Self-Focusing of Spin Waves in Ferromagnets with and without DMI

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The Dzyaloshinskii-Moriya interaction (DMI) is known for producing interesting static and dynamic effects such as skyrmions and nonreciprocity. We look at some different consequences of an interfacial DMI interaction in thin films, particularly in regard to the flow of energy.

There are a number of unusual behaviors:

1) A short oscillating pulse from a point source produces an expanding bulls-eye pattern in the dynamic magnetization. What is surprising is that the center of the bulls-eye drifts from the source over time with a constant velocity.

2) We examine power-flow in a thin film with both DMI and dipolar interactions. In the ultrathin film limit and without DMI, the power flow is essentially isotropic, radiating energy approximately equally in all directions. The results are very different when both effects are present. We find, both analytically and through micromagnetics, that with DMI one can create caustics, highly focused, narrow, beams of energy, at particular frequencies. Furthermore, the focusing patterns are highly nonreciprocal, with the caustic beams appearing only on one side of the film surface.

3) We find that the power flow can create interface patterns a single point-source excitation.

These results have important implications for spintronic devices and applications, such as in magnonics, where the transfer of angular momentum and energy plays a key role.

Domain wall solutions in nanowires with Dzyaloshinskii-Moriya interaction

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It is widely known that the Dzyaloshinskii-Moriya interaction (DMI) may stabilize Néel walls rather than Bloch walls in magnetic thin films. When the DMI is weak, it results in a "tilted" Bloch wall that is between a Bloch and Néel solution. However, for most of the proposed applications, domain walls are in nanowires, rather than thin films.

In the first half of this talk I will present a 1D analytic theory for determining the domain wall type in a nanowire as a function of the wire's aspect ratio and the DMI strength. It turns out that very different domain wall solutions occur in nanowires than occur in films with the same DMI strength, due to the demagnetizing effects. In the second half of the work, I will extend the work to consider the effect of an applied magnetic field to tune the domain wall type. A 1D model works well for small applied fields, but numerical solutions must be sought for large fields.

Low dimensional quantum magnetism in a J_{eff} = 1/2 honeycomb lattice of Cobalt

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Quantum magnetism in the case of J_{eff} = 1/2 moments on a honeycomb lattice is investigated using layered hexagonal $BaCo_2(PO_4)_2$ as a prototype. Theoretical predictions following 'spin liquid state in maximally frustrated honeycomb lattice'[1] and 'quantum *J1-J2-J3* model on honeycomb lattice'[2] form the basis for our experimental investigations comprising of magnetometry and neutron scattering. $BaCo_2(PO_4)_2$ crystals and powder samples were prepared following hydrothermal synthesis[3]. By adopting this method of synthesis, the metastable γ-phase (*R-3*) of $BaCo_2(PO_4)_2$ was synthesized. Magnetization and specific heat measurements indicate a broad phase transition occurring at approximately 4 K as reported previously[4]. The broad nature of phase transition as seen in specific heat rules out the possibility of a first-order phase transition. The magnetic measurements indicate ferromagnetic exchange interactions along with competing antiferromagnetic ones. Rietveld analysis of elastic line-cuts extracted from the inelastic scattering data confirms the nuclear structure as *R-3*. The magnetic structure at 2.7 K was modeled by assuming a helical (in-commensurate, k[0.25 0 0.13]) and a zig-zag (collinear, k[0.5 0 0]) spin structure[4]. Our study confirms that the helical and zig-zag phases co-exist in the sample as different regions of domains at low temperatures. However, the spin-spin correlations are observed to persist even up to 40 K. The exchange-driven frustrated nature of $BaCo_2(PO_4)_2$ is brought out through this work and the location of the resultant ground state magnetic structure in the *J1-J2-J3* quantum model is estimated based on inelastic neutron scattering.

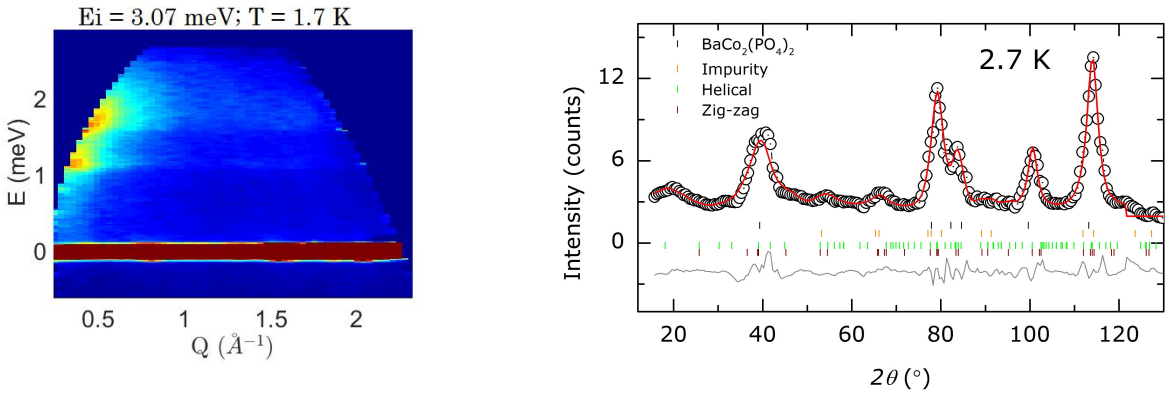

Fig: (*left)* The inelastic scattering observed in $BaCo_2(PO_4)_2$ at 1.7 K. (*right*) Elastic scattering at 2.7 K as a function of momentum transfer fitted to nuclear and magnetic models.

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Magnetic Properties of Aligned, Single-Chirality Carbon Nanotube Films

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The magnetic properties of single-walled carbon nanotubes (SWNTs) – both metallic and semiconducting species – change with the direction of the magnetic field with respect to the tube axis, yielding a magnetic anisotropy given by $\Delta\chi = \chi_{//} - \chi_{\perp}$. Metallic nanotubes are paramagnetic along the tube axis ($\chi_{//} > 0$) and diamagnetic in the perpendicular direction ($\chi_{\perp} < 0$), whereas semiconducting tubes are diamagnetic in all directions ($\chi_{//}, \chi_{\perp} < 0$). Our previous magnetic linear dichroism spectroscopy measurements on a length-sorted, (6,5)-enriched CoMoCAT SWNT suspension found that the (6,6), (5,5), and (7,4) nanotubes align more rapidly with the magnetic field than the semiconducting nanotubes found in our sample. As a complementary experiment, we also investigated a metallic-enriched SWNT sample. By relating these values with the nematic order parameter for alignment, we found that the metallic carbon nanotubes do not follow strict diameter dependence across the 7 chiralities present in our sample.

We are currently pursuing direct measurement of the magnetization in aligned, single chirality carbon nanotube films to deduce information on the diameter and chirality dependence of the magnetic properties in SWNTs. Recently, it was shown that SWNTs indeed follow a diameter dependence through the measurement of the magnetization in diameter sorted unaligned SWNT films. Due to advancements in carbon nanomaterial sorting and film fabrication, specifically the aqueous two-phase extraction separation method along with a new vacuum filtration technique, we have fabricated aligned monodomain SWNT films that can be considered to be a new class of 2D material with a chirality degree of freedom. Here, we present results from the direct measurement of the magnetization of a (6,5) aligned SWNT film at room temperature. The samples were measured in the MPMS3 SQUID magnetometer using the VSM mode and found the saturation moment of the sample to be between 1 to 2e-7 emu. We are currently measuring magnetization for additional chiralities/diameters, specifically (6,6), (7,4), (8,8) and (10,3). We expect that our results will not only determine the true diameter dependence of the magnetic properties of SWNTs but they will also yield exact numbers for the difference in susceptibility for specific chiralities for the first time.

Probing Magnetic Susceptibility Anisotropy of Large-Diameter Metallic Carbon Nanotubes via Magnetic Linear Dichroism Spectroscopy

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Using the strongly anisotropic optical and magnetic properties arising from the one-dimensional nature of carbon nanotubes, we aligned single-wall carbon nanotubes (SWCNTs) in aqueous suspension in magnetic fields up to 22 T. Specifically, we measured the orbital magnetic susceptibility anisotropy ($\Delta\chi$), via magnetic linear dichroism spectroscopy enabled by the unique Florida Split-Helix magnet system, of multiple large-diameter metallic and semiconducting SWCNT species. In particular for the metallic species, we observed $\Delta\chi$'s on the order of 10^{-4} emu/mol, an order of magnitude larger than any $\Delta\chi$ measured previously for SWCNTs. Additionally, we have observed broadening and the beginnings of peak splitting of metallic optical absorption features, due to the Aharanov-Bohm effect. The emergence of such magneto-optical behavior at such relatively "low" magnetic fields, combined with new developments in carbon nanotube sample preparation science, opens the door to observing new many-body effects through magneto-optics.

Photo-Spin-Voltaic Effect

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This presentation reports that a spin voltage can be created by photons in a non-magnetic metal that is in close proximity to a magnetic insulator.[1] This phenomenon is referred to as the photo-spin-voltaic (PSV) effect, in light of its analogy to the photo-voltaic effect. The effect offers a new method for generation of pure spin currents, as an alternative to the well-established spin pumping, spin Hall, and spin Seebeck effects. The experiments used normal metal/magnetic insulator bi-layered structures where the normal metal (NM) was a nm-thick Pt, Pd, or Cr layer and the magnetic insulator (MI) was an $Y_3Fe_5O_{12}$ or $BaFe_{12}O_{19}$ film with a thickness in the 10-10^5 nm range. When light illuminates the NM layer, photons induce a spin voltage near the NM/MI interface and a corresponding pure spin current across the NM thickness. Such a spin current can produce an electric voltage in the NM film via the inverse spin Hall effect. Measurements using various control samples, light sources, and optical filters revealed the magnetic and optical nature of the PSV effect and excluded any thermal origin.

[1] "Photo-spin-voltaic effect," David Ellsworth, Lei Lu, Jin Lan, Houchen Chang, Peng Li, Zhe Wang, Jun Hu, Bryan Johnson, Yuqi Bian, Jiang Xiao, Ruqian Wu, and Mingzhong Wu, Nature Phys., doi:10.1038/nphys3738 (2016).

Synthesis and Magnetic Properties of bimetallic transition metal carbides

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Transition metal carbides have a wide variety of interesting properties but are much less studied for their magnetic properties. We have synthesized several transition metal carbide materials using low temperature methods to produce nano-materials with size, shape, and composition control. By including a second metal, we have formed several bimetallic carbide materials with interesting magnetic properties. From doping iron into molybdenum carbide to forming a solid solution of iron and chromium carbides, we can precisely control the composition and resulting properties for future applications.

Magnetic Properties of Transition-Metal Antimonates and Tantalates

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Transition-metal antimonates and tantalates with the chemical formula $M(\mathrm{Sb,Ta})_2\mathrm{O}_6$ commonly form the tri-rutile structure in which the transition metal atom M is centered within an oxygen octahedron separated from other octahedra by planes of diamagnetic Sb or Ta atoms. The octahedron in the center of the unit cell is rotated 90° from those in the corners allowing for the formation of low-dimensional spin chains along [110] at z=0 and along $[1\bar{1}0]$ at z=1/2. Single crystals have been grown and their magnetic properties measured. Magnetization anisotropy is observed as a characteristic of the spin chains. Anisotropy in heat capacity with an applied magnetic field is also observed. This occurs as field applied along one set of spin chains is perpendicular to the other set. The applied magnetic field lowers the Néel temperature T_N in the former case and leaves the latter unaffected. The shift in the peak associated with T_N signifies there is a change in heat capacity at a given temperature through the application of magnetic field. This leads to a magnetocaloric effect that is anisotropic by means of the low-dimensional spin chains.

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Growth of $BaFe_{12}O_{19}$ Thin Films via Sputtering and Spin Transfer across $BaFe_{12}O_{19}$/Pt Interfaces

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Due to its strong magneto-crystalline anisotropy, $BaFe_{12}O_{19}$ (BaM) has high potential for memory applications. This may be realized, for example, by taking a BaM/Pt bi-layered structure and using the spin Hall effect-produced spin currents in the Pt film to switch the magnetization in the BaM film. Such switching is expected to be more efficient than that in the ferromagnetic metal/Pt counterpart, thanks to the absence of the shunting current in the BaM film and the relatively low damping of the BaM film. This presentation reports on the growth of BaM thin films via sputtering and the demonstration of spin transfer across BaM/Pt interfaces. The films were deposited by RF sputtering at room temperature and subsequently annealed in O_2 at high temperatures. The films with thicknesses of 4-10 nm show an rms surface roughness of 0.2-0.4 nm, an effective perpendicular anisotropy field of about 17 kOe, and a remnant-to-saturation magnetization ratio of 85%-97%. Multiple BaM(9 nm)/Pt(5 nm) Hall bar structures were fabricated by photolithography and ion milling. Those structures show the anomalous Hall effect (AHE), the planar Hall effect, and magneto-resistance behaviour, which together clearly indicate the presence of strong interactions between the moments in the BaM and the spins in the Pt at the interfaces. When the coercivity of the BaM film was measured by sweeping an out-of-plane field, its value decreased or increased by as much as 200 Oe with applied charge currents. These results provide strong evidence for spin transfer at the interfaces.

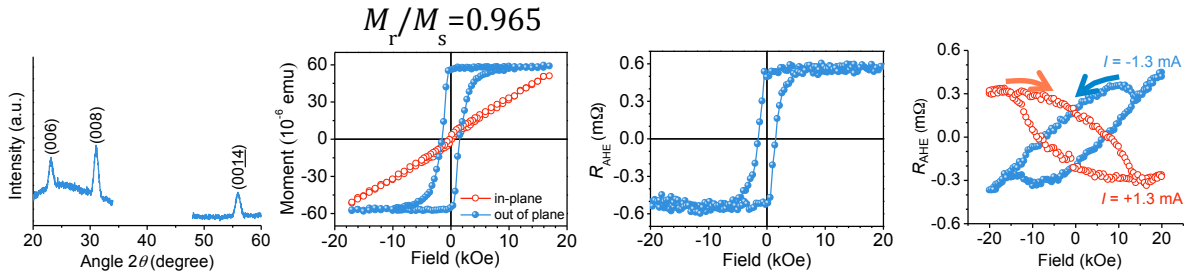

Figure 1: (a) X-ray diffraction spectrum and (b) hysteresis loops of a BaM (9 nm) film. Graph (c) presents the AHE resistance (R_{AHE}) measured on a Pt (5 nm)/BaM (9 nm) Hall bar with a perpendicular field, which shows a loop response very close to the out-of-plane loop in (b). Graph (d) presents the R_{AHE} loops measured for two charge currents of opposite signs, which evolved in an opposite manner.