Coherent Control of Magnonic Spin Transport in an Antiferromagnetic Insulator

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The spin-1/2 of an electron makes it an archetypal two-level system and inspires the description of other two-level systems using an analogous pseudospin. The quantized spin excitations of an ordered antiferromagnet are such pairs of spin-up and -down magnons and can be characterized by a magnonic pseudospin, which has eluded experiments thus far. The similarity between electronic spin and magnonic pseudospin has triggered the prediction of exciting phenomena like emergent spin-orbit coupling and topological states in antiferromagnetic magnonics. Here, we report experiments demonstrating coherent control of magnon spin transport and pseudospin dynamics in a thin film of the antiferromagnetic insulator hematite. We quantitatively explain our experiments in terms of diffusive magnon transport and a coherent precession of the magnon pseudospin caused by the easy-plane anisotropy and the Dzyaloshinskii-Moriya interaction. This experimental observation can be viewed as the magnonic analogue of the electronic Hanle effect and the Datta-Das transistor, unlocking the high potential of antiferromagnetic magnonics towards the realization of rich electronics-inspired phenomena.

The different phases of electronic matter manifesting distinct transport properties are cornerstones of condensed matter physics and modern technologies. The electron spin together with spin-orbit interaction play a fundamental role in hosting and controlling several of these phases, such as topological insulators [1, 2]. Spin-dependent electronic transport has further underpinned industrial devices such as magnetoresistive read heads and memories. In these spin-electronic phenomena, the spin-orbit interaction results in an incoherent loss of spin currents, but can also be exploited for coherent control of spin and its transport [3, 4].

An emerging paradigm for spin and information transport via magnons in magnetic insulators offers distinct advantages [5–14]. While ferromagnetic magnons carry spin in only one direction, antiferromagnetic magnons come in pairs with opposite spins or Néel order precession chiralities. The latter can combine to form zero-spin excitations corresponding to linearly polarized oscillations of the Néel order [15, 16]. In general, the pairs of antiferromagnetic magnons and their superpositions can be described via a pseudospin [17–20] in a manner similar to the actual spin of an electron (Fig. 1(a)). Besides the unique magnonic pseudospin feature, antiferromagnets also offer crucial advantages such as immunity to stray fields [21, 22], THz magnon frequencies [21–24], and ultrafast response times [25, 26]. Within our chosen convention, the z-component of such a pseudospin corresponds to the measurable magnon spin, while the transverse component characterizes the mode ellipticity. The formal equivalence between electron spin and antiferromagnetic magnon pseudospin has been predicted to result in a range of phenomena that are completely analogues in electronic systems and antiferromagnetic insulators (AFIs) [17–20, 27–29]. The experimental realizations of these theoretical predictions promise to lift antiferromagnetic magnonics to a new level of functionalities. Here, we report the first observation of the magnonic analogue of the electronic Hanle effect [30–32]. This is achieved by realizing the coherent control of the magnon spin and transport in a thin AFI.

In our experiments, spin current is injected from a heavy metal (HM) strip into an adjacent AFI via the spin Hall effect (SHE), producing an excess of spin-up magnons [11, 33, 34]. The injection thus creates a magnon pseudospin density directed along \( \hat{z} \) (Fig. 1(b)-(d)). In the presence of an easy-plane anisotropy and Dzyaloshinskii-Moriya interaction (DMI), spin-up and -down magnons are coherently coupled and therefore no longer eigenexcitations [20, 35]. As a result, the pseudospin precesses in the \( x-z \) plane with time while the magnons diffuse away from the injector. Its precession frequency \( \Omega \) is determined by the anisotropy and a combination of the DMI field and canting-induced net magnetic moment. We control the latter by an external magnetic field and hereby obtain a handle on \( \Omega \). At the compensation field \( H_c \), the anisotropy and the DMI contributions just cancel, resulting in \( \Omega = 0 \). The pseudospin, in this case, propagates through the AFI without any precession (Fig. 1(b)). In contrast, for the field \( H_0 \), the pseudospin of the magnons arriving at the detector electrode points orthogonal to the \( z \)-axis (Fig. 1(c)). This corresponds to zero magnon spin density and thus a vanishing magnon spin signal (Fig. 1(e)). For \( H_{\text{avg}} \), the magnon pseudospin and actual spin densities have reversed directions while propagating from injector to detector (Fig. 1(d)). This
Figure 1. **Manipulation and transport of antiferromagnetic magnon spin.** (a) Pseudospin $S$ description of magnonic excitations obtained by linear superpositions of spin-up and spin-down antiferromagnetic magnons that respectively correspond to right- and left-circular precessions of the Néel vector $\mathbf{n}$. A pseudospin collinear with the $z$-axis corresponds to spin-up or spin-down magnons carrying spin $\pm 1$. As the pseudospin rotates away from the $z$-axis, the precession of the Néel vector becomes increasingly elliptical merging into a linear oscillation for $S \parallel \hat{z}$, corresponding to zero-spin excitations. The $z$-component of pseudospin $S_z$ determines the actual magnonic spin which is probed in our measurements. (b), (c) and (d) Magnonic spin along $\hat{z}$ is injected and detected respectively by the left and right heavy metal (HM) electrodes deposited on an antiferromagnetic insulator (AFI). The pseudospin precesses with a frequency controlled by the applied magnetic field while diffusing from the injector to the detector. As a result, positive (b), zero (c), or negative (d) magnon spin is detected giving rise to an analogous behavior of the measured spin signal between the two electrodes as shown in (e). The white curve depicts the theoretical model fit to the experimental data shown via black circles.

situation corresponds to a negative magnon spin signal observed in our experiments (Fig. 1(e)).

We employ a 15 nm thin film of hematite ($\alpha$-Fe$_2$O$_3$) as the AFI. Our film is characterized by an easy $y$-$z$-plane anisotropy and an out-of-plane DMI vector. The equilibrium Néel vector $\mathbf{n}$ and the sublattice magnetizations $\mathbf{m}_1$, $\mathbf{m}_2$ thus lie in the $y$-$z$-plane with a small canting angle between $\mathbf{m}_1$ and $\mathbf{m}_2$ (Fig. 2(a)). An applied magnetic field along $\hat{y}$ orients the Néel vector along $-\hat{z}$. The magnitude of the external magnetic field $\mu_0 H$ further controls the canting angle and the net induced magnet moment $\mathbf{m}_{\text{net}} = \mathbf{m}_1 + \mathbf{m}_2$, both bearing a constant DMI-induced offset and a variable contribution linear in $\mu_0 H$. We employ platinum as the HM for electrically injecting and detecting magnonic spin [7]. A charge current driven through the injector platinum electrode generates a $z$-polarized electron spin accumulation at its interface with the AFI (Fig. 2(a)). Thus, a $z$-polarized magnon spin and pseudospin current is injected into the AFI. The reverse process enables the detection of the magnon spin in the AFI at its interface with the detector electrode as a charge current/voltage.

For the configuration discussed above, the dynamics and diffusive transport of the magnon pseudospin density $S$ in the AFI is described as

$$\frac{\partial S}{\partial t} = D \nabla^2 S - \frac{S}{\tau_s} + S \times \Omega \hat{y},$$

in direct analogy with the spin diffusion and dynamics.
for itinerant electrons [30]. Here, $D$ is the magnon diffusion constant [36] and $\tau_s$ is the spin relaxation time accounting for the incoherent effect of spin-nonconserving interactions [19]. The pseudospin precession frequency $\Omega$ characterizes the moment effect $m_{\text{net}}$ as well as the Néel order parameter $n$ are illustrated. Upon applying a charge current $I_{\text{inj}}$ to the injector, a spin current $I_s$ with spin polarization $s$ is generated via the SHE and injected into the hematite ($\alpha$-Fe$_2$O$_3$) with thickness $t$. The emerging antiferromagnetic magnon current is then detected via the reverse SHE-induced current $I_{\text{det}}$ at the detector by measuring the electrical voltage drop $V_{\text{det}}$. (b) Angle dependent magnon spin signals $R_{\text{det}}^{\text{el}} \propto V_{\text{det}}^{\text{el}}/I_{\text{inj}}$ for electronically excited magnons measured at the detector for $T = 200$ K with a center-to-center distance of $d = 700$ nm. The light colored solid lines are fits to a $\sin^2(\varphi)$-type function.

$H_{\text{DMI}}$ is the effective DMI field. $\hat{m}$ is an equivalent magnetic moment that parametrizes the DMI strength [40]. It allows for elucidating the linear $\mu_0 H$-dependence of the noncollinearity-mediated contribution to $\Omega$. Considering $z$-polarized magnon spin and pseudospin current density $j_{s0} \propto z$ injected by the electrode at $z = 0$, the steady state solution (see SI [39]) to Eq. (1) yields for the magnon spin density $s(z) = S_\pm(z)$:

$$s(z) = \frac{j_{s0} \lambda_s}{D(a^2 + b^2)} e^{-\frac{z}{\lambda_s}} \left(a \cos b z - b \sin b z \right),$$

where $a \equiv \sqrt{(1 + \sqrt{1 + \Omega^2 \tau_s^2})/2}, \ b \equiv \sqrt{(-1 + \sqrt{1 + \Omega^2 \tau_s^2})/2}, \ \lambda_s \equiv \sqrt{D \tau_s}$ is the spin diffusion length. Equation (3) describes the magnon spin density at a distance $z$ from the injector. It is proportional to the magnon spin signal measured by the detector electrode at $z = d$. Together, Eqs. (2) and (3) describe the key phenomenon reported here and form the basis for analyzing our experimental data. An example theoretical curve is shown as the white solid line together with the experimental data in Fig. 1(e). Consistent with our model, we see a pronounced peak in the positive magnon spin signal regime at the compensation field $\mu_0 H_{c}$ for which $\Omega = 0$. For increasing field strength, the spin signal decreases until it approaches zero signal at $\mu_0 H_{c}$, corresponding to a 90° rotation of the pseudospin vector, i.e. a linear polarization of the propagating magnon modes carrying zero spin. A sign inversion of the spin signal is evident when the field is further increased to $\mu_0 H_{\text{inv}}$, corresponding to a full 180° rotation of the pseudospin vector $\mathbf{S}$ and therefore an inversion of the magnon mode chirality/spin (c.f. Fig. 1(a)). As evident from Fig. 1(e), the same behaviour is observed for decreasing field strength $\mu_0 H < \mu_0 H_{c}$, corresponding to a pseudospin precession in the opposite sense.

Subsequently, we measure the magnon spin signal $R_{\text{det}}^{\text{el}} \propto V_{\text{det}}^{\text{el}}/I_{\text{inj}}$ at the detector (see SI for details [39]) as a function of the external magnetic field orientation $\varphi$ within the $y$-$z$-plane as illustrated in Fig. 2(a). The result is shown in Fig. 2(b) for a center-to-center strip distance of $d = 700$ nm. The data exhibit a 180°-symmetric modulation consistent with the SHE-mediated spin injection and detection of magnons [7, 41]. Hence, the angle dependence can be fitted with a simple $\Delta R_{\text{det}}^{\text{el}} \sin^2(\varphi)$ function, where $\Delta R_{\text{det}}^{\text{el}}$ represents the amplitude of the electrical magnon spin signal. The signal modulation is shifted by $\approx 90°$ compared to similar measurements on ferrimagnetic materials [7, 41, 42]. This is due to the fact that the electrical magnon excitation is only active when $\mu_s \parallel \hat{n}$, i.e. for $\mathbf{H} \perp \hat{n}$ in our experiments. Thus, we can confirm that the excited magnons in our experiments originate from the antiferromagnetic Néel order consistent with previous experiments in AFIs [11]. Most importantly, we indeed observe two sign inversions of $R_{\text{det}}^{\text{el}}$.
Figure 3. Temperature dependence of magnon transport parameters. (a) Electrically excited magnon spin signals $\Delta R^\text{el}_{\text{det}} \propto V^\text{el}_{\text{det}}/I_{\text{inj}}$ for a structure with strip distance $d = 750$ nm plotted as a function of magnetic field for different temperatures. Light colored solid lines are fits to Eq. (3). (b) Compensation field $\mu_0 H_c$ versus temperature extracted from experiments with devices of varying $d$. The temperature dependence of $\mu_0 H_c$ follows the temperature trend of the uniaxial anisotropy of hematite. (c) Spin diffusion length $\lambda_s$ as a function of temperature extracted from experimental data from different devices with varying $d$. $\lambda_s$ increases with increasing temperature for all investigated structures.

in the investigated field range. While a positive signal is measured for $\mu_0 H = 1$ T and 6 T, a negative signal ensues at 4 T. These measurements are further evidence for the rotation of the pseudospin vector via the coherent coupling $\Omega$ between the antiferromagnetic magnon modes described in the spin diffusion equation (1).

Last but not least, we extract the relevant magnon transport parameters from our data using the diffusive spin transport model given in Eq. (3). To this end, we carried out temperature-dependent measurements of the field-dependent magnon spin signals $\Delta R^\text{el}_{\text{det}}$, which are shown in Fig. 3(a). Here, light colored solid lines correspond to fits to Eq. (3) (see SI for details [39]). For all investigated temperatures and devices with varying $d$ we obtain excellent agreement between our experiments and the theoretical model, strongly supporting the validity of our theory. As evident from Fig. 3(a), we observe a decrease of the peak amplitude at $\mu_0 H_c$ with decreasing temperature, which is expected from the electrically excited magnon transport effect [41, 43–45] (see also SI [39]). Moreover, we find a clear decrease of the compensation field with decreasing temperature in Fig. 3(a). For a quantitative treatment of this behaviour, we extract $\mu_0 H_c$ for each temperature from the fits and plot its temperature dependence in Fig. 3(b). For each structure, we observe a constant behaviour in the temperature range from 100 K to 150 K. A significant increase is evident for larger temperatures up to 300 K. As evident from Eq. (2), the compensation field can be expressed as $\mu_0 H_c = \hbar \tilde{w}_{\text{an}} (\tilde{m}^2)^{-1}$. Therefore, $\mu_0 H_c$ directly corresponds to the normalized anisotropy energy $\tilde{\omega}_{\text{an}}$ of the hematite. We thus expect that $\mu_0 H_c$ follows the temperature dependence of the easy-plane anisotropy. This is supported by previous measurements of the temperature dependence of the anisotropy energy in hematite, which qualitatively agree with the temperature dependence of $\mu_0 H_c$ [46]. Hence, our results support the assumption that the coupling strength $\Omega$ defined in Eq. (2) is related to the easy-plane anisotropy in hematite. Finally, we calculate the magnon diffusion length $\lambda_s$ using the extracted diffusion constant $D$ and the spin relaxation time $\tau_\text{s}$ from our fits. The obtained temperature dependence of $\lambda_s$ is shown in Fig. 3(c). Overall, we find an increase of $\lambda_s$ with increasing temperature for all studied injector-detector distances $d$. At room temperature, we extract $\lambda_s \approx 0.5 \mu$m, which is in perfect agreement with recent reports measuring the spin diffusion length in the easy-plane phase of hematite thin films using distance-dependent measurements [47, 48].

As a key result, we have experimentally demonstrated the coherent control of spin currents and magnon pseudospin dynamics in antiferromagnetic insulators. This opens new avenues for antiferromagnetic magnonic applications such as spin based transistors or field-controlled switchable devices. Moreover, our experimental exploitation of the magnonic equivalent of a spin-1/2 electron system provides the first crucial step towards various pseudospin-based concepts such as an unconventional non-Abelian computing scheme [18].

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See Supplementary Information at [url], which includes Refs. [49–55], for details on growth conditions and magnetometry measurements of our hematite films, details on the measurement technique and geometry of the nanostructures, a rigorous description of the fitting routine of the field-dependent magnon spin signals, a more detailed study of the temperature-dependent magnon spin signals, a verification of the linearity of the current-voltage characteristics of the magnon spin signals as well as measurements ruling out electric leakage currents between the injector and the detector electrode. Additionally, we present a detailed description of the diffusive spin transport theory including the antiferromagnetic pseudospin dynamics.

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