Remanence effects in the electrical resistivity of spin glasses

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received 16 November 2010; accepted 4 January 2011
published online 7 February 2011

PACS 73.23. -b - Electronic transport in mesoscopic systems
PACS 75.50.Lk - Spin glasses and other random magnets
PACS 75.20.Hr - Local moment in compounds and alloys; Kondo effect, valence fluctuations, heavy fermions

Abstract – We have measured the low-temperature electrical resistivity of Ag:Mn mesoscopic spin glasses prepared by ion implantation with a concentration of 700 ppm. As expected, we observe a clear maximum in the resistivity \( \rho(T) \) at a temperature in good agreement with theoretical predictions. Moreover, we observe remanence effects at very weak magnetic fields for the resistivity below the freezing temperature \( T_{sg} \): upon Field Cooling (FC), we observe clear deviations of \( \rho(T) \) as compared with the Zero-Field Cooling (ZFC); such deviations appear even for very small magnetic fields, typically in the Gauss range. This onset of remanence for very weak magnetic fields is reminiscent of the typical signature on magnetic susceptibility measurements of the spin glass transition for this generic glassy system.

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Spin glasses are one of the most intriguing states of matter, and have been the subject of intense theoretical as well as experimental works over the last decades [1,2]; this is due to the fact that they can be considered as the most generic example of a glassy phase [3] but also because the very nature of the ground state of these systems is still heavily debated and may eventually consist in a very peculiar state of matter [4,5]. In spin glasses (SG), magnetic moments occupying random positions in a metallic host interact via RKKY interactions; the randomness in the position of these moments leads to a randomness in both the sign and the amplitude of their mutual interaction. Below the spin glass transition temperature \( T_{sg} \), the interplay between disorder and frustration will freeze the magnetic spins in a complex way far from being well understood. Most of the experimental studies on spin glasses has been carried out on macroscopic systems: only few papers addressed the question of mesoscopic spin glasses, either theoretically [6–10] or experimentally [11–13]. Moreover, most of the measurements concerned thermodynamic quantities, mainly magnetic susceptibility [14–16]: very few experiments addressed the question of the transport properties of mesoscopic spin glasses [17–19] and their interpretation remains a theoretical challenge [20–22].

The most convincing signature that the spin glass transition may actually be a real phase transition is the cusp which appears in the low-field magnetic susceptibility at the transition temperature [14]. On the other hand, one of the most fascinating properties of spin glasses, which makes this state of matter a very peculiar one, is the onset of remanence effects for very weak magnetic fields below \( T_{sg} \): the dc susceptibility \( \chi_{dc} \) of a spin glass depends strongly on the way the experiment is performed, in particular if the cooling through \( T_{sg} \) has been made under a small magnetic field (Field Cooled) or without magnetic field (Zero-Field Cooled). Experimentally, \( \chi_{dc} \) is much larger after Field Cooling than after Zero-Field Cooling [14,23]. We would like to stress that the magnetic fields involved in these experiments are very small, typically in the Gauss range, i.e. \( \mu_B B \ll k_B T_{sg} \), with \( \mu_B \) the Bohr magneton, \( k_B \) the Boltzmann constant and \( B \) the magnetic field: this means that the remanence effect
has nothing to do with a trivial effect of polarization of the spins, but is a true signature of the somehow “unconventional” nature of the spin glass transition.

In this letter, we show that such remanence effects can also be observed on the electrical resistivity of metallic spin glasses. We show that the resistivity $\rho$ as a function of temperature $T$ of a Ag:Mn spin glass exhibits a clear maximum at a temperature, in excellent agreement with the theoretical prediction of Vavilov et al. [22] and with previous experiments on bulk spin glasses [17–19]. In addition, we observe a remanence effect on the $\rho(T)$ curve, an effect that has never been observed so far on transport properties: when cooling down from above $T_{sg}$ under very small magnetic field, i.e. when Field Cooling the sample, the resistivity is significantly lower compared to when cooling down under zero magnetic field. Such irreversibilities disappear at the transition temperature, as observed on thermodynamic quantities.

Samples are fabricated on a silicon substrate using electron-beam lithography on polymethyl-methacrylate resist. Silver has been evaporated in an electron gun evaporator from a 99.9999% purity source without adhesion-layer. The geometry of the samples can be seen in fig. 1: it consists of a short wire of length $\approx 1 \mu m$, width $\approx 50 \text{ nm}$ and thickness $\approx 50 \text{ nm}$. Several voltage contacts have been designed in order to perform four-points measurements. Mn$^{2+}$ ions are then implanted at an energy of 70 keV; the energy has been chosen so that the implantation takes place mainly in the silver layer. The reason for choosing manganese as magnetic impurity is twofold: firstly, Ag:Mn is a “generic” spin glass system which has been widely studied [17–19] and thus its physical characteristics are well known. Secondly, the Kondo temperature $T_K$ of manganese in silver is in the millikelvin range [24]: it is thus easy to reach a regime where the spin glass transition appears at a much higher temperature than the Kondo temperature, $T_{sg}>T_K$; in this case the Kondo-related physics can be neglected [25]. In our case the ion dose, measured via the current out of the implanter, has been chosen such that the final concentration in the sample is 700 ppm; this leads to a spin glass transition temperature of $\approx 700 \text{ mK}$, i.e. $T_{sg}>10T_K$. Finally, let us stress that the implantation process excludes the possibility of clustering or diffusion of the Mn$^{2+}$ ions as no further annealing has been performed on the samples.

Resistance measurements have been performed using a standard ac lock-in technique with a very low current ($\leq 500 \text{ nA}$) at a frequency of 11 Hz. The signal is amplified using an ultra-low noise (400 pV/$\sqrt{\text{Hz}}$) homemade preamplifier at room temperature. As the relative variations of the signal we want to extract are very small, the measurements are made in a bridge configuration in order to compensate for the residual resistance of the sample.

The sample is fixed at the coldest part of a dilution refrigerator and connected to the measurement setup via coaxial cables which ensure a very efficient radio-frequency filtering [26] and thus allow electrons to be cooled down to less than 40 mK [27]. At 4.2 K, the resistance of our samples is of the order of $\approx 100 \Omega$.

At low temperature, the variation of the resistance as a function of temperature is due to three main contributions: the electron-phonon interaction, mainly efficient at “high” temperature, the electron-electron interaction which leads to a modification of the density of states at the Fermi energy (the “Altshuler-Aronov” (AA) correction) [28] and an extra term $\Delta R_{sg}$ which we attribute to the glassy nature of the system:

$$\Delta R = \Delta R_{e-ph} + \Delta R_{e-e} + \Delta R_{sg}$$

where $\Delta R_{e-ph}$ being dominant only at high temperature ($T>4 \text{ K}$). The second one can be expressed as [29]

$$\Delta R_{e-e} = \alpha_{e-e} \frac{R^2}{R_K} \frac{L_T}{L},$$

where $R_K$ is the quantum of resistance $R_K = h/e^2$ with $h$ Planck’s constant and $e$ the charge of the electron, and $L_T$ is the thermal length, $L_T = \sqrt{\frac{hD}{k_B T}}$. $D$ being the diffusion coefficient, $k_B$ Boltzmann’s constant and $T$ the temperature. In order to evaluate the prefactor $\alpha_{e-e}$, we have measured the AA correction to the resistance on a longer and pure (non-implanted) wire fabricated in the same evaporation run as the short wires: when plotted as a function of $1/\sqrt{T}$, the low-temperature resistance of the wire varies linearly, as can be seen in fig. 2; this ensures a good and reliable determination of the parameter $\alpha_{e-e}$, that we find equal to 2.42, in good agreement with values found in the literature [29].

We now turn to the resistivity measurements on the Ag:Mn spin glass system under zero magnetic field.
Resistivity as a function of $1/\sqrt{T}$ is displayed in the inset of fig. 3: contrary to the case of pure silver, clear deviations from the $1/\sqrt{T}$ are observed below 1.5 K, and can be attributed to the spin glass transition. In order to separate the spin glass contribution to the resistivity, we have subtracted the electron-electron interaction contribution to the resistivity (second term of the eq. (1)); the resulting $\Delta \rho_{sg}(T)$ is displayed in fig. 3.

A clear maximum in the $\Delta \rho_{sg}(T)$ curve appears at a temperature of $T_m \approx 2$ K. This maximum, which has been observed in different magnetic alloys at higher concentrations [18], is a clear signature of the spin glass transition. We can go further in the analysis by fitting the data with the formula suggested by Vavilov et al [22]:

$$\Delta \rho_{sg}(T) \propto \frac{S(S + 1)}{\ln^2(T/T_K)} \left( 1 - \frac{\beta T_{sg}}{T} \right), \quad (3)$$

where $S$ is the spin of the magnetic impurity, $T_K$ its Kondo temperature (40 mK for Mn in Ag), $T_{sg}$ the spin glass transition temperature and $\beta$ a numerical factor of order 1. As can be seen in fig. 3, a qualitative agreement is obtained between formula 3 and the experimental data using the parameters $T_{sg} \approx 700$ mK and $\beta = 2.33$ as expected for a spin $S = 5/2$ [22]. The discrepancies can be understood by noting that the theoretical formula is valid only for $T_{sg} \leq T \leq T_m$: within this interval, one can verify that the agreement is quantitatively good. Moreover, the $T_{sg}$ obtained by this procedure is in agreement with the transition temperature measured on macroscopic Ag:Mn spin glasses of equivalent concentration using other measurement techniques (magnetic susceptibility, specific heat) [17,18].

One of the most striking characteristics of spin glasses lies in the onset of remanence effects below $T_{sg}$; the most spectacular manifestation of this remanence appears in the static magnetic susceptibility $\chi_{dc}$, which has been shown to strongly depend on the history of the sample [15]: even for very small magnetic field (in the Gauss range), if the field is applied above $T_{sg}$ and kept fixed down to a temperature below $T_{sg}$ (FC), $\chi_{dc}^{(FC)}$ is larger than after Zero-Field Cooling (ZFC) and roughly temperature independent [30,31].

Spin glass transitions have been previously observed in transport using the anomalous Hall effect [32], but never in the resistivity. In particular, remanence effects are well known in the susceptibility but have never been identified in the resistivity. Such a characteristic effect has ever been observed on any physical quantity other than the magnetic susceptibility; in particular, no remanence effect has ever been reported concerning the transport properties of spin glasses. We have thus measured the ZFC and FC resistivity of our Ag:Mn alloy under small magnetic fields of 5G, 10G and 35G (applied above $T_{sg}$ and kept fixed during cooling-down). Raw data are presented in the inset of fig. 4: the change in the resistivity when decreasing the temperature is mainly due to the electron-electron interaction (AA correction). In order to highlight the onset of remanence on the resistivity of the spin glass below $T_{sg}$, we have subtracted to the Field Cooled ($\Delta \rho_{FC}(T)$) curves the Zero-Field–Cooled curve ($\Delta \rho_{ZFC}(T)$) used as a “reference” measurement. The result ($\Delta \rho_{FC}(T) - \Delta \rho_{ZFC}(T)$) is displayed in fig. 4. In order to estimate the uncertainty on these data, we have also measured the drift of our experimental setup over the typical time of our measurements (several hours), at constant temperature: the result is displayed on the same graph, and clearly shows that this drift is much smaller than our signal; moreover, the FC curve is perfectly reversible, i.e. the $\Delta \rho_{FC}(T)$ curve follows exactly the same trace when subsequently heating the sample up to

![Graph showing resistivity as a function of 1/√T for a pure silver wire. The variation is perfectly linear and the fit allows to determine the coefficient α_pure silver]
We have measured the resistivity of mesoscopic Ag:Mn spin glass wires. The Mn$^{2+}$ magnetic impurities have been implanted in the metal with an energy of 70 keV and a concentration of 700 ppm. At low temperature, the resistivity of the spin glass as a function of the temperature exhibits a clear maximum at a temperature in excellent agreement with theoretical predictions; when lowering further the temperature, the resistivity decreases, a behaviour that is also captured by recent theoretical models. Finally, we observe the onset of remanence effects below $T_{sg}$: when cooling down under a very small magnetic field (in the G range) (fc procedure), the temperature dependence of the resistivity is significantly different than the one measured when cooling down with no magnetic field (zfc procedure). This fc behaviour is perfectly reversible and appears at the freezing temperature, similarly to what is observed on bulk samples when measuring the magnetic susceptibility. A deeper theoretical comprehension of the spin glass transition is certainly necessary in order to have a quantitative description of these remanence effects.

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We are indebted to H. BOUCHIAT and the Quantronics group for the use of their Joule evaporators. We thank G. PAULIN, E. ORIGNAC, L. GLAZMAN, B. SPIVAK and R. WHITNEY for fruitful discussions. This work has been supported by the French National Agency (ANR) in the frame of its “Programmes Blancs” (MesoGlass project).

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