Spin-orbit and spin-lattice dynamics in magnetic nanostructures

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Abstract

We studied the influence of the interplay of spin-orbit interactions and spin-lattice couplings on the dynamics and transport of magnetic structures, such as domain walls and spin currents in alloys. We related these to observations of Spin Seebeck effects and spin pumping.

1. Research Objectives

Spin-orbit interactions constitute the microscopic mechanism for many key effects in both pure and applied magnetism, involving coupling of orbital and spin degrees of freedom. Spin-orbit effects are also basic to the effects of crystalline anisotropy in magnetic systems and the coupling between magnetism and lattice effects. The interplay between lattice vibrations, quantized as phonons and magnetic degrees of freedom leads to couplings between heat and spin currents which can lead to a new generation of devices, for example spin-current injectors. Our aim is to relate the more microscopic measurements, for example of neutron scattering to nano-magnetic transport as is exploited in novel devices.

2. Research Contents

We extended our previous calculations, with particular emphasis on frustrated systems, guided by choices of experimental colleagues at the ASRC and elsewhere in order to make direct comparisons between theory and experiment [1,2].

Magnon-phonon and magnon-polaron couplings were studied both from the point of view of microscopic analysis of bulk materials, as can be compared in great detail to experimental results by neutron scattering, taking advantage of close contacts at the ASRC and ILL, but increasingly also by delicate measurements in nano-scale devices by measurements such as spin-current injection and spin Seebeck effects at the ASRC, IMR, Delft. From a theoretical point of view the spin dynamics can be treated more classically starting with coupled Landau Lifshitz Gilbert equations or, as appropriate at low temperatures, by explicit quantum mechanical methods such as Density Matrix Renormalization Group or high order perturbation theory.

3. Research results

Brillouin light scattering is an established technique to study magnons. Its efficiency can be enhanced by cavities that concentrate the light intensity. In Ref. [3], we considered the inelastic scattering of photons by a magnetic sphere that supports optical whispering gallery modes in a plane normal to the magnetization (see Fig. 1). Magnons with low angular momenta scatter the light in the forward direction with a pronounced asymmetry in the Stokes and the anti-Stokes scattering strength while magnons with large angular momenta constitute Damon Eshbach modes and were shown to reflect light inelastically. We calculated the reflection spectrum and derived selection rules based on the chirality of the Damon Eshbach magnons. This gives a means of controlling energy transfer to the magnet by light.

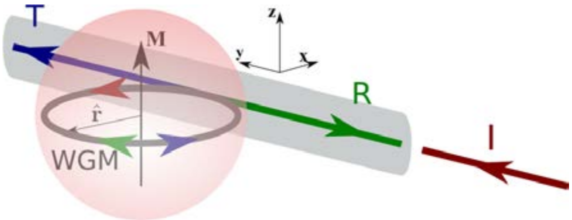

Fig 1 : Interaction of incoming light with the whispering gallery modes of a spherical cavity

Terbium gallium garnet (TGG) is well known for its high Verdet constant and is the prototypical system for the thermal Hall effect. The theoretical explanation for this effect was proposed to stem from resonant phonon scattering from crystal field levels at superstoichiometric Tb^{3+} ions. Using recent inelastic neutron scattering results which have demonstrated that these excess ions are at sites of tetragonal symmetry, we have constructed a detailed description of the crystal field levels for the orthorhombic stoichiometric ions and superstoichiometric sites [4]. In particular, the tetragonal sites are predicted to have low-lying doublet states. This should enable a more quantitative comparison for the measured thermal Hall effects, starting from the theory of Mori et al. [5].

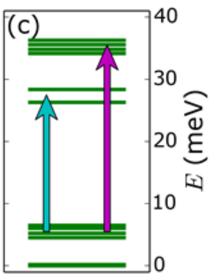

Fig 2 : Crystal field levels analysed in TGG: the prototypical system of the thermal Hall effect

The spin Hall effect is affected by the Coulomb interaction as well as spin–spin correlations in metals. In Ref. 6, we summarized effects of the enhancement in by resonant skew scattering induced by electron correlations (See Figs.3 and 4). For example local Coulomb correlations may significantly change the observed spin Hall angle. Additional effects because of the special atomic environment close to a surface — extra degeneracies compared to the bulk, enhanced correlations that move the local atomic levels, and interference effects coming from the local geometry. We also reconsidered impacts on the spin Hall effect of cooperative effects, most recently in metallic spin glasses, where exchange via slowly fluctuating magnetic moments may lead to the precession of an injected spin current.

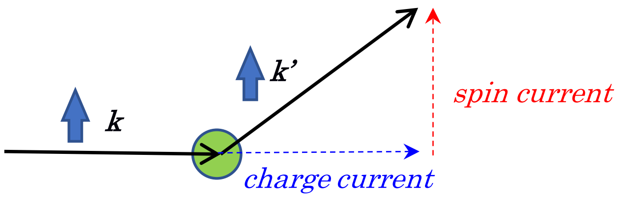

Fig 3 : Schematic figure of skew scattering of electron from momentum ***k*** to ***k'*** . Its scattering amplitude depends on the electron spin shown by blue arrows. This converts charge current (blue broken line) into spin current (red broken line).

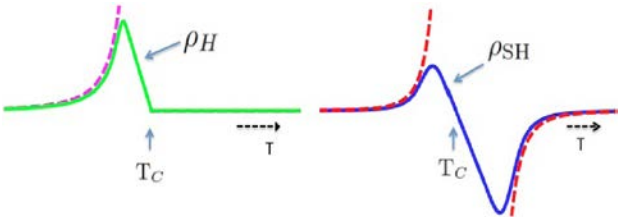

Fig 4 : Schematic behavior of the anomalous Hall effect, (left), and spin Hall effect, (right). Figures from Ref. [6].

4. Conclusion

The experimental advances in spintronics devices continue to pose many challenging questions to the theoretical community, and pressing new questions, are raised especially concerning modes that are hybrids of phonons, magnons and, most recently light. Skew effects are small but significant and occur for both electron and phonon scattering. Understanding from a microscopic point of view is a source of novel theory and may suggest novel control mechanisms.

5. References

[1] M. Mori, 'Broad line-width of antiferromagnetic spinwave due to electrons correlation', J. Phys. Soc. Jpn. **86**, 124705 (2017).

[2] M. Matsuda, H. Onishi, A. Okutani, J. Ma, H. Agrawal, T. Hong, D. M. Pajerowski, J. R. D. Copley, K. Okunishi, M. Mori, S. Kimura, and M. Hagiwara, 'Magnetic structure and dispersion relation of the S=1/2 quasi-one-dimensional Ising-like antiferromagnet BaCo2V2O8 in a transverse magnetic field', Phys. Rev. B **96**, 024439 (2017).

[3] Sharma, Ya. M. Blanter, and G. E. W. Bauer, 'Light scattering by magnons in whispering gallery mode cavities', Phys. Rev. B **96**, 094412 (2017)

[4] R. Wawrzynczak et. al., 'Magnetic order and single-ion anisotropy in the frustrated magnet - $Tb_3Ga_5O_{12}$', in preparation.

[5] M. Mori, A. Spencer-smith, O. P. Sushkov, S. Maekawa, ' Origin of the Phonon Hall Effect in Rare-Earth Garnets', Phys. Rev. Lett. **113**, 265901 (2014)
[6] T. Ziman, Bo Gu, and S. Maekawa, 'Skew Scattering from Correlated Systems: Impurities and Collective Excitations in the Spin Hall Effect', J. Phys. Soc. Jpn. **86**, 011005 (2017).