence is precisely what is expected for a quasi-1D disordered wire: $1/\sqrt{T}$. This serves as an important first check as to whether a sample is well behaved or not.

The second moment or the the RMS value of the fluctuations δG_{RMS} is due to quantum mechanical interference. For a completely phase-coherent sample, the size of the fluctuations has the universal value of e^2/h. However, finite temperature, characterized by the length $L_T = \sqrt{\hbar D/k_B T}$, suppresses the fluctuations by energy averaging. Likewise, finite dephasing, characterized by $L_\phi = \sqrt{D\tau_\phi}$, causes a further suppression by breaking the sample into a number of statistically-independent segments. The RMS-value of the conductance fluctuations[9] is given by

$$\delta G_{RMS} \simeq C\frac{e^2}{h}(\frac{L_\phi}{L})^{3/2}\frac{L_T}{L_\phi}. \tag{5}$$

The constant C is $\sqrt{8\pi/3}$. Using this expression the dephasing length L_ϕ and dephasing time $\tau_\phi = L_\phi^2/D$ can be easily determined.

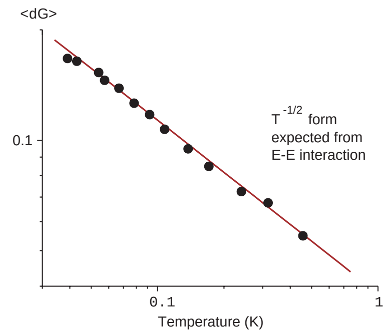

Fig. 8. Temperature dependence of the mean value of the conductance is well described by the electron-electron interaction correction to conductivity with the expected form $1/\sqrt{T}$.

In order to visually inspect the temperature dependence we plot the RMS value of the conductance fluctuations. The straight line is a fit to $L_T \propto 1/\sqrt{T}$. It is obvious from the fit that the temperature dependence of ΔG_{RMS} is mostly governed by the temperature dependence of L_T, and L_ϕ is almost temperature independent. The second set of data in the bottom show the corresponding τ_ϕ, which clearly saturated below 500 mK. Note that at higher temperatures the determination of τ_ϕ becomes inaccurate due to the rapid suppression of the fluctuations.

Comparison of τ_ϕ obtained from fluctuations above 1 tesla with the conventional $T^{-2/3}$-dependence of Nyquist noise is shown in figure 10 for an additional sample.

τ_ϕ from conductance fluctuations can also be obtained from the autocorrelation function of the conductance. An important aspect of the method is that the autocorrelation function does not involve the energy averaging or the L_T dependence. Fig. 11 shows the autocorrelation function for a sample at 39 mK. The correlation field B_c is given by the field lag ΔB where the autocorrelation

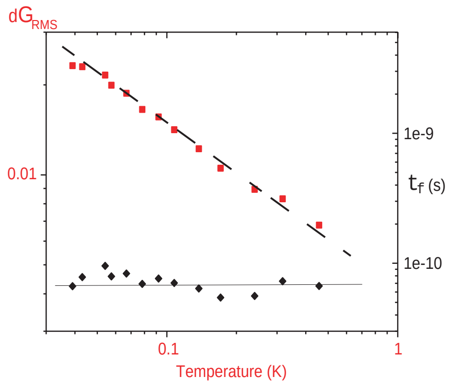

Fig. 9. The root-mean-square of the conductance fluctuation is well described by energy averaging, or $L_T \propto 1/\sqrt{T}$. The corresponding τ_ϕ shows a strong saturation below 500 mK.

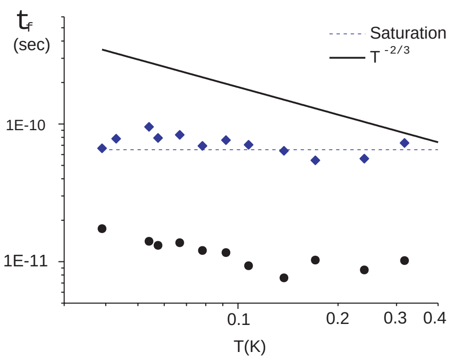

Fig. 10. Decoherence time extracted from the rms value of conductance fluctuations.

function is half of its zero field value.

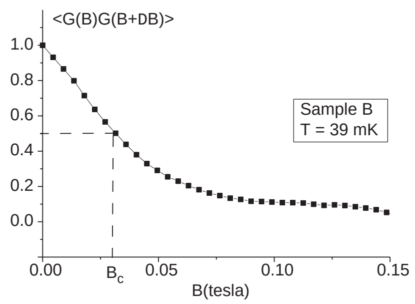

Fig. 11. The typical autocorrelation function of the conductance fluctuations in one of the samples.

5. Discussion

From the series of measurements, reported here and elsewhere, it is observed that the decoherence time measured at high fields also saturates at low temperature. In the new experimental data presented here, the saturation is observed in both methods of extraction of τ_ϕ from conductance fluctuations: the rms value and the autocorrelation. The saturation observed here commensurates with the saturation observed in the weak localization measurements.

These measurements suggest that the saturation observed at high fields are independent of mechanisms in-

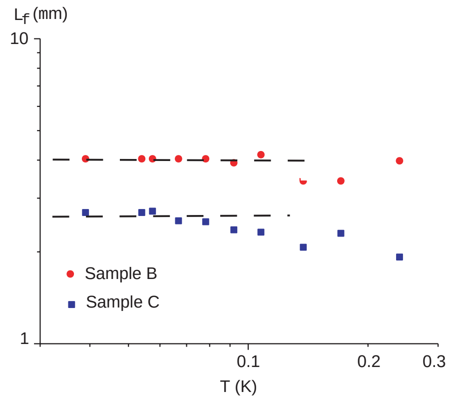

Fig. 12. Temperature dependence of the dephasing length for two samples extracted from the correlation field scale B_c.

volving magnetic impurities at any level.

As mentioned in this paper, the proposed mechanism of electron-electron interaction is valid only under certain conditions, and most of these, including the nonequilibrium condition is not met in our measurements of conductance fluctuations and weak localizations reported here and elsewhere.[4] The original experiments on weak licalization reported in ref[4] also included the checks for magnetic impurities by a variety of high-field and low-field measurements. For example, in the experiments reported in ref,[4] the temperature dependence of τ_ϕ is done only in the linear-response regime where τ_ϕ (or weak localization) is completely independent of the bias current. Therefore, the observed saturation in those samples could not be due to any mechanism which predicts a (strong) dependence on the bias. Furthermore, being equilibrium measurements in the linear response regime, the data of the experiments in ref[4]could not possible be affected by a nonequilibrium mechanism such as the one discussed at length in this paper.

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