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Universal conductance fluctuations and low-temperature $1/f$ noise in mesoscopic AuFe spin glasses

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We report on intrinsic time-dependent conductance fluctuations observed in mesoscopic AuFe spin-glass wires. These dynamical fluctuations have a $1/f$-like spectrum and appear below the measured spin-glass freezing temperature of our samples. The dependence of the fluctuation amplitude on temperature, magnetic field, voltage, and Fe concentration allows a consistent interpretation in terms of quantum interference effects, that are sensitive to the slowly fluctuating spin configuration.

The low-field magnetic susceptibility of a spin glass[1] shows a sharp peak near the freezing temperature T_f. Below T_f, the magnetic impurity spins gradually freeze into random directions. The magnetization contains a $1/f$ noise component[2] that appears in the vicinity of T_f and saturates below the freezing temperature.[3,4] The resistance of small spin-glass samples also contains a $1/f$ noise component related to the slow dynamics of the frozen spins.[5] The resistance noise may appear because of electron quantum interference effects that are sensitive to the slow fluctuations of the magnetic impurity configuration in the spin-glass phase.[6,7]

Quantum interference effects give rise to universal conductance fluctuations (UCF), which for a stable defect configuration induce reproducible fluctuations of the magnetoconductance (magnetofingerprint).[8] In a sample having dimensions comparable to the phase-coherence length L_φ, the fluctuation amplitude is of the order of the conductance quantum e^2/h.[9] In larger samples, a slow stochastic averaging of the UCF occurs. For sufficiently small non-magnetic samples, switching of a defect between two stable configurations (two-level system) gives rise to a UCF-induced telegraph noise signal.[10] For larger nonmagnetic samples, superposition of telegraph noise signals results in a $1/f$ noise spectrum.[11,12] In mesoscopic spin glasses, the UCF will be largely destroyed by the spin-flip scattering in the paramagnetic phase above T_f. Below T_f, the dramatic slowing down of the spin-glass dynamics should allow the experimental observation of a UCF-induced noise signal.[6]

Israeloff *et al.*[13] have measured the $1/f$ electrical noise in CuMn spin-glass films with a Mn content between 4.5 and 19.5 at. %. The noise amplitude shows a rapid increase near T_f followed by a saturation at lower temperatures, which is interpreted in terms of the UCF-induced noise mechanism. In smaller, mesoscopic samples, the noise signal strongly deviates from the usual Gaussian statistics.[14] The resulting spectral wandering of the noise spectrum favors a description of the spin-glass dynamics in terms of a hierarchical model with correlated fluctuations. Similar experiments by Meyer and Weissman on AuFe samples reveal deviations from both the droplet model and the hierarchical model for mesoscopic sample sizes.[15] Measurements by de Vegvar *et al.*[16] on mesoscopic CuMn wires with a Mn concentration of 0.1 at. % indicate the presence of a magnetofingerprint that is stable in time. The fingerprint is strongly altered after heating the samples to temperatures well above T_f. According to the authors, this supports the idea that the UCF are sensitive to the specific frozen spin configuration. Very recently, Jaroszyński *et al.*[17] have observed a $1/f$ noise signal in heavily doped $Cd_{1-x}Mn_xTe$ spin-glass wires with a Mn concentration $x=0.02$ and $x=0.07$. The $1/f$ noise in the dilute magnetic semiconductors is consistent with the presence of UCF-induced fluctuations. The onset of the $1/f$ noise signal coincides with the bulk T_f value, while typical spin-glass properties such as aging and irreversibility are clearly present. For the $Cd_{1-x}Mn_xTe$ spin-glass compounds, the spectral wandering of the noise spectrum rather favors an interpretation in terms of uncorrelated droplet excitations.

In this paper, we report on high-resolution measurements of the electrical noise in small samples of the archetypical spin glass AuFe with Fe concentrations of 0.85 and 5 at. %. The spin-flip scattering at the Fe impurities largely destroys the static magnetofingerprints. We are able to detect an excess $1/f$ noise signal whose amplitude rapidly grows at lower temperatures. Both the temperature and current dependence of the $1/f$ noise are in agreement with UCF reflecting the dynamics of the impurity spin configuration. Our $1/f$ noise is strongly suppressed at the elevated measuring currents that have been used by Israeloff *et al.*[13,14] The low-frequency noise in the AuFe spin glasses can be observed because of a dramatic slowing down of the spin dynamics due to the freezing process.

We have performed detailed measurements of the electrical noise in narrow AuFe spin-glass wires as well as in a pure Au test wire. Table I gives the relevant parameters for the samples that have been studied. The narrow wires are obtained by flash evaporation of small pieces of a AuFe mother alloy in resist profiles defined by electron-beam lithography, followed by lift-off. For the pure Au sample, thermal evaporation of 99.9999 % pure Au has been used. Secondary-ion mass spectroscopy (SIMS) measurements indicate that distillation effects occurring during the AuFe flash evaporation are negligible. The absence of distillation effects is confirmed by the temperature dependence of the spin-glass resistivity[20] as well as by the temperature dependence of the anomalous Hall resistivity[21] in thicker AuFe

TABLE I. Relevant parameters for the AuFe wires with different Fe concentration c: width w, length L, thickness t, resistivity ρ, and elastic mean free path l_{el}.

Sample	c (at. %)	L (μm)	w (nm)	t (nm)	ρ ($\mu\Omega$ cm)	l_{el} (nm)
$W1$	0	1.48	184	30	3.15	26.7
$W2$	0.85	1.46	187	23	13.1	6.44
$W3$	0.85	7.82	752	23	13.5	6.24
$W4$	5	1.49	170	35	34.3	2.45

films (see also below). The noise experiments have been performed with a five-terminal bridge configuration and an ac measuring current of a few kHz. A transformer (100:2000 winding ratio) cooled with liquid helium amplifies the voltage fluctuations produced by the sample and at the same time adapts the sample impedance to obtain an optimum noise figure for detecting the sample voltage with a lock-in amplifier (PAR 124A). We are able to reliably detect voltage variations having a root-mean-square (rms) amplitude of only 0.1 nV.

In Fig. 1, we show the time dependence of the conductance fluctuations that appear in a 5 at. % AuFe sample (sample $W4$ in Table I) at different temperatures. For the measurements, a 1-s cutoff filter has been used, implying that fluctuations with a higher frequency are filtered out. At $T=0.47$ K, the peak-to-peak variations of the conductance noise correspond to $0.1e^2/h$. This is a first hint that supports an interpretation in terms of UCF that are coupled to the slow dynamics of the impurity spins below T_f.[6] The additional steplike changes of the conductance, which become visible at $T=1.00$ K and $T=2.94$ K in Fig. 1, may be linked to the thermally induced motion of spin clusters.[1]

In Fig. 2(a), the noise power spectra $S_G(f)$ corresponding to the data in Fig. 1 have been plotted on a double logarithmic scale. The low-frequency noise rapidly grows at lower temperatures. Below 1 K, the noise spectra can be fitted to a $1/f^{\alpha}$ dependence indicated by the dashed lines in Fig. 2(a). The exponent $\alpha \simeq 1.5$ for $T=1.00$ K and decreases towards $\alpha \simeq 1.3$ for $T=0.47$ K. At higher temperatures, the $1/f^{\alpha}$ dependence is on average still present, but an accurate determination of α is not possible for the available time window. Averaging noise spectra for different cooling cycles should be avoided in view of the sensitivity to the particular frozen spin-glass state (see also below). Above 5 K, the noise spectra become independent of frequency and temperature and are governed by external noise sources. In Fig. 2(b), we compare the voltage noise spectra $S_V(f)$ at $T=0.47$ K for the 5 at. % AuFe sample and a pure Au test sample of comparable dimensions (sample $W1$ in Table I). For the pure Au sample, no excess $1/f$ noise can be detected within our measuring sensitivity.

An excess noise signal is also clearly present at lower temperatures for the AuFe samples having an Fe concentration of 0.85 at. %. Again, the noise rapidly grows at lower temperatures $T<1$ K and can be described by a $1/f^{\alpha}$ dependence with α in the vicinity of 1. In Fig. 3, we compare the temperature dependence of the integrated noise power for the 5 at. % sample and a 0.85 at. % sample with comparable dimensions (sample $W2$ in Table I). The plotted noise pow-

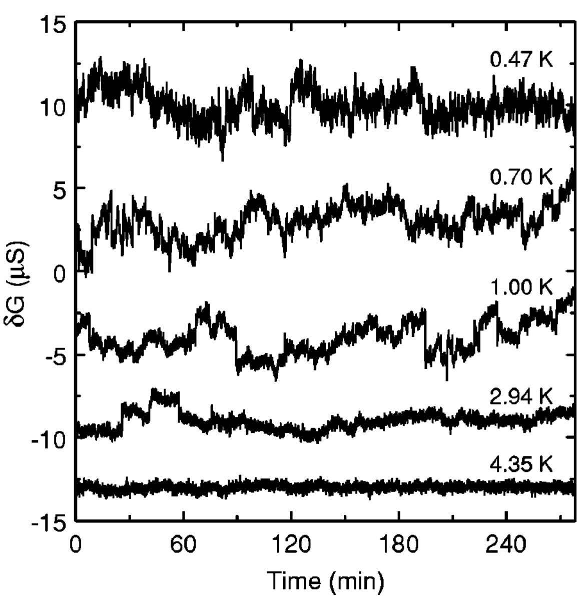

FIG. 1. Time-dependent fluctuations of the conductance in a 5 at. % mesoscopic AuFe structure (sample $W4$ in Table I). The data are obtained by subsequent cooling of the sample toward lower temperatures, i.e., without cycling through the spin-glass freezing temperature T_f.

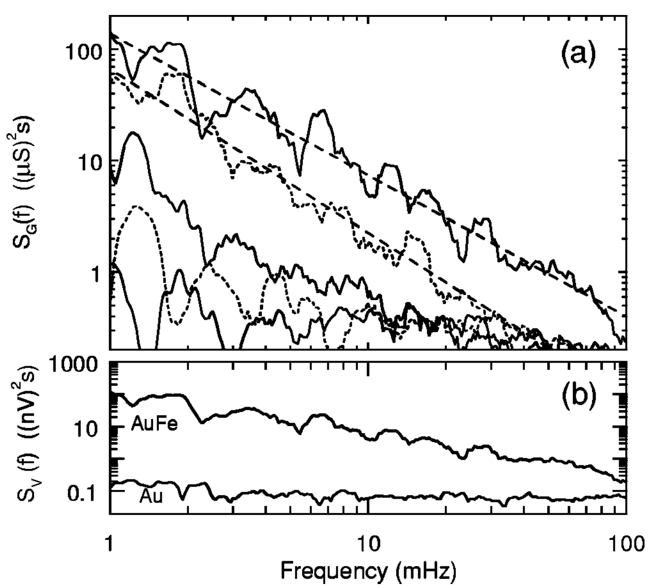

FIG. 2. (a) Noise spectra corresponding to the data shown in Fig. 1 at temperatures $T=0.47,1.00,2.94,7.20,12.3$ K from top to bottom. The dashed curves correspond to a $1/f^{\alpha}$ dependence (see text). (b) Comparison of the voltage noise spectra at $T=0.47$ K for the 5 at. % sample and for a pure Au sample (sample $W1$ in Table I).

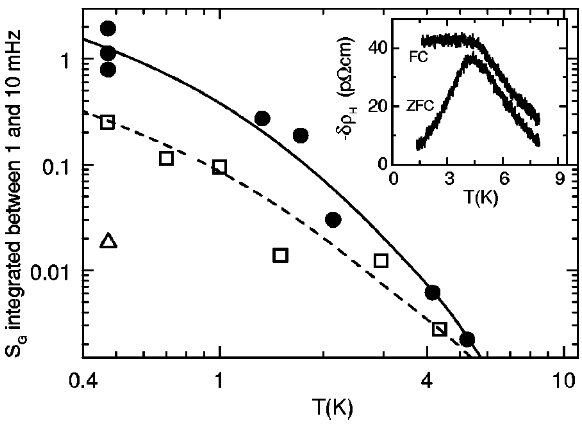

FIG. 3. Temperature dependence of the integrated conductance noise power for the 5 at. % AuFe sample (□) shown in Fig. 1 and Fig. 2(b) as well as for a 0.85 at. % sample (●) (sample $W2$ in Table I). Both samples have the same dimensions. The curves through the data points are only a guide to the eye. For comparison, the integrated noise power is also shown for a wider 0.85 at. % sample (△) (sample $W3$ in Table I). The inset shows the temperature dependence of the Hall resistivity for a 0.85 at. %, 3-mm-wide film measured for field-cooled (FC) and for zero-field-cooled (ZFC) conditions, respectively.

ers have been integrated between 1 and 10 mHz and have been corrected for the extrinsic white background noise. The integrated noise power has a comparable temperature dependence for both Fe concentrations, but is larger in the sample with the lower Fe concentration.

According to Feng *et al.*[6] the conductance noise is related to the electron phase-coherence length $L_\varphi(T)$ and the imaginary part χ'' of the spin susceptibility:[18]

$$S_G(f)=\frac{e^4}{2\pi h^2}\frac{k_F L_\varphi^3(T)}{L l_{el}}\frac{2k_B T^2}{E_F}\frac{\chi''(T,f)}{f}, \tag{1}$$

with l_{el} the elastic mean free path of the electrons. If we assume that χ'' depends only weakly on frequency for $T<T_f$,[19] Eq. (1) predicts a spectrum for S_G that is close to $1/f$. Below T_f, both χ' and χ'' slowly decrease with decreasing temperature reflecting the spin-glass freezing. The increase of the noise power at lower temperatures can then be linked to a drastic enhancement of the phase-coherence length L_φ which dominates all other temperature-dependent factors in Eq. (1). While inelastic scattering at phonons and the other electrons becomes less effective at lower temperatures, an additional increase of L_φ is caused by a reduction of the spin-flip scattering rate due to the spin-glass freezing process. This reduction of the spin-flip scattering at lower temperatures is confirmed by a decrease of the spin-glass resistivity below the freezing temperature.[20] The knowledge of $\chi''(T,f)$ in principle allows us to determine the influence of the spin-glass freezing on L_φ. This kind of information cannot be obtained from static magnetoresistance measurements. Since it is known that the spin-glass freezing [i.e., $\chi(T,f)$ and $R(T)$] becomes size dependent in reduced dimensions,[20] it is necessary to measure the susceptibility of mesoscopic samples with dimensions comparable to our samples. To our knowledge, such measurements have not yet been performed. While we cannot extract L_φ from Eq. (1), an alternative method to estimate L_φ will be discussed below.

The larger noise amplitude in Fig. 3 for the 0.85 at. % sample can be explained by a reduced spin-flip scattering rate due to the smaller Fe content. As pointed out by Jaroszyński *et al.*,[17] the emergence of the low-frequency noise requires that the spin-glass dynamics, which couples to the UCF, has become sufficiently slow, with characteristic relaxation rates corresponding to our experimental measuring frequencies.

In order to be sure that the pronounced increase of the conductance noise below 5 K is indeed related to the spin-glass freezing, we have monitored the freezing process via measurements of the anomalous Hall effect.[21] The inset of Fig. 3 shows the temperature dependence of the Hall resistivity for field-cooled (FC) as well as for zero-field-cooled (ZFC) measuring conditions. The data have been obtained for a 0.85 at. % AuFe film that is about 3 mm wide and has been deposited simultaneously with the samples $W2$ and $W3$ (see Table I). From the ZFC data we obtain a freezing temperature $T_f\simeq4.4$ K, which is considerably smaller than the bulk value $T_f\simeq7.8$ K. The reduction of T_f can be linked to finite-size scaling effects.[21] Although $T_f\simeq17$ K is considerably larger for the 5 at. % films ($T_f\simeq22$ K for the bulk alloy), the temperature dependence of the integrated noise power in Fig. 3 is similar for the 5 at. % sample and the 0.85 at. % sample, in contrast to the results obtained by Israeloff *et al.*[13] for CuMn alloys. Unlike these authors, we also do not find any evidence for a saturation of the $1/f$ noise signal at lower temperatures.

In Fig. 3, we have included the integrated noise power for a wider and longer 0.85 at. % AuFe sample (sample $W3$ in Table I) at the lowest measuring temperature ($T=0.47$ K). For sample sizes exceeding the phase coherence length L_φ (see below), stochastic self-averaging implies that the UCF amplitude scales with the inverse of the square root of the sample volume.[8] Consequently, the integrated noise power should scale with the inverse of the sample volume.[12] Our experiments indicate a reduction by a factor of 8.7, while theory predicts a reduction by a factor of 6.4.

While turning on a magnetic field of 3 T below T_f leaves the noise amplitude unchanged, field cooling in the presence of a 3 T field delays the increase of the spin-glass noise above the white background noise. This is illustrated in the inset of Fig. 4 for sample $W2$ (see Table I). In contrast to Fig. 3, the white background noise (corresponding to the dotted line) has not been subtracted from the data points in the inset of Fig. 4. A shift of the noise onset toward lower temperatures was observed before in CuMn (Ref. 13) and in AuFe (Ref. 15) samples. For the CuMn samples,[13] a dependence on field history similar to ours was reported. A suppression of the noise amplitude, which depends on the magnetic field applied during thermal cycling, supports the intrinsic spin-glass origin of the excess $1/f$ noise.[1] In contrast to noise experiments in nonmagnetic Bi samples,[12] we do not observe any reproducible magnetofingerprints. The coupling between the UCF and the fluctuating spin configuration is sufficiently strong in our samples to induce a complete scrambling of the magnetofingerprints.

An additional important piece of evidence in favor of the interpretation of the excess noise in terms of UCF is pro-

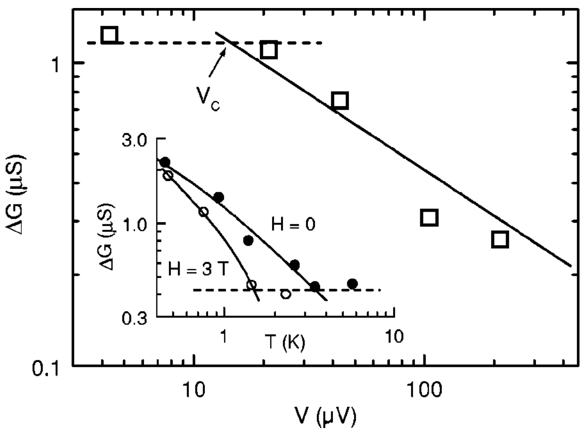

FIG. 4. Reduction of the rms conductance noise amplitude when increasing the voltage applied across the 5-at.% AuFe sample (sample $W4$ in Table I). The full line corresponds to the stochastic averaging $\propto V^{-1/2}$ that is expected to occur above the threshold voltage V_c (see text). The inset illustrates the reduction of the rms conductance noise amplitude when applying a 3-T magnetic field under field-cooled conditions for a 0.85-at.% AuFe sample (sample $W2$ in Table I). The full curves in the inset are only a guide to the eye, while the dotted line indicates the extrinsic white noise level.

vided by the strong reduction of the noise signal when increasing the measuring current. This is illustrated in Fig. 4 for the 5 at.% sample (sample $W4$ in Table I) at $T = 0.47$ K. The data points have in this case again been corrected to take into account the current independent white background noise. Due to the finite voltage across the sample, the carriers will sample $N = eV/E_c$ incoherent interference patterns, with $E_c = eV_c = \hbar D/L_\varphi^2$ the Thouless energy and D the diffusion constant. This leads to an increased current noise $\delta I \propto \sqrt{N}$. On the other hand, the conductance fluctuations $\delta G = \delta I/V$ decrease as $1/\sqrt{N} = (E_c/eV)^{1/2}$ (see also the discussion of Fig. 12 in Ref. 8). The full line in Fig. 4 corresponds to this theoretically expected reduction of the UCF at sufficiently large voltages. From the saturation at low voltages (dashed line), we infer a value for the Thouless energy $E_c \simeq 0.01$ meV, corresponding to a phase-coherence length $L_\varphi(T = 0.47\ \mathrm{K}) \simeq 0.3$ μm. Due to the spin-flip scattering, L_φ is about an order of magnitude smaller than for the pure Au sample. On the other hand, L_φ is about five times smaller than the sample length, but remains larger than the sample width. Taking into account the stochastic self-averaging of the UCF,[8] the rms conductance noise amplitude for the AuFe sample ($0.03e^2/h$, see Fig. 4) is about three times smaller than the rms amplitude of the magnetoconductance fluctuations in the pure mesoscopic Au sample at $T = 0.47$ K ($0.2e^2/h$). Taking into account that the finite frequency window of our noise measurements results in a reduction of the measured noise amplitude, this supports our interpretation that the observed noise indeed results from a scrambling of the magnetofingerprints due to the (slow) dynamics of the Fe impurity spins.

The results shown in Fig. 4 confirm that the UCF that cause the excess noise can only be observed for very small measuring currents. Israeloff *et al.*[13,14] have used measuring current densities that are about two orders of magnitude larger than in our case. This implies that their UCF-induced noise signal may have been strongly suppressed by electron heating effects.

Finally, we note that the conductance of our samples is always much larger than e^2/h, i.e., our samples reveal a pronounced metallic character. Jaroszyński *et al.*[17] have studied doped magnetic semiconductors that are very close to the metal-insulator transition. This results in a strong enhancement of the resistance noise amplitude (allowing to observe aging and hysteresis effects), but at the same time makes it more difficult for these authors to compare different samples. The noise properties are, however, remarkably similar, supporting a common origin of the $1/f$ noise for both experiments.

In conclusion, we have identified an intrinsic $1/f$ noise mechanism in narrow AuFe wires. The noise can be directly related to the spin-glass freezing process and can only be observed for very small measuring currents. Our results support the idea that the noise is caused by the time dependence of the universal conduction fluctuations. The noise only appears for temperatures below the freezing temperature T_f, where the electron phase coherence length is sufficiently long and the spin dynamics is sufficiently slow. Combined with measurements of the ac magnetic susceptibility in small samples, our noise measurements may be able to reveal the interplay between spin freezing and electron dephasing in mesoscopic spin glasses.

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