Quantum coherence in a ferromagnetic metal: time-dependent conductance fluctuations

Sungbae Lee, Aaron Trionfi, and Doug Natelson
Department of Physics and Astronomy, Rice University, 6100 Main St., Houston, TX 77005
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Quantum coherence of electrons in ferromagnetic metals is difficult to assess experimentally. We report the first measurements of time-dependent universal conductance fluctuations in ferromagnetic metal (Ni$_{0.8}$Fe$_{0.2}$) nanostructures as a function of temperature and magnetic field strength and orientation. We find that the cooperon contribution to this quantum correction is suppressed, and that domain wall motion can be a source of coherence-enhanced conductance fluctuations. The fluctuations are more strongly temperature dependent than those in normal metals, hinting that an unusual dephasing mechanism may be at work.

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While quantum coherence effects in normal metals are well established, few experimental examinations of such physics have been performed in ferromagnetic (FM) metals. Quantum corrections to conduction in FM systems are of fundamental interest due to correlation-induced degrees of freedom not present in normal metals (e.g. spin waves), and the interplay of FM order with coherence. These corrections have been discussed while considering domain walls effects on conduction in FM nanowires and magnetoresistive effects in thin FM films. The conductance of a mesoscopic ferromagnet is expected to be highly sensitive to domain wall motion, just as the conductance of a mesoscale normal metal is sensitive to the motion of an individual elastic scatterer. Domain wall motion can thus lead to time-dependent (TD) universal conductance fluctuations (UCF). Further non-trivial coherence effects proposed in FMs include Berry’s phase due to coherent diffusion of spins through nonuniform magnetization, and dephasing via domain wall and spin wave scattering. Quantum coherence in FM systems may also have technological relevance in understanding novel mesoscale devices based on FM semiconductors.

No systematic experimental examination has been reported of electronic coherence in FM materials and the effects of domains. Two common techniques for assessing quantum coherence in normal metals, weak localization (WL) and UCF as a function of field, rely on magnetoresistive measurements. In FM metals the anisotropic magnetoresistance (AMR), a bandstructure effect, significantly complicates efforts to find WL and UCF. Examinations of mesoscale magnetic structures hint at UCF, and Aharonov-Bohm (AB) oscillations have been observed in multidomain and single-domain mesoscopic NiFe rings at mK temperatures.

TDUCF noise is an alternative probe of electronic coherence, and noise measurements are comparatively immune to the obscuring effects of AMR. TDUCF noise results from the motion of localized defects, thought to be tunneling two-level systems (TLS) in the polycrystalline metal. With the typical TLS relaxation time distribution, the resulting resistance noise power, $S_R$, has a $1/f$ dependence. In a nonmagnetic metal, applied magnetic flux suppresses the cooperon contribution to the fluctuations relative to the diffusion over a field scale related to the coherence length, $L^{TDUCF}_c$, reducing $S_R$ by a factor of two. In spin glasses TDUCF noise resulting from slow rearrangements of frozen spin configurations has also been observed.

We report the first TDUCF measurements on a FM metal, permalloy (Ni$_{0.8}$Fe$_{0.2}$). There is no discernable difference between $S_R(T)$ at zero external magnetic field and large external fields (several Tesla), indicating suppression of the cooperon contribution to the TDUCF due to the FM state. Additional noise is found over a range of low temperatures and fields when domain walls are favored, demonstrating experimentally that domain walls can act as coherent scatterers of carriers. We argue that the fluctuators responsible for TDUCF in disordered FM metals are likely TLS similar to those in disordered normal metals. If this is so, the unusual $S_R(T) \sim T^{-2}$ as $T \to 0$ may suggest an unconventional dephasing mechanism in FM materials.

Each sample is fabricated by two steps of electron beam lithography on an undoped GaAs substrate. A permalloy wire $10$ nm thick is patterned and deposited by electron beam evaporation from a Ni$_{0.8}$Fe$_{0.2}$ source. To minimize Py oxidation, e-beam resist is baked in a forming gas environment. Current and voltage leads are then patterned, and the exposed contact areas are ion-milled for 40 seconds immediately before evaporation of leads. Contact resistances are $< 100$ Ω, a factor of five lower than in samples without ion-milling. The leads are $1.5$ nm Ti / $40$ nm Au, $1$ μm wide. Each segment of wire between leads is $10$ μm in length. Figure (a) shows the sample configuration, and the sample parameters are given in Table I.

Since permalloy is a relatively soft ferromagnet, geometric anisotropy strongly influences domain configurations. Increasing wire aspect ratio favors a single-domain configuration with magnetization along the wire axis. Nonmagnetic leads preserve a simple FM geometry and maintain uniaxial geometric anisotropy. Room tempera-
with the wire axis and hence the current density the geometric anisotropy aligns the magnetization, a cutoff set by the data acquisition speed. At low fields ±2 T. The data are independent of sweep rate below 78 mHz and a few Hz. The high currents necessary for the noise measurements limit these measurements to between 78 mHz and a few Hz. The high currents necessary for the noise measurements limit these measurements to between 78 mHz and a few Hz.

TABLE I: Samples used in magnetotransport and noise measurements. All samples are 10 nm thick permalloy, and each segment is 10 µm in length.

| Sample w [nm] | ρ(T=2 K) [µΩ·cm] | AMR (2 K) | B_{sw} [T] |
|---------------|-------------------|-----------|-------------|
| A 27          | 44.86             | 3.1%      | 0.47        |
| B 50          | 48.63             | 3.5%      | 0.63        |
| C 100         | 50.87             | 3.8%      | 0.59        |
| D 450         | 50.55             | 3.7%      | 0.34        |

structure domain walls are characterized via the AMR. Analogous measurements with \( B_{||} \) show essentially no AMR signal, consistent with full alignment of \( M \) along the wire at zero field. The AMR resistivity ratio \( (R_{||} - R_{⊥})/R_{||} \) of 3-4% agrees with previous results \[27, 28\]. The MR discontinuity occurs at the switching field, \( B_s \), corresponding to reorienting unstable domains \[29\]. The switching field decreases with increasing temperature. When \( B_{⊥} >> B_s \), the magnetization, \( M \), is believed to be uniform and aligned with the applied external field. Disorder and edge effects may cause the local magnetization to deviate from the bulk value \[30\].

No detectable WL magnetoresistance was seen in any of the samples, down to 1.7 K.

At low temperatures, the voltage noise power is very well described by a \( 1/f \) dependence, and scales with the square of the drive current, indicating that its source is a fluctuating sample resistance. The frequency dependence remains \( 1/f \) for all currents and all parallel and perpendicular fields examined between 0 and 8 T, even when the magnetic field is very close to \( B_s \).

Figure 2 shows typical AMR data in the 100 nm wide wire at 8 K, with \( B_s \) sweeping at 100 Oe/s between ±2 T. The data are independent of sweep rate below a cutoff set by the data acquisition speed. At low fields the geometric anisotropy aligns the magnetization, \( M \), with the wire axis and hence the current density \( J \). At large values of \( B_{⊥} \), \( M \cdot J = 0 \), leading to a lower resistivity via the AMR. Analogous measurements with \( B_{||} \) show essentially no AMR signal, consistent with full alignment of \( M \) along the wire at zero field. The AMR resistivity ratio \( (R_{||} - R_{⊥})/R_{||} \) of 3-4% agrees with previous results \[27, 28\]. The MR discontinuity occurs at the switching field, \( B_s \), corresponding to reorienting unstable domains \[29\]. The switching field decreases with increasing temperature. When \( B_{⊥} >> B_s \), the magnetization, \( M \), is believed to be uniform and aligned with the applied external field. Disorder and edge effects may cause the local magnetization to deviate from the bulk value \[30\].

Figure 3 shows typical AMR data in the 100 nm wide wire at 8 K, with \( B_s \) sweeping at 100 Oe/s between ±2 T. The data are independent of sweep rate below a cutoff set by the data acquisition speed. At low fields the geometric anisotropy aligns the magnetization, \( M \), with the wire axis and hence the current density \( J \). At large values of \( B_{⊥} \), \( M \cdot J = 0 \), leading to a lower resistivity via the AMR. Analogous measurements with \( B_{||} \) show essentially no AMR signal, consistent with full alignment of \( M \) along the wire at zero field. The AMR resistivity ratio \( (R_{||} - R_{⊥})/R_{||} \) of 3-4% agrees with previous results \[27, 28\]. The MR discontinuity occurs at the switching field, \( B_s \), corresponding to reorienting unstable domains \[29\]. The switching field decreases with increasing temperature. When \( B_{⊥} >> B_s \), the magnetization, \( M \), is believed to be uniform and aligned with the applied external field. Disorder and edge effects may cause the local magnetization to deviate from the bulk value \[30\].

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loy, Au$_{0.6}$Pd$_{0.4}$ known to have a short coherence length.

Quantitative analysis of TDUCF in normal metals is done via the magnetic field dependent suppression of the cooperon contribution to the noise power, mentioned above$^{21}$. In these permalloy wires, no such decrease in $S_R$ is observed. As demonstrated in Fig. 3, $S_R(T, B = 0)$ and $S_R(T, B_\perp = 8\,\text{T})$ are indistinguishable at low $T$. While some (diffusion-based) quantum coherence effects are observable in FM nanostructures, this data and the lack of detectable WL suggest that cooperon phenomena are suppressed in this material. This also implies, unfortunately, that the field-dependence of the TDUCF cannot be used to analyze coherence lengths quantitatively in such FM metals.

The noise power data taken for $B_\perp = B_\parallel$ are particularly interesting. Noise measurements are not possible precisely at $B_\perp = B_\parallel$ due to large, irreversible fluctuations in bridge signal from domain rearrangements. Instead, noise data are acquired at fields $0.05-0.1\,\text{T}$ away from $B_\parallel$ while sweeping $B \rightarrow B_\parallel$. At these values of field and between 10 K and 20 K, $S_R$ is enhanced relative to the single-domain case. Interestingly, the power spectrum of the noise remains $1/f$ under these circumstances, implying the fluctuators responsible for the noise continue to have a broad distribution of relaxation times.

One can consider whether the noise in this field regime is purely a result of magnetization reorientation and AMR (i.e. not related to electronic quantum coherence). This is unlikely, since simple AMR should be visible over all temperatures. Rather, these data support the idea$^3$ that domain walls can act as coherent scatterers of electrons, and their motion can be a source of TDUCF. The limited temperature range over which these effects are measurable would then be determined by a combination of domain wall dynamics (magnetization must fluctuate on the slow timescales probed by the noise measurement) and the requirement of quantum coherence (as $T$ increases, TDUCF are increasingly suppressed because of thermal averaging and decreasing $L_\phi(T)$). More direct tests of these ideas should be possible, e.g. in structures engineered to contain only a single domain wall$^{31}$.

Even though the cooperon contribution to TDUCF is apparently suppressed in these FM samples, decoherence processes may still be examined via the temperature dependence of $S_R$. Figure 4 compares the temperature dependence of the TDUCF noise power in the 50 nm-wide Py wire and a 35 nm-wide nonmagnetic Au$_{0.6}$Pd$_{0.4}$ wire. The difference between low and high fields is clear in the normal metal at low temperatures, while immeasurably small in the ferromagnet, again demonstrating the suppression of the cooperon contribution. Note that $S_R(T) \sim T^{-2}$ between 2 and 8K for narrower permalloy wires. While the temperature dependence is slightly weaker in wider wires ($\sim T^{-1.4}$ for 450 nm wide wire), it is always appreciably steeper than $1/T$. This differs significantly from the normal metal case, and may have implications for dephasing mechanisms, as we discuss below.

With some assumptions, $S_R(T)$ can be related to the coherence length, $L_\phi(T) = \sqrt{D\tau_\phi(T)}$, where $D$ is the electronic diffusion constant and $\tau_\phi^{-1}$ is the decoherence rate. In normal metals, the predicted $S_R(T)$ depends on the relationship between several length scales: seg-

FIG. 3: Noise power as a function of temperature for all four samples: (a) $w = 27\,\text{nm}$, (b) 50 nm, (c) 100 nm, and (d) 450 nm. For all four sets of data, solid squares are $B=0\,\text{T}$; open squares are $B_\perp = 8\,\text{T}$; open triangles are $B_\perp = 8\,\text{T}$; and solid triangles are $B_\perp = B_\parallel$.

FIG. 4: Comparison of noise power plot between 50 nm wide Py wire (triangle points) and 35 nm wide nonmagnetic samples (square points). Solid symbols are for $B=0\,\text{T}$ and open symbols are for $B=0.512\,\text{T}$ for nonmagnetic wire and $B=8\,\text{T}$ for magnetic wire. Nonmagnetic wire data was shifted upward by a factor of 5 for clarity. Inset: Noise power as a function of sample volume at 2 K. Solid squares are for Py wires and open square are for nonmagnetic AuPd wires (identical sample geometry, with thicknesses from 6.5 nm to 9 nm).
Fig. 4 shows that walls or glassy spins[22, 23]. Furthermore, the inset to cally in normal metals (AuPd) and the permalloy. Fi-

We argue that the relevant fluctuators in the FM away from the switching field are likely the same TLS as in normal metals (and hence would have the same n(T)). The lack of field dependence or field-cooling effects show that the dominant fluctuators are not moving domain walls or glassy spins[22, 23]. Furthermore, the inset to Fig. [11] shows that $S_R$ scales with sample volume identically in normal metals (AuPd) and the permalloy. Finally, the $1/f$ dependence of $S_R$ is identical between AuPd and Py, showing that the fluctuators in both material systems have identical distributions of relaxation times. While not definitive, these observations and the ubiquitous presence of TLS in a variety of polycrystalline metals suggest that it is reasonable that such fluctuators are active in the FM materials.

The dimensionality of our wires with respect to coherence phenomena remains unclear, though the most likely dimensionality is quasi-2d. A reasonable estimate for $D$ in these wires suggests that $L_T \sim 10 \text{ nm}$ at 10 K. AB measurements in Py rings[14, 17] at 30 mK estimate $L_0 \sim$ hundreds of nanometers, and is much shorter at 4.2 K. $L_0$ values between 2 K and 20 K shorter than sample thinknesses or much larger than sample widths seem incompatible with these AB observations.

If $n(T) \sim T$ in these FM samples as in normal metals, then the implications for $L_0(T)$ are interesting. The unusually steep $S_R \sim T^{-2}$ is stronger than that expected in any dimensionality assuming standard electron-electron dephasing. Furthermore, the identical temperature dependences of $S_R$ for low and high $B_{||}$ are inconsistent with spin wave scattering[13] as the dominant decoherence mechanism, since high $B_{||}$ is expected to exponen-

tially suppress that mechanism. Lower temperature measure-
ments should be revealing, as would measurements independently assessing TLS properties in these FM materials.

We present the first measurements of time-dependent universal conductance fluctuations in ferromagnetic wires. We find that the cooperon contribution to the UCF is suppressed in this material. We also find evidence that domain wall motion leads to enhanced conductance fluctuations, supporting the statement[2] that domain walls may act as coherent scatterers of carriers. In single-domain configurations, the field and sample size dependence of the noise power suggest that the dominant fluctuators may be TLS similar to those in disordered normal metals. Within this picture, the steep $T$ dependence of the noise power in the FM samples is surpris-
ing if conventional dephasing is at work. In concert with other techniques such as Aharanov-Bohm measurements, it should be possible to examine decoherence in FM systems quantitatively, and search for other novel coherence effects[11, 33].

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