Quantum Spin Tomography in Ferromagnet-Normal Conductors

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We present a theory for a complete reconstruction of non-local spin correlations in ferromagnet-normal conductors. This quantum spin tomography is based on cross correlation measurements of electric currents into ferromagnetic terminals with controllable magnetization directions. For normal injectors, non-local spin correlations are universal and strong. The correlations are suppressed by spin-flip scattering and, for ferromagnetic injectors, by increasing injector polarization.

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Spintronics utilizes the electron spin in electronics applications and is an important subfield of condensed matter physics. It is possible to create metallic or semiconductor hybrid ferromagnet-normal conductor systems smaller than the spin-flip length \(12\), yet semiclassically large. Topics of current interest such as spin injection, precession, and relaxation \(13, 14\), spin Hall effects \(15, 16\), current induced magnetization excitations \(17, 18\), the reciprocal magnetization dynamics induced spin-pumping \(19\), spin based transistors \(7\), and ferromagnet-superconductor heterostructures \(8\) focus on the average non-equilibrium spin accumulation and dynamics.

The correlations between injected spins in ferromagnet-normal conductor systems have received much less attention. In two-terminal junctions, current correlations have been investigated in few-level quantum dots \(9\) as well as semiclassically large systems \(10, 11\). The prime targets have been noise due to spin-flip scattering and the super or sub poissonian nature of the auto correlations.

In multiterminal junctions, current cross correlations allow investigations of non-local spin transport properties. Of main interest has been the cross correlations, studied in quantum dots \(12\), diffusive \(13\) and superconducting \(14\) systems and chaotic cavities \(15\). Moreover, in the context of entanglement of itinerant spins, works on few-mode \(16\) and recently also semiclassical \(17, 18\) conductors considered non-local detection schemes with cross correlations between currents in non-collinear ferromagnetic terminals.

A fundamental and important question which has not been addressed is if known non-local spin injection and detection schemes \(1, 2\) can be extended to identify non-local spin-correlations. Imagine spins injected into a normal conductor and detected at two different spatial locations by ferromagnetic terminals. What are the non-local spatial correlations between the spins? Is it possible to completely characterize the correlations by experimentally accessible electrical current correlations? We provide answers to these questions for semiclassical systems: i) non-local spin correlations are strong, and for normal injectors, universal and ii) spin-correlations can be reconstructed by a sequence of measurements of correlations of currents at ferromagnetic detectors with controllable magnetization directions, a quantum spin tomography.

We consider a semiclassically large, normal (metal or semi-) conductor connected to a normal or ferromagnetic injector, biased at a voltage \(V\), and two spatially separated detectors, \(A\) and \(B\), see Fig 1. Detector \(A\) (\(B\)) consists of a normal node coupled to grounded ferromagnetic terminals \(A1\) and \(A2\) \((B1\) and \(B2\)) via tunnel contacts with conductances \(G_{A1}\) and \(G_{A2}\) \((G_{B1}\) and \(G_{B2}\)). Throughout, conductances are dimensionless and in units of the conductance quantum \(2e^2/h\). The detectors \(A\) and \(B\) probe non-invasively the non-local spin correlations.

Let us first summarize and explain our main results i) and ii) for the non-local correlated spin transport properties in the device in Fig. 1. First, combining scattering theory and a Boltzmann-Langevin approach we derive an expression for the current correlations \(S_{A1Bj} = (2e^2/h) \int_{E=0}^{eV} dE s_{A1Bj}(E)\) with

\[
s_{A1Bj} = 4G_{A1}G_{Bj} \langle (\delta f_A + P_{A1} \cdot (\delta f_A))(\delta f_B + P_{Bj} \cdot (\delta f_B)) \rangle_f,
\]

where \(P_{A1}\) \((P_{Bj})\) is the polarization of the tunnel contact to terminal \(A1\) \((Bj)\), \(\delta f_{A/B} = \delta f_{A/B} \hat{1} + \delta f_{A/B} \cdot \hat{\sigma}\)

FIG. 1: a) A normal conductor is connected to an injector biased at voltage \(V\) and two detector nodes \(A\) and \(B\). The node \(A\) \((B)\) is coupled to grounded ferromagnetic detector terminals \(A1\) and \(A2\) \((B1\) and \(B2\)). b) Node \(A\) is connected to the normal conductor, as well as nodes \(A1\) and \(A2\) via tunnel contacts with conductances \(G_{A1}\) and \(G_{A2}\), \((G_{B1}\) and \(G_{B2}\)). The polarizations \(P_{A1}\) and \(P_{A2}\) of the contacts to the ferromagnetic terminals are in opposite directions.
is the fluctuating part of the $2 \times 2$ spin distribution matrix at $A/B$, \( \vec{\sigma} = [\sigma_x, \sigma_y, \sigma_z] \) is a vector of Pauli matrices, and \( \langle . \rangle_f \) denotes the average over fluctuations. The matrix \( \delta f_{AB} \), with elements \( \delta f_{AB}^{pq} = \langle \delta f_{AB}^{\vec{f}_A} \delta f_{AB}^{\vec{f}_B} \rangle_f \), \( p, q \in \{c, x, y, z\} \), is the spin correlation matrix, describing the irreducible, or exchange, correlations between spins at A and B.

We then show our result ii): \( \delta f_{AB} \) can be reconstructed by a sequence of measurements of e.g. \( S_{AB}^{B1} \) with different settings of \( P_{A1} \) and \( P_{B1} \). Importantly, this quantum spin tomography can be performed for arbitrary (finite) magnitudes of the polarizations \( |P_{A1}| \) and \( |P_{B1}| \) and spin-flip scattering in the conductor. Moreover, global spin symmetries limit the number of finite elements of \( \delta f_{AB} \), allowing for a simplified quantum spin tomography with fewer cross correlation measurements.

For a normal injector we derive a generic expression for \( \delta f_{AB} \), with nonzero elements
\[
\delta f_{AB}^{cc} = \delta f_{AB}^{00}/2, \quad \delta f_{AB}^{xx} = \delta f_{AB}^{yy} = \delta f_{AB}^{zz} = \gamma \delta f_{AB}^{00}/2, \quad (2)
\]
where \( \delta f_{AB}^{cc} \) is the equal-spin correlator and \( \gamma \) quantifies the spin coherence in the conductor. \( \gamma = 1 \) for a coherent system, i.e. no spin-flip scattering, and \( \gamma = 0 \) for a system with strong spin-flip relaxation. For a ferromagnetic injector, the correlations depend on the properties of the conductor, as shown below.

Inserting Eq. (2) into (1) gives a cross correlator
\[
s_{A1B1} = 2G_{A1}G_{B1}\delta f_{AB}^{00}[1 + \gamma P_{A1} \cdot P_{B1}], \quad (3)
\]
depending on the relative orientation of the polarizations \( P_{A1} \) and \( P_{B1} \). This together with Eq. (2) demonstrate our counter-intuitive result i): any conductor with a normal injector displays strong and universal non-local spin-correlations. We note that for the current cross correlator, similar results have been obtained in particular geometries \cite{14,17} with no spin-flip scattering, \( \gamma = 1 \).

We now describe the quantum spin tomography, starting for clarity with the known properties \cite{19} of the average spin distribution matrix in node A, \( \hat{f}_A = f_A^c \hat{f}_A + f_A \vec{\sigma} \), where the real polarization vector \( f_A = [f_A^c, f_A^x, f_A^y, f_A^z] \) with \( |f_A| \leq 1 \). The average current is \( I_{A1} = (e/h) \int_0^V dE i_{A1}(E) \) with \cite{17}
\[
i_{A1} = 2G_{A1} [f_A^c + P_{A1} \cdot f_A]. \quad (4)
\]
For the quantum spin tomography, we transform the orbital scheme developed in Ref. \cite{21} to the spin degree of freedom and extend it to account for arbitrary detector polarization. Formally, to determine \( f_A^c, f_A^x, f_A^y, f_A^z \) four independent measurements of the current are needed. The theoretically most convenient set \{\( f_A^{(k)} \)\}, \( k = 1 \rightarrow 4 \) has the polarizations \( P_{A1}^{(1)}/P_{A1} = [0, 0, 1], P_{A1}^{(2)}/P_{A1} = [0, 0, -1], P_{A1}^{(3)}/P_{A1} = [1, 0, 0] \) and \( P_{A1}^{(4)}/P_{A1} = [0, 1, 0] \), where \( P_{A1} = |P_{A1}| \), but other settings are also feasible. The expression in Eq. (4) then allows writing
\[
\{k\} = \{c, x, y, z\}
\]
\[
f_A^k = \frac{\sum_{j=1}^4 Q_{A1}^{k(j)} f_A^{(j)}}{4G_{A1} eV/h}, \quad Q_{A1} = \begin{pmatrix} P_{A1}^{-1} & P_{A1}^{-1} & 0 & 0 \\ -1 & -1 & 2 & 0 \\ -1 & -1 & 0 & 2 \\ 1 & -1 & 0 & 0 \end{pmatrix}, \quad (5)
\]
Knowing the polarization \( P_{A1} \) and the conductance \( G_{A1} \) from independent measurements, the spin-distribution matrix \( \hat{f}_A \) is fully reconstructed by current measurements. Importantly, for a normal injector, only \( f_A^c \) is non-zero. For a ferromagnetic injector, when the spin quantization axis along the direction of polarization, only \( f_A^c \) and \( f_A^z \) are non-zero.

We then turn to the spin correlation matrix \( \delta f_{AB} \), with the 16 real elements \( \delta f_{AB}^{pq} \). This implies that we need 16 independent cross correlator measurements to determine all elements \( \delta f_{AB}^{pq} \) and reconstruct \( \delta f_{AB} \). From Eq. (1) we obtain the formal relation between the coefficients \( \delta f_{AB}^{00} \) and the cross correlators
\[
\delta f_{AB}^{pq} = \frac{1}{8G_{A1}G_{B1}eV/h} \sum_{k,l=1}^4 Q_{A1}^{pk} Q_{B1}^{ql} S_{A1B1}^{(k,l)}, \quad (6)
\]
where \( S_{A1B1}^{(k,l)} \) is the cross correlator with the detector terminal setting \( k \) at A and \( l \) at B1. Here \( Q_{B1} \) is obtained from \( Q_{A1} \) by changing \( P_{A1} \) to \( P_{B1} \).

For a normal injector, the requirement \cite{22} of invariance of \( \delta f_{AB} \) under any global spin rotation means that there is only four non-zero elements \( \delta f_{AB}^{cc} = \delta f_{AB}^{xx} = \delta f_{AB}^{yy} = \delta f_{AB}^{zz} \). For a ferromagnetic injector (defining the spin quantization axis) invariance of \( \delta f_{AB} \) under the global rotation \{ \( \{\uparrow, \downarrow\} \rightarrow \{e^{i\phi}\uparrow, e^{-i\phi}\downarrow\} \) yields \cite{23} six non-zero elements \( \delta f_{AB}^{cc}, \delta f_{AB}^{xx}, \delta f_{AB}^{x}, \delta f_{AB}^{zz} \) and \( \delta f_{AB}^{xx} = \delta f_{AB}^{zz} \).

From Eqs. (5) and (6) the detector polarization settings necessary to determine the non-zero components of \( \hat{f}_A \) and \( \delta f_{AB} \) are found: For a normal injector, only collinear polarizations at A and B are needed for both \( f_A \) and \( \delta f_{AB} \). For a ferromagnetic injector, for \( \hat{f}_A \) the detector polarizations in addition have to be collinear with the injector one. However, for \( \delta f_{AB} \), non-collinear polarizations at A and B are necessary, e.g. both along the \( x \) and \( z \) axis, since \( \delta f_{AB}^{xy} \neq \delta f_{AB}^{xz} = \delta f_{AB}^{yz} \). Importantly, for an unknown direction of the injector polarization or two (or more) non-collinear ferromagnetic injectors, the full tomographic scheme with detector polarizations along all three axes \( x, y, z \) are required.

We will now detail our calculations, assumptions, and approximations. In addition to the information given above, the normal conductor in Fig. 1 is connected to detector nodes A and B via tunnel barriers with conductances \( G_A \) and \( G_B \). The two ferromagnetic terminals A1 and A2 (B1 and B2) have opposite directions of polarization. We assume the limit of low temperature \( kT \ll eV \). All conductances are much larger than unity.
It is assumed that the normal conductor consists of diffusive and/or chaotic parts, allowing a semiclassical treatment of the orbital properties. In contrast, spin is treated fully quantum mechanically. Furthermore, scattering is elastic. Following the magnetoelectronic circuit theory of Ref. 19, we discretize the system into nodes connected via tunnel barriers, see Fig. 1. Each node \( \nu \), spatially much smaller than the spin-flip length, is characterized by a \( 2 \times 2 \) distribution matrix with an average, \( f_\nu \), and a fluctuating, \( \delta f_\nu \), part. To ensure that the detectors do not influence the spin-properties of the system, we require i) \( G_A \ll G_{A1}+G_{A2} \) and \( G_B \ll G_{B1}+G_{B2} \) so that an electron entering e.g. node \( A \) from the conductor is emitted into \( A1 \) or \( A2 \) and do not return to the conductor and ii) \( G_{A1}P_{A1} = -G_{A2}P_{A2} \) and \( G_{B1}P_{B1} = -G_{B2}P_{B2} \), which ensures that no spin polarization is induced into the conductor from the ferromagnetic terminals, i.e. the measured spin signal arises from the conductor exclusively and not from the detector circuits.

Deriving Eqs. (9) and (10), we first review 14 the spin information present in the average spectral current \( i_{A1}(E) \). In the scattering approach 20, with no particles incident from terminal \( A1 \) in the bias window \( (0 \leq E \leq eV) \), the spectral current is

\[
i_{A1} = \sum_{n\sigma} \langle n^\sigma_{A1,n} \rangle \quad n^\sigma_{A1,n} = b^{\dagger}_{A1,n}b^\sigma_{A1,n} \tag{7}
\]

where \( b^{\dagger}_{A1,n} \) creates an electron on the ferromagnetic side in the contact between \( A1 \) and \( A \), in conduction mode \( n \) propagating into \( A1 \) and the energy-dependence is suppressed. The spin quantization axis \( \sigma = \uparrow, \downarrow \) is along the direction of \( P_{A1} \). The creation operators \( b^{\dagger}_{A1,n} \) are related to the operators \( b^{\dagger}_{Am} \) for electrons on the normal conductor side, emitted from node \( A \) towards \( A1 \), via the spin-dependent transmission matrix of the normal-ferromagnetic interface \( t_{A1} \) with elements \( t^\sigma_{A1,nm} \). Following Ref. 19, we make the semiclassical approximation that the spin distribution matrix in node \( A \) is independent on mode index, i.e. \( \langle b^{\sigma}_{Am}b^{\sigma'}_{Am} \rangle = f^\sigma_{A1}\delta_{nm} \), giving

\[
i_{A1} = \sum_{\sigma\tau} \tilde{\mathcal{T}}_{A1}^{\sigma\tau} f^\tau_{A1} = G_{A1} \text{tr} \left\{ (\hat{1} + P_{A1} \cdot \sigma) \hat{f}_A \right\} . \tag{8}
\]

Here \( \tilde{\mathcal{T}}_{A1} = \sum_{nm} (\hat{t}_{A1,nm})^T (\hat{t}_{A1,nm})^* \) is a sum of the \( 2 \times 2 \) matrix where the elements of the \( 2 \times 2 \) matrix are \( (\hat{t}_{A1,nm})^\sigma = t^\sigma_{A1,nm} \). Eq. (8) directly gives Eq. (9).

Similar relations hold for the average currents into \( A2 \) and \( B1 \). We then turn to the low frequency correlations between electrical currents in e.g. terminals \( A1 \) and \( B1 \), \( S_{A1B1} = \int dt \langle \Delta I_{A1}(0) \Delta I_{B1}(t) \rangle \). Scattering theory 20 gives

\[
s_{A1B1} = \sum_{nm,\sigma \tau} \left[ \langle n^\sigma_{A1,n}n^\tau_{B1,m} \rangle - \langle n^\sigma_{A1,n} \rangle \langle n^\tau_{B1,m} \rangle \right] \tag{9}
\]

where \( n^\sigma_{B1,m} = b^{\dagger}_{B1,m}b^\sigma_{B1,m} \) and \( b^{\dagger}_{B1,m} \) creates an outgoing electron on the ferromagnetic side, in conduction mode \( m \) in \( B1 \) with spin quantization axis along the direction of the magnetization \( n_B \). Disregarding terms of second order in \( G_A/(G_{A1}+G_{A2}) \) or \( G_B/(G_{B1}+G_{B2}) \), the operators \( \delta f^\sigma_{A1,n} \) and \( \delta f^\tau_{B1,m} \) are expressed in terms of the operators \( \delta f^{\sigma \tau}_{Ak} \) and \( \delta f^{\tau \sigma}_{Bk} \) and the scattering amplitudes of the respective normal-ferromagnetic interfaces. Making the semiclassical approximation that the non-local irreducible correlator \( \langle b^{\sigma}_{Am}b^{\tau}_{Bm} \rangle - \langle b^{\sigma}_{Am} \rangle \langle b^{\tau}_{Bm} \rangle \) is a sum of the \( \delta f^{\sigma \tau}_{AB} \) and \( \delta f^{\tau \sigma}_{BA} \) the polarization vector of node \( \mu \) (\( P_{\mu} = 0 \) for a normal node). The distribution matrices for normal and ferromagnetic terminal nodes are \( 1 \) for biased terminals and \( 0 \) for grounded. This allow us to calculate the distribution matrices of all nodes.

For the fluctuating part of the distribution matrix, we first note that the total fluctuations of the matrix current \( \Delta I_{\nu \mu} \) flowing between two nodes \( \nu \) and \( \mu \) is a sum of the bare fluctuations \( \delta\hat{I}_{\nu \mu} \) and \( \delta\hat{L}_{\nu \mu} \) due to the fluctuating distribution matrices. For \( \nu \) normal and \( \mu \) normal or ferromagnetic the \( \delta\hat{L}_{\nu \mu} = (G_{\gamma \mu}/2) \left\{ (\hat{1} + P_{\mu} \cdot \sigma), (\hat{f}_{\nu} - \hat{f}_{\nu'}) \right\} \) with \( \{ .. \} \) the anti-commutator, \( G_{\gamma \mu} \) the tunnel conductance between the nodes and \( P_{\mu} \) the polarization vector of node \( \mu \) (\( P_{\mu} = 0 \) for a normal node). The distribution matrices for normal and ferromagnetic terminal nodes are \( 1 \) for biased terminals and \( 0 \) for grounded. This allow us to calculate the distribution matrices of all nodes.

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denote hermitian conjugate and the permutation ma-

neutral elements $W_{11} = W_{23} = W_{32} = W_{44} = 1$. For $\nu$ normal and $\mu$ ferromagnetic we have

\[
\langle \delta_i \nu \otimes \delta_i \nu \rangle_f = (G_{i \nu} / 2) \{ (1 + P_{\mu} \cdot \sigma) f_i \} \otimes (1 - f_i) + (1 + P_{\mu} \cdot \sigma) [1 - f_i] \otimes f_i \} \hat{W} + h.c.
\]

Here we used that ferromagnetic (i.e. terminal) distributions do not fluctu-
ate. From these relations any electrical current correlator $\langle A_i A_{f} \rangle_f$, with $A_i = \text{tr}[A_i]$, can be obtained.

Spin flip scattering is taken into account on the level of the relaxation time approximation. This amounts to

coupling each node $n$ to a spin-flip node $\varphi \nu$ with a tunnel contact with conductance $G_{\varphi \nu} \propto 1/\tau_{\varphi \nu}$, with $\tau_{\varphi \nu}$ the spin-flip time of the node, and requiring conservation of electrical current and current fluctuations into the spin-

The relaxation time approximation. This amounts to $\tau / \tau_c = 1$. This

Further insight is obtained by calculating the properties of the simplest possible conductor, a single node $\hat{A}$. For a normal injector we find the distribution function at $e.g.$ $A$ as $\hat{f}_A = G_A / (G_A + G_A)$, with $f = G / (G + G_A + G_B)$ the distribution function of the conductor node and $G$ the injector-conductor node function. This is independent on spin-flip scattering. For the spin-correlation matrix we get the result in Eq. (11) with $\hat{f}_{AB} = f^3 G_A G_B / [G(G_A + G_A + G_B)]$ and $\gamma = [1 + \tau G_c / \tau_c]^{-1}$ with $\tau G_c = G_c / (G_A + G_B + G$) the ratio of spin-flip and dwell times in the central node.

For a ferromagnetic injector with polarization $P_f$ the spin distribution matrix at $e.g.$ $A$ has two non-zero components $(\hat{f}_A)^{11} = \hat{f}_A^1$ with $f_A^{11} = f([1 \mp P_I f_I] / \tau_G / \tau_c / \tau_P f^2) + \tau_G / \tau_c / \tau_P f^2)$ with $P_I = |P_I|$. For the spin-correlation matrix, the full expression, including spin-flip scattering, becomes very lengthy and we only present the result for $\gamma = 1$. This is $\hat{f}_{AB} = \hat{f}_{BA} = \hat{f}_{AB} = \hat{f}_{AB} = \delta f_{AB} = \delta f_{AB} = \delta f_{AB} = \delta f_{AB} = \delta f_{AB} = \delta f_{AB} = \delta f_{AB}$ with $c_+ = (1 + P_I f_I) / (1 + P_I f_I)^3$ and $c_0 = (1 - P_I f_I)^3 / (1 - P_I f_I)^2$. Inserting this into Eq. (10) we get the cross correlator

\[
S_{AB} = 2 G_{A1} G_{A1} \delta f_{AB} (c_1 + c_0 [1 + P_{1} \cdot P_{B1}])
\]

with $c_1 = (1 + P_{1} \cdot P_{B1}) (c_+ + c_- - 2c_0) / 2 + (P_{1} + P_{B1}) (c_+ + c_-) / 2$. This clearly demonstrates that while a ferromagnetic injector leads to a polarization of the conductor, it suppresses the spin-correlations.

In conclusion we have presented a scheme for quantum state tomography of non-local spin correlations in normal-ferromagnetic conductors. Non-local correlations are generically strong but suppressed by spin-flip scattering and ferromagnetic injectors.

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