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Length scale for magnon-polaron formation from nonlocal spin transport

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We develop a theory for nonlocal spin transport through magnetic insulators that treats the coherent magnetoelastic interaction on equal footing with incoherent relaxation processes. In particular, our theory is able to describe the formation of magnon polarons, hybridized spin and elastic waves, near an interface where spin is injected into the magnetic insulator. Our theory is based on the stochastic Landau-Lifshitz-Gilbert equation coupled to stochastic equations of motion for the lattice displacement. By solving these equations, we obtain the charge voltage generated in a detector on one side of the magnetic insulator in response to spin biasing with an injector on the other side. We find that though magnon-polaron formation causes anomalous features in the spin transport, a length scale exists, however, below which magnetoelastic coupling does not affect the nonlocal spin current. This finding may motivate experiments to explore this aspect of magnon-phonon coupling in magnetic materials.

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Introduction. Lattice distortions can affect spin waves within a magnet due to magnetoelastic coupling (MEC). The dynamics of phonons, the quanta of lattice distortions, is likewise influenced by magnons, the quanta of spin waves. The MEC leads to magnon polarons (MPs), i.e., coherently hybridized quasiparticles that form near the anticrossing of the uncoupled magnetic and acoustic dispersions [1]. This hybridized state has been reconsidered very recently in the magnetic insulator yttrium iron garnet (YIG) [2–5]. This material allows one to access the strong-coupling regime due to its unique acoustic and magnetic quality. In this regime the rate for coherent energy exchange exceeds the dissipative loss rates. The interconversion between magnons and phonons via MEC can be detected in various experimental setups such as magneto-optical [3,6] and transport [7] measurements.

The spin and thermal transport properties of magnetic insulators are altered by the resonant coupling of magnons and phonons. The signature of this resonant coupling has been found in several transport experiments, such as the spin Seebeck effect [8] and the spin Peltier effect [9]. It has been observed that MEC can lead to a resonant enhancement of the local spin Seebeck effect [4], where a thermal gradient drives a magnon spin current through the magnetic insulator. While these local transport measurements thus provide insights on the magnon-phonon interaction, we focus in this Rapid Communication on a nonlocal spin transport setup which, as we shall show, provides additional information on the formation of MPs.

Generally, nonlocal spin transport experiments are able to probe the transport properties of spin carriers not only in metals [10] and semiconductors [11], but also in magnetic insulators [12], where magnons act as information and energy carriers. Nonlocal spin transport schemes have proven useful in elucidating the transport features of magnons in YIG [13] that cannot be probed by a local configuration. Recently, nonlocal magnon spin transport devices have been used to address not only the generation but also the transport properties of MPs in YIG [14], showing that the nonlocal spin Seebeck signals in YIG/Pt bilayers are suppressed rather than enhanced due to the MP resonances.

Previous works concerning transport have thus focused on the influence of MPs on the local [4,5] and nonlocal spin Seebeck effect [14]. In this Rapid Communication, we point out that a nonlocal spin transport experiment probes the length scale for MP formation that is not straightforwardly extracted from spin Seebeck effect measurements. This length scale comes about because in a nonlocal setup the spin that is injected near the interface enters the magnon system only. For MPs to play a role in the nonlocal spin transport, the injector-detector distance needs to be larger than the MP formation length scale. This is reminiscent of a normal metal/superconductor bilayer in which the superconductivity is induced only over the superconducting coherence length, the length scale over which Cooper pairs can penetrate into the normal metal from the adjacent proximity coupled superconductor. Another example is the absorption, over a small length, of spin injected into a metallic magnet that has polarization transverse to the local magnetization direction [15].

To theoretically address the length scale for MP formation, we present a theory based on the stochastic Landau-Lifshitz-Gilbert equation [16] coupled to stochastic equations of motion for the lattice displacement. We determine the inverse spin Hall voltage drop in the detector in linear response to a spin accumulation, $\mathbf{\mu} = |\mathbf{\mu}|$, generated in the injector by the spin Hall effect. We recover the anomalous features in the spin current related to MP formation that manifest themselves as peaks or dips in the spin current as a function of field. Moreover, we indeed find that these features disappear for
short injector-detector distances, indicating a length scale over which the MP forms. The theoretical description of this formation requires the inclusion of both incoherent and coherent dynamics which our formalism includes straightforwardly, but may be more cumbersome to incorporate in the Boltzmann approach of Ref. [5].

**Model and formalism.** The minimal model Hamiltonian that describes the coupling between elastic waves and magnetization in magnetic insulators reads

\[ \mathcal{H} = \mathcal{H}_{\text{el}} + \mathcal{H}_{\text{mag}} + \mathcal{H}_{\text{MEC}}. \]  

(1)

Here, a cubic unit cell with spatially constant magnetization is considered for a magnetic insulator with the equilibrium saturation magnetization \( M_0 \) along the applied magnetic field \( H \). The magnetization Hamiltonian \( \mathcal{H}_{\text{mag}} \) consists of linearized Zeeman \( \mathcal{H}_Z \), and exchange \( \mathcal{H}_{\text{ex}} \) energies,

\[ \mathcal{H}_Z = \mu_0 H M_0 (m_x^2 + m_z^2)/2, \]

(2a)

\[ \mathcal{H}_{\text{ex}} = \lambda_0 \mathbf{M} \cdot \mathbf{S}, \]

(2b)

where \( m_x \) and \( m_z \) are the transverse components of the magnetization vector \( \mathbf{m} = M_0 \mathbf{M} \), and \( \lambda_0 \) denotes the exchange parameter. The lattice dynamics in an isotropic solid, with both kinetic and elastic contributions, is given by \( \mathcal{H}_{\text{el}} = (\rho/2) \mathbf{R} \cdot \mathbf{R} + (\lambda/2) \mathbf{S} \mathbf{S} + \mu \sum_{ij} S_{ij}^2 \), with \( S_{ij} = (\partial_i R_j + \partial_j R_i)/2 \) denoting the components of the strain tensor, \( \rho \) the mass density, \( \lambda \) and \( \mu \) elastic constants, and where \( \mathbf{R} \) represents the small displacements from an equilibrium state. The lowest-order expression for the MEC, satisfying the underlying symmetry, reads \( \mathcal{H}_{\text{MEC}} = \sum_{ij=x,y} (a \delta_{ij}) S_{ij} m_i m_j + 2b \sum_{i=x,y} S_{0i} m_i \), where \( a \) and \( b \) are phenomenological magnetoelastic coupling coefficients.

We consider a magnetic insulator sandwiched between two heavy metal (Pt) contacts, as the injector and detector, with interfaces located along the planes \( x = 0 \) and \( x = d \), which is translationally invariant in the \( yz \) plane (see Fig. 1). The system is driven out of equilibrium by a spin accumulation \( \mu = \mu z \) maintained in the left lead by, e.g., the spin Hall effect [17]. At nonzero temperatures, the adequate treatment of the dynamics of the magnetization driven by thermal fluctuations requires that bulk and boundary fluctuations and losses of both magnons and phonons be considered in the equations of motion. The lattice displacement vector may be recast into the form of longitudinal \( R_L \), in-plane transverse \( R_T \) and out-of-plane transverse \( R_R \) modes. The small amplitude excitations of coupled magnetization and lattice dynamics, \( \Psi = (m_x, m_y, R_L, R_T, R_R)^T \), are governed by the linearized coupled equation of motion in the bulk,

\[ \mathcal{L}_B \Psi = \eta_B. \]  

(3)

Here, \( \mathcal{L}_B \) denotes the bulk differential operator that follows from the coupled magnetoelectronic equations of motion given in the Supplemental Material [18], while \( \Psi = \psi(x, q, \omega) \) is the Fourier transform of the displacement vector. The stochastic force \( \eta_B = (\eta_m, \eta_m, \eta_R, \eta_R, \eta_R)^T \), that describes thermal agitation due to nonequilibrium magnetization and lattice noise in the bulk, is related to the Gilbert damping \( \alpha \) and phonon relation time \( \tau_P \) by the fluctuation dissipation theorem,

\[ \langle \eta_l(x, q, \omega) \eta_{l'}(x', q', \omega') \rangle = (2\pi)^3 \delta_{ll'} \delta_{q q'} \delta(\omega - \omega') \tan h[(\hbar \omega - \mu_{i, l})/2k_B T_i], \]

(4)

where \( \eta_{1,2} \equiv q^{1/2}/4\pi \), with the interfacial spin mixing conductance \( g^{1/2} \), and \( \eta_{3,4,5} \equiv \eta_p \), describing dissipation due to

![FIG. 1. Nonlocal spin transport configuration comprising a Pt/YIG/Pt heterostructure as a model system: A charge current \( I \) through the left Pt builds up a nonequilibrium spin accumulation \( \mu = \mu z \) at the left Pt/YIG interface (injector) via the spin Hall effect. With MEC being present, the angular momentum is transferred, through the exchange interaction at the interface, to the excitations with a mixed character; magnon polaron. The diffusing MPs through the magnetic insulator induce a spin accumulation in the right Pt/YIG interface, which is used to be detected as a nonlocal charge voltage \( V \) in the detector, through the inverse spin Hall effect. The magnetization is saturated along the \( z \) axis by a magnetic field \( H \). The injector-detector distance \( d \), electrical injection, and detection schemes are indicated schematically.]

The boundary conditions on \( \Psi \) at the two interfaces, considering both stochastic and deterministic spin-transfer torques, read

\[ \mathcal{L}_L \Psi = \eta_L (x = 0), \]

(5a)

\[ \mathcal{L}_R \Psi = \eta_R (x = d), \]

(5b)

in which \( \mathcal{L}_{LR} \) represents the interface operator for the left (right) boundary, which acts on \( \Psi \), and \( \eta_L(R) \) corresponds to spin and phonon fluctuations in the normal lead at the left (right) interface. The spin current noise and lattice fluctuations in the normal metal lead to stochastic surface forces \( \eta_{0, L(R)} \) which relate to generalized damping coefficients \( \eta_q \) according to the fluctuation-dissipation theorems for the \( l = L, R \) interfaces,

\[ \langle \eta_{0, l}(q, \omega) \eta_{0, l'}(q', \omega') \rangle = (2\pi)^3 \delta_{ll'} \delta_{q q'} \delta(\omega - \omega') \tan h[(\hbar \omega - \mu_{0, l})/2k_B T_{0, l}], \]

(6)
The material parameters of YIG are adopted here; saturation magnetization $M_0 = 1.4 \times 10^5$ A/m, magnetoelastic coupling $b = 6.96 \times 10^3$ J/m$^3$, exchange stiffness $D_{\text{ex}} = 2\gamma J_{\mu_0} M_0 / \rho = 8.2 \times 10^{-6}$ m$^3$/s, gyromagnetic ratio $\gamma / 2\pi = 2.8 \times 10^{10}$ Hz/T, mass density $\rho = 5170$ kg/m$^3$, and elastic constant $\mu = 7.4 \times 10^{10}$ Pa, transverse sound velocity $c_t = 3.8 \times 10^2$ m/s, and Gilbert damping $\alpha = 10^{-4}$.

The peak and dip in the signal correspond to $\mu_0H = \mu_0H_1 \sim 2.5$ T, where the magnon-polaron formation is enhanced. The inset in (a) shows a closeup around the touching field. Magnon-polaron (MP), magnon, and transverse phonon dispersions are indicated in the right panels. (b) For $H < H_1$, the transverse phonon and magnon dispersions intersect at two points where magnetoelastic coupling is maximized (see insets), while (c) for the touching field $H = H_1$, the magnon and phonon dispersions become tangent to each other where the MP phase space formation is enlarged (see inset).

The generated spin current, $j_s$, as a function of magnetic field for different values of phonon relaxation times $\tau_p$, an injector-detector distance of $d = 5$ $\mu$m, and $T = 10$ K, is shown. Without MEC, the spin current flowing through the right interface decreases monotonically with increasing magnetic field as magnons are frozen out by the magnetic field, while MEC leads to resonant features that appear close to the touching field $\mu_0H_1 = c_t^2/4D_{\text{ex}} \sim 2.5$ T (see Fig. 2), as the phase space of MP coupling is then maximal [4,14]. When the quality of the phonon transport channel is better than the magnon one, the hybridization of magnons which leads to an enhanced nonlocal spin current, is valid because the YIG thickness, along the $z$ direction, is much smaller, typically a few hundred of nm, than the injector-detector separation distance $d$.

The generated spin current $j_s$, as a function of magnetic field for varying injector-detector distances $d$ from 1.4 to 5.0 $\mu$m at $T = 10$ K. The peaks correspond to $\mu_0H \sim 2.5$ T, where phonon and magnon dispersions become tangent to each other which maximizes the phase space of MP formation. The MP peak disappears for short lengths, indicating a length scale over which the MP forms.
Delta dipolar interactions to the nonlocal spin voltage, Max($\Delta \omega$), shows a decaying oscillatory behavior as a function of injector-detector distance (Fig. 4) due to the interference of the MP wave function with its reflection at the right boundary of the magnetic insulator. This is reminiscent of an FFLO-like state generated in a ferromagnet-superconductor bilayer, which results in the oscillation of the induced superconducting pairing wave function as a function of the ferromagnet layer thickness. Here, the short-wavelength limit of the dipolar interaction, $\mathcal{H}_{\text{dip}} \approx (\mu_0 M_0^2) m^2 \sin^2 \theta$, is adopted. The dipolar interaction is responsible for the anisotropy in the magnon dispersion, which appears in the distance dependence of the spin current.

**Conclusion and discussion.** We have developed a nonlocal MP spin transport theory in magnetic insulators, showing that magnetoelastic coupling can affect magnon spin transport above a specific length scale. Above this length, an anomalous peak structure appears in the nonlocal spin voltage as a function of field, for fields around the touching field. In our treatment, we have not included the coupling between the spin of the electrons in the Pt to the phonon spin in the YIG across the interface, which we expect to be weak. Future work should investigate the validity of this assumption, as well as the role of disorder.

Finally, we mention that the experimental results of Cornelissen et al. are consistent with our findings. Although the MP-related resonant feature at the touching field is clearly resolved in the signal due to the thermal magnon generation which can be measured in the second-harmonic response, it is hardly observed, however, in the nonlocal electrically generated signal, detected from the first-harmonic response. This could be because the injector-detector separation distances are already below or comparable to the MP formation length scale. We hope that our results motivate experiments to further explore the proposed length scale for MP formation.

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