Long-distance spin transport in a disordered magnetic insulator

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Spin transport through magnetic insulators via magnons has been explored for a variety of crystalline materials. Here we show dramatic effects of spin transport through an amorphous magnetic insulator, which is both magnetically and structurally disordered. We observe spin flow though amorphous yttrium-iron-garnet (a-YIG) thin films in a non-local geometry by use of the spin Hall and inverse spin Hall effects in platinum strips separated by ten or more micrometres. By comparing a-YIG grown on suspended micromachined thermal isolation platforms to the same film on bulk substrates, we show strong effects of in-plane thermal gradients on spin transport in the disordered film. The resulting signals are orders of magnitude larger than those seen in crystalline magnetic insulators, and easily measurable even for distances greater than 100 μm. In analogy to heat transport in glasses, where a range of vibrational excitations can allow large thermal conductivities, we suggest that efficient spin transport in disordered systems can occur via a similar spectrum of excitations that relies on strong local exchange interactions and does not require long-range order. This opens a new area for experimental and theoretical studies of spin transport, and sets a new direction in materials science for magnonic and spintronic devices.

Motivated by new paradigms for information processing, spintronics research has recently focused on the transport of spin information via spin-wave, or magnon, excitations in magnetic insulators. Much of this work uses yttrium iron garnet, Y3Fe5O12 (YIG), as the spin transport medium, due mostly to its very low damping of magnetization dynamics and the resulting long spin-wave propagation lifetime. In its bulk crystalline form YIG is a ferrimagnet with an electronic bandgap of approximately 2.8 eV, which is also achieved in thin films, so that electronic excitations cannot contribute to transport. The ferrimagnetism arises due to the location of Fe3+ ions in two inequivalent sites in the relatively complicated unit cell, leading to antiferromagnetic exchange interactions between octahedrally and tetrahedrally coordinated Fe3+ ions, but with slightly different moments, leaving a net imbalance of magnetization and macroscopic properties often described using the typical language of ferromagnets.

Among the most exciting spin transport studies in YIG are experiments demonstrating electrical excitation of spin waves in the YIG via the spin Hall effect (SHE), and subsequent detection of the spin information some distance away from the injection site via the reciprocal inverse spin Hall effect (ISHE). This non-local generation and detection of spin information transport in YIG, shown schematically in Fig. 1a, was first described by Kajiwara et al., where propagation with a very long length scale was claimed. Only recently have other reports of similar experiments also on YIG emerged, showing shorter propagation length scales. All of these experiments focus on crystalline or epitaxial YIG, although depending on the process steps used in fabrication some level of disorder could arise. The study by Kajiwara et al. also reported the excitation of magnetization dynamics in crystalline YIG by SHE-driven torques, a phenomenon also recently reported using different device structures, including some that deliberately enhance the role of thermal gradients. The SHE excitation of YIG magnetization has also been theoretically described. The characteristic feature of this SHE spin-wave excitation is an onset of the dynamics at a critical current where the applied spin torque balances the damping of the magnetization dynamics in the YIG. Furthermore, thermal gradients and spin-wave excitations have been shown to have other dramatic interactions in YIG, opening the possibility that the application of thermal gradients in these experiments, whether intentional or unintentional, could play a strong role in measured effects. This has been observed by some groups, although the applied thermal gradients tested to date are overwhelmingly perpendicular to the plane of the YIG/Pt interfaces. Nevertheless, the thermal generation of a population of magnons that subsequently diffuses through the YIG is one possible mechanism for the long-distance spin flow.

Other recent reports have shown that spin transport is possible through a much wider range of materials than previously thought. These include studies of spin transport, and possible enhancement of spin flow, through very thin nickel oxide and other nominally antiferromagnetic insulating layers inserted between YIG and Pt layers, and through thin native oxides of nickel and Permalloy between transition metal ferromagnets and heavy metal films. These initially unexpected experimental results have stimulated theoretical consideration of spin transport by magnons in antiferromagnetic insulators. In addition to these studies, where spin transport was shown via electrically detected measurements of the ISHE in response to spin pumping, the longitudinal spin Seebeck effect has been demonstrated in antiferromagnets by paramagnets and ferromagnets above the Curie temperature. These results clearly demonstrate that long-range magnetic order is not a requirement for spin transport in an insulator, which is also implicit in any spin transport experiment using a very thin film of a material that is antiferromagnetic in bulk, but with a blocking temperature well below the temperature of the experiment. New experiments to test a broader range of disordered magnetic insulators, where magnetic correlations persist...
due to strong local exchange interactions despite the lack of a low symmetry state, are therefore critical for spintronics.

In this paper we show that a disordered magnetic insulator allows long-distance spin transport. We demonstrate non-local spin transport (see Fig. 1b), with large signal voltages indicating propagation over dozens of micrometres, through amorphous YIG (a-YIG), a magnetic insulator with strong local antiferromagnetic exchange interactions but neither magnetic nor structural long-range order. We describe non-local spin transport in a-YIG films sputtered both on suspended amorphous Si-N sample platforms and on bulk Si substrates. Comparing these allows us to identify a strong effect on in-plane thermal gradients. We show two separate contributions to the non-local spin transport, with one showing a clear onset at a well-defined critical current density in the Pt across a fairly broad range of samples and measurement conditions, while the other is linear with applied current through the strip. Finally, when the non-equilibrium spin carriers are injected into a-YIG the temperature profile suggests efficient heat transport by this spin population, which echoes the strong magnon–phonon coupling often observed in crystalline YIG. These results open a new frontier in insulating spintronics, proving that magnetic order is not required, and may not be desirable, for an efficient spin transport medium.

Amorphous YIG was originally studied, although far from exhaustively, decades ago. Results indicated that disordered YIG (rarely grown in thin-film form) showed a broad peak in magnetization ($M$) versus temperature ($T$) between 50 and 100 K (refs 38, 39), with a splitting between curves measured in zero-field-cooled and field-cooled conditions$^{39}$. Above this splitting, some groups reported reasonable agreement of $M$ versus $T$ with a Curie–Weiss law, $M \propto 1/T - \theta$, with a large negative Weiss constant ($\theta$) on the order of 100 K indicating the presence of strong antiferromagnetic (AF) exchange interactions. Since the expectation for a-YIG is that the nearest-neighbour environment is largely unchanged from the crystalline state, local AF interactions are reasonable, although existing reports disagree on this issue$^{38,39}$. The lack of long-range order gives rise to frustration, pushing a-YIG towards spin glass or more complex non-equilibrium behaviour. Here one expects strong AF correlations between neighbouring spins up to a temperature scale comparable to the bulk transition temperature, with lower temperature freezing phenomena that depend on the balance of competing interactions in a particular structure.

Using techniques previously shown to produce high-quality epitaxial YIG films when the proper crystalline substrate was used and the proper post-annealing was conducted$^{40}$, we sputtered 100- and 200-nm-thick films of a-YIG on amorphous silicon-nitride (a-Si-N) coated Si substrates and also on a-Si-N thermal isolation platforms$^{41}$ developed for thermal and thermolectric characterization of thin films and nanostructures$^{42,43}$. Figure 1 shows X-ray diffraction (XRD) patterns comparing a polycrystalline bulk YIG sample (panel a) to an a-YIG film on the Si-N coated Si substrate (panel b). The former indicates randomly oriented polycrystalline YIG, whereas the latter exhibits no medium- or long-range order in the YIG layer. We also performed magnetization measurements of a similar a-YIG sample on a Si substrate via superconducting quantum interference device (SQUID) magnetometry. $M$ versus $T$ (after subtraction of backgrounds from the substrate and sample mount as described in Supplementary Methods) shows a broad peak near 50 K, described in the literature$^{38,39}$, and a second, not previously observed feature near 230 K, discussed further below.

Results from the membrane experiments appear in Fig. 2. First note that the open circles in panel f for $T_s = 300$ K result from...
the non-local measurement performed on a Si-N structure with no a-YIG layer, and are essentially zero for all $I$, as expected. Note also that there is a finite but very small amount of charge current leakage through the YIG (resistance from the injector to the detector is always >100 kΩ at room temperatures and much larger at low temperatures) that is always too small to account for the measured non-local voltages (for additional details see Supplementary Methods). Across all four measured base temperature $T_o$, a nonlinear component to $V_{nl}$, with a sign change that rules out simple heating effects, is reminiscent of the pattern seen in the original experiments on magnon spin currents in YIG, keeping in mind that the disordered material has no net magnetization and no preferred direction, so that either sense of spin current can propagate. Despite this similarity, which suggests that a non-equilibrium spin population could become self-oscillatory when enough spin torque is provided by the SHE, the voltages we measure are many orders of magnitude larger. We also reiterate that this large voltage was measured across a distance of nearly 10 μm.

Another extremely unusual feature of the data is seen most clearly in Fig. 2fg, where the measured temperature of the Si-N island coated with a-YIG actually drops dramatically with increasing $I$. The thermometer is measured using an a.c. technique, which is very unlikely to suffer interference from the large d.c. current applied to the Pt strip. This also cannot be due to the Peltier effect\(^{10}\), which would be linear with applied $I$, causing heating with one polarity and cooling with the other. We believe this large drop in the temperature of the Si-N island made via an entirely separate thin-film thermometer. For large $I$ this $T$ first slows its rise with increasing $I$, then for higher $T_o$ actually cools due to increased heat transport by spin excitations. Again the open circles in f for $T_o = 300 K$ show the result of the same non-local measurement performed on a Si-N island, with the simple parabolic dependence expected. We measured the same patterns in a platform coated with a-SiO\(_2\) (see Supplementary Information). Inset to g shows calculated in-plane thermal gradients, as described in the text. Inset to g shows the simple two-body model used to determine thermal conductance.
Figure 3 | Intentional manipulation of the direction of the thermal gradient. a, Compares $T$ measured on the island thermometer versus $I$ applied to the Pt spin injector for the a-YIG coated Si-N membrane structure with and without He exchange gas surrounding the membrane. The helium thermally shorts the structure to the surroundings, such that heating is dramatically reduced, as is the associated lateral thermal gradient between the thermometer, spin detector, and spin injector. The high thermal conductance of the gas drives any existing thermal gradient out of the plane of the sample. As seen in b, this change dramatically reduces the nonlinear component of the non-local signal, although, as shown in the inset, a linear component remains essentially unchanged. c, d, Compare the total non-local voltage measured in the membrane with exchange gas to the a-YIG on the bulk Si substrate. In both cases the thermal gradient created is perpendicular to the film normal, as shown in Fig. 4a. Subtracting the linear term in these plots, as shown in e and f, reveals a similar nonlinear signal as seen in the membrane, although with reduced signal size. Note that this nonlinear signal turns on at a similar current density despite much wider Pt strips used in the substrate experiment. This suggests the nonlinear part is indeed due to spin-torque-compensated dynamics in the disordered YIG.

a-YIG by more than two orders of magnitude (for further details see Supplementary Methods).

As shown in the inset to Fig. 2f and in Supplementary Methods, we use two-dimensional (2D) finite-element (FEM) analysis software to estimate the size of in-plane thermal gradients generated in the suspended thermal platform during non-local spin transport. The image depicts $T$ calculated for the condition where $\Delta T = 50 \, \text{K}$ between the Si frame held at 300 K and the island thermometer. Since heat is dissipated in the Pt lead that runs along the entire length of the legs of the structure, the peak $T = 360 \, \text{K}$ is actually on the leg. In general, the in-plane thermal gradient along the leg has components along both the $x$ and $y$ directions, with $\nabla T$, reaching absolute values near 6 K mm$^{-1}$ in the region between the two Pt leads at the peak $T$ location, and with a maximum value of 18 K mm$^{-1}$ achieved near the connection to the bulk Si frame. Peak values of $\nabla T \approx 70 \, \text{K mm}^{-1}$ along the legs occur in a similar region. These much larger gradient areas could dominate the additional heat-sinking via spin excitations that drives the overall cooling of the suspended island. Finally, we note that $\nabla T$, which we hypothesize plays a role in increasing the non-local voltage signal, actually varies in magnitude and sign across the structure, suggesting that similar devices optimized to produce large and uniform $\nabla T$ could lead to even more dramatic spin transport effects in suspended a-YIG.

Figure 3 describes two different approaches to manipulate the direction of the applied thermal gradient in the non-local spin transport experiment. First, we compare $V_{nl}$ measured in vacuum as in Fig. 2 with the signal measured on the same sample but with helium gas added to the cryostat to thermally short the Si-N structures to the sample environment. As is clear from the measured $T$ as a function of $I$ shown in Fig. 3a, in-plane gradients are nearly entirely eliminated, and the dominant gradient is normal to the interface of the heated Pt strip and the gas, and the gas very similar to the situation when the Pt/a-YIG is supported on a bulk substrate. As shown in Fig. 3b, this reduces the size of the non-local signal. Despite the reduced size, both a linear and a nonlinear term remain easily measurable when only an out-of-plane gradient exists, as shown in Fig. 3c–f. Figure 3c,d shows the total measured $V_{nl}$ while Fig. 3e,f shows the signal after subtraction of the linear term (determined via least-squares fit to the small $I$ region) in order to examine nonlinear contributions. Note that in both experiments, where the exciting Pt strips have very different width, the nonlinear $V_{nl}$ turns on at similar current density, $10 \times 10^8 \, \text{A m}^{-2} < j < 20 \times 10^8 \, \text{A m}^{-2}$. This large difference in magnitude of $V_{nl}$ between in-plane gradient and out-of-plane gradient cases could relate to the presumed large difference in the absolute magnitude of thermal gradients produced in the two experiments. However, these comparisons are complicated by the difficulty in estimating out-of-plane gradients when the constituent materials’ thermal properties and nature of the interfaces between them are poorly known. Here we can use FEM to roughly estimate a value near 0.8 K mm$^{-1}$ for the out-of-plane gradient, with negligible in-plane gradients on distances greater than even one micrometre away from the Pt current strip. In our view the most reasonable assumption is that our experiments on the substrate do not involve significant thermal gradients, and instead probe purely electrical spin generation, transport, and detection, although further experiments are required to confirm this.

Although the largest effects come on the membrane, the exact temperature of the a-YIG transport spin there is difficult to discuss. In light of this we explore the $T$- and $L$-dependence of the effect in detail using the substrate-supported case, as shown in Figs 4 and 5. Figure 4a shows the component of $V_{nl}$ purely linear in $I$ (determined from fits to the slope of $V_{nl}$ versus $I$ at each $T$) for both 100- and 200-nm-thick a-YIG films. Figure 4b shows the maximum recorded value of the nonlinear component (here taken at $I = 8 \, \text{mA}$), $V_{nl,max}$ versus $T$. Both components become measurable...
Figure 4 | $V_{nl}$ versus $T$ from 5 to 300 K indicating spin transport through 100- and 200-nm-thick a-YIG on the substrate. a, Linear component (slope) of $V_{nl}$ (driven by purely electrical spin injection and subsequent diffusion). Inset: Schematic view of the non-local experiment. b, Maximum nonlinear $V_{nl}$ provides an estimate of the component potentially related to ST-driven spin excitations. Both components of $V_{nl}$ appear only above $\sim 230$ K. Inset: Optical micrograph of isolation platform frame showing the location of the substrate-supported non-local measurement. c, Magnetization of the a-YIG versus $T$ from 5 K to 300 K cooled in zero field (ZFC, red symbols) and in the 5,000 Oe measuring field (FC, black symbols) shows the broad peak near 50 K described in the literature\textsuperscript{18,19} and a second, not previously discussed feature near 230 K. This higher-$T$ feature correlates well to the onset of spin transport effects.

Figure 5 | Distance dependence of $V_{nl}$ on the substrate. a, Voltage components related to spin drop off sharply with distance. Here blue symbols indicate slope (right axis) and black symbols maximum nonlinear component (left axis). Stars, boxes, and circles indicate three different samples (Insets Nonlinear spin signals after linear subtraction show clear effects even for $L > 100\,\mu$m). b, Estimation of the (small) heating effects drops off much more slowly, reinforcing that the spin signals are not simply temperature driven but require SHE excitation.

only above $\sim 230$ K. Figure 4c indicates that this temperature correlates with the disappearance of spin freezing in the a-YIG. Here we plot $\Delta m$ versus $T$, the component of magnetization due to the a-YIG film deposited on a Si-N coated Si substrate (isolation of this component from total measured SQUID magnetization is described in Supplementary Methods) for both zero-field-cooled (red symbols) and field-cooled (black symbols) states using a magnetic field of 5,000 Oe. In contrast to existing literature on a-YIG, we see splitting of these curves at two temperatures, near the expected 50 K peak in the ZFC curve, and at a temperature nearly equal to the observed onset of spin transport effects. This suggests that spin transport occurs in the presence of disorder and strong spin correlations, but only when sufficient thermal energy is available to overcome spin freezing.

As seen in non-local spin transport in crystalline YIG, Fig. 5 indicates a sharp drop in spin signal with increased separation between Pt strips, $L$, for both the linear and nonlinear components of $V_{nl}$. These data do not fit a simple exponential dependence. We require more data to effectively probe existence of diffusive and relaxation regimes\textsuperscript{11}, and more detailed examination of separation dependence is ongoing. We are able to clarify that any thermal component to $V_{nl}$ here is small, and has a different dependence on $L$, further evidence that electrical effects dominate spin transport in the experiment on the substrate.

In disordered spin systems, even above any freezing temperature, strong AF spin correlations typically lead to small magnetic susceptibility and very large saturation fields. This is the case for a-YIG, where $M$ is a very small fraction of either the saturation magnetization of crystalline YIG or of the even larger estimated $M$ of free Fe atoms at the same density. Despite achieving a magnetization less than 10% of the YIG value (described further in Supplementary Methods), as shown in Fig. 6 there is an observable effect of applied field on $V_{nl}$. Figure 6a shows $V_{nl}$ as a function of applied $I$ for the substrate-supported a-YIG film, here measured in air at room temperature. Figure 6b isolates the nonlinear component, which is near zero for $I \leq 2$ mA. We applied fields up to 14 kOe perpendicular to the film, large enough to have saturated $M$ and completely eliminated spin transport in crystalline YIG\textsuperscript{12}. Figure 6c,d shows $\Delta V_{sd}/V_{nl}$ versus $H$ for $I = 8$ mA and $I = 2$ mA, respectively, and show that both the linear and nonlinear regimes react to $H$ in a similar manner as expected if the field dependence arises from magnetic-field-dependent properties of the medium. Here $\Delta V_{sd}/V_{nl} = (V_{sd}(H) - V_{sd}(H = 14$ kOe))/V_{nl}(H = 14$ kOe). Reduction from maximum $H$ does increase the signal, with the zero-field values slightly reduced from a peak that occurs at intermediate fields. The small asymmetry in the peak value when starting from either value of maximum field is probably due to error on the subtraction procedure. The small shifts in $V_{nl}$ are consistent with the small shift in total magnetization achieved here. Despite the small
size, this field dependence is strong evidence that $V_{nl}$ for a-YIG relies on spin transport.

The recent theories that explain spin transport in antiferromagnetic insulators invoke a well-defined antiferromagnetic magnon spectrum that is either absent or substantially modified in the case of a truly disordered system, as we use here. The magnon spectrum of disordered magnets has been rarely explored in the past, although existing work suggests an analogy to phonon spectra in glassy systems. Vibration modes of amorphous systems certainly exist, and a long history of study shows that whether called a phonon or given a more specific name (such as propagon), heat transport via a broad spectrum of vibrational excitations is possible in amorphous systems. Recent work shows that this transport is often surprisingly efficient, with long phonon mean free paths despite the disorder. Our work is the first indication of similar effects for spin transport via magnetic correlations in a disordered system.

In fact, use of a disordered system has potential advantages for magnonics. Two traditional challenges for magnonic materials are the presence of a gap in the magnon spectrum and the highly anisotropic nature of the magnon transport. Both of these challenges are overcome in a novel material introduced in a recent publication. Neither should occur in a disordered system. A central question is if spin transport effects in disordered systems persist over long enough length scales to be useful in technology. The data shown here proves emphatically that they do. The easy compatibility of the a-YIG material in any device process is also compelling, suggesting a potential paradigm shift in materials science for magnon transport.

**Methods**

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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**Figure 6 | Dependence of $V_{nl}$ on applied field.** Here $H$ up to 14,000 Oe was applied perpendicular to the substrate as shown in the inset to a, which shows $V_{nl}$ versus $I$, here measured in ambient conditions, and displaying the same linear and nonlinear contributions as earlier figures. The nonlinear component is isolated by subtraction of the linear term. These clarify that when biased at $I = 2$ mA the signal is dominated by the linear term, whereas at $8$ mA the nonlinear term contributes. Panels c, d show that at both bias points, clear field dependence is observable, with similar relative magnitude and trends.

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Author contributions
Thermal isolation platforms were designed by D.W. and B.L.Z., and fabricated, measured, and analysed by D.W. under supervision of B.L.Z. a YIG films were deposited by T.L. under supervision of M.W. XD in permalloy and nickel thin films with in-plane thermal gradients. Phys. Rev. B 89, 144303 (2014).
Methods

Device fabrication. Thermal isolation platforms are fabricated from 500-nm-thick Si-N coated Si wafers (nominally 500 µm thick) via bulk Si micromachining via an anisotropic Si etch in tetramethylammonium hydroxide (TMAH) performed after defining the platform geometry by patterning the Si-N layer, which acts as a hard mask for the Si etch. Before this etch, an evaporated Cr/Pt (10 nm/40 nm) film is patterned via liftoff, which forms the leads, heaters, and thermometers used in thermal experiments. Additional fabrication details are available elsewhere41.

a-YIG deposition. 200- and 100-nm-thick a-YIG films were sputtered onto amorphous Si-N thermal isolation platforms and 1 cm × 1 cm blank Si-N coated silicon substrates from a stoichiometric YIG target in argon gas. The substrates were held near room temperature, and the material grown at ~0.5 nm min⁻¹. Other parameters follow the sputtering step described in ref. 40.

X-ray diffraction. X-ray diffraction data were collected in the Bragg-Brentano symmetrical θ = 2θ reflection geometry by using CuKα characteristic energy (8 keV), excited at 30 kV and 30 mA. Reflected intensity was scanned by a proportional detector every 0.05° in the angle 2θ for 10 s per step. XRD was measured on a 200-nm-thick a-YIG layer deposited on a 500-nm-thick Si-N coated Si substrate, where the a-YIG was grown in the same deposition as films on thermal isolation platforms tested for spin transport and magnetization. For polycrystalline YIG the spectrum was normalized to the (420) peak, which had a raw value of 13,000 counts.

Non-local transport measurements. After depositing this a-YIG film on our thermal isolation platform we carried out two series of non-local spin transport experiments. We first drove a current I down the length of a Pt lead traversing both legs of one Si-N island while measuring a voltage on a parallel but totally separate Pt strip with a gap of ~9 µm. The total length of these strips is greater than 2 mm and both are suspended on the Si-N membrane for this entire length. We measured this non-local signal as a function of temperature from cryostat temperatures of ~80–350 K. When large I is driven through the Pt wire on the suspended membrane significant heating occurs, which we can monitor using the separate thermometer patterned on the island. When heated, a thermal gradient in the suspended structure is generated that is nearly entirely confined to the plane of the film by the essentially 2D nature of the structure. The second set of experiments explores the opposite regime of thermal gradient by performing the non-local injection and detection entirely supported by the substrate (Figs 4 and 5). There the overwhelming heat sink provided by the bulk substrate forces the thermal gradient to be perpendicular to the plane of the film.

For all zero-field transport measurements the platforms are mounted in gold-coated OFHC copper sample mounts, leads are ultrasonically wire-bonded to custom circuitboards, and a radiation shield installed ensuring an isothermal sample environment. This mount is attached to the cold finger of a sample-in-vacuum cryostat. In all experiments not specifically stated to use exchange gas, vacuum of 10⁻⁷ torr or better is maintained around the sample. Transport measurements here use standard computer-controlled sourcemeter equipment. Voltage is measured as a function of applied current, and analysed to determine its components. Linear terms in V₆ₙ are determined by fitting the low-I portion of the curve (≤ 100 GA m⁻¹), and in the case of substrate measurements, the thermally driven Ω² term plotted in Fig. 5b is estimated by taking the average value of the maximum and minimum I data points, which show a slight but reproducible asymmetry indicating the presence of this parabolic contribution. In the case of measurements on membranes, the temperature of the suspended islands are measured using entirely separate patterned thermometers connected to an a.c. lock-in based resistance bridge. We also separately measured the (very high) direct resistance of the devices at various temperatures to ensure these are due to spin transport (discussed in more detail in Supplementary Methods).

Field-dependent measurements were performed in ambient conditions, with the sample placed between the 10 cm-diameter pole pieces of an electromagnet with a gap of <1 cm. Due to the strong temperature dependence of V₆ₙ, as well as any thermoelectric background voltages, voltage measurements recorded while cycling a set bias current on and off were averaged over several cycles to reduce backgrounds. The small field dependence is observable over the remaining background, which is linear over short enough time periods, and removed with a simple linear fit.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.