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## APPLIED MAGNETISM

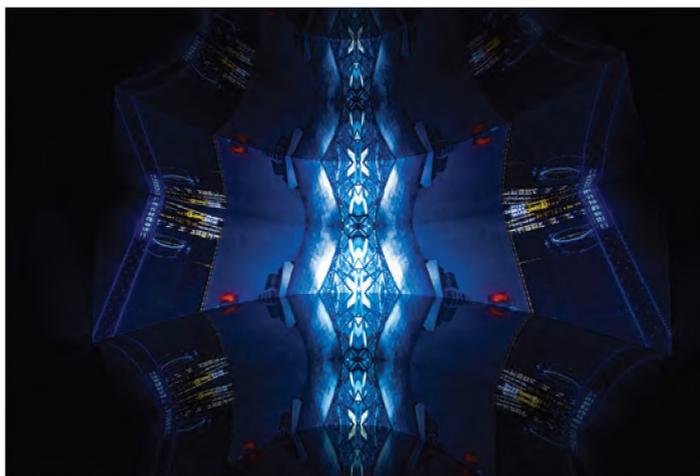
## LE MAGNÉTISME APPLIQUÉ

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by Davis Jian Kun Zhu,  
St. George's School, Vancouver BC

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Nous espérons que vous profiterez de cette occasion d'explorer l'art de la physique en soumettant une oeuvre pour la prochaine compétition.



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Detection of mechanical torque by light interferometry enhances the sensitivity of magnetic resonance spectroscopy (for details see article by Losby and Freeman, p. 71).

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La détection d'un moment de force avec un interféromètre optique accroît la sensibilité de la spectroscopie par résonance magnétique (pour plus de détails voir l'article de Losby et Freeman, p. 71).

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## APPLIED MAGNETISM

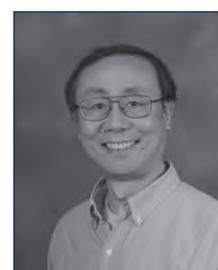
**A**lbert Fert (Orsay) and Peter Grünberg (Jülich) were recognized in 2007 for the discovery of Giant Magnetoresistance (GMR) with the Nobel prize in physics, based on independent discoveries two decades earlier. Technology based on this fundamental effect involving spin-dependent electron scattering in thin ferromagnetic films has been used in the hard drive industry to enhance sensor sensitivity and helped to facilitate the drive towards increased storage capacity ([http://www.nobelprize.org/nobel\\_prizes/physics/laureates/2007/press.html](http://www.nobelprize.org/nobel_prizes/physics/laureates/2007/press.html)). GMR is one of the better known examples in the growing field of spintronics, where the magnetism of a material is used as a means to manipulate the electronics of nanometer scale devices. This rapidly expanding field has invigorated research into magnetic sensors and memories, creating promising new avenues for energy harvesting, data storage, and communicating and processing information.

Spintronics is just one of the many avenues of research discussed in this issue, which explores a variety of topics in applied magnetism. They all involve two important factors: the fundamental characteristics of the magnetic materials used, and the shape and dimensions in which they are made. Discovery of new applications of magnetism in recent decades has been fueled by both the synthesis of new materials and the means by which to fabricate nanoscale particles, thin films and patterned devices. Photolithography, developed for the semiconductor industry, is now a key tool in the development and manufacture of magnetic devices. New techniques for the deposition of magnetic materials into thin films of a few monolayers has driven the discovery of new surface and interface phenomena associated with changes in atomic electron orbital geometry.

In recent decades, research into applications of the magnetic properties of materials has also expanded due to the enhanced understanding of the interactions between the magnetic and other microscopic and macroscopic properties of materials. An explosion of research activity has resulted from new materials synthesis and nanofabrication techniques which exploit coupling between spin and other degrees of freedom, such as the optical, electrical and mechanical.

This issue was inspired by work presented at a number of recent Magnetic North workshops (<http://www.magnetic-north.mun.ca/>) and contains a small sample describing eight selected experimental and theoretical research activities in applied magnetism, with a Canadian focus. It is not intended to be a comprehensive review (also see M.L. Plumer, J. van Ek, and W.C. Cain, *Physics in Canada* **67**, 25 (2011)). Due to journal space limitations, the majority of those working in this field have not been represented here. It is hoped that these will be included in future theme issues of *Physics in Canada*. The articles presented here also serve to complement the 2012 theme issue on *Frustrated Magnetism* (vol. 68, no. 2).

Beginning with an educational article, “Bob the Builder and his electron shovel: Planning and constructing nanomagnets for jobs from drug delivery to electric car motors,” **Johan van Lierop et al.** (Univ. of Manitoba) explain the strategies involved in designing nanoparticle systems for targeted drug delivery and other applications, thereby highlighting how magnetism is used to direct the “pushing” of atoms and their electrons to enable novel applications. This is followed by **Rogério de Sousa’s** (Univ. of Victoria) review, “The holy grail of multiferroic physics,” where he introduces an example of coupling between spin and ferroelectric properties with a focus on BiFeO<sub>3</sub>. He describes the theory of how magnetism can be controlled by electric fields, and places BiFeO<sub>3</sub> close to the “holy grail” of multiferroic physics: the realization of a ferromagnet-ferroelectric at room temperature. An understanding of the magnetization dynamics is essential to applications for high-frequency switching devices. Two articles address the basic physics of magnetization dynamics. In “Instability Processes for Magnons in Ferromagnetic Nanostructures,” **Michael Cottam and Zahra Haghshenasfard** (Western Univ.) describe “spin waves” and a theory of nonlinear dynamic processes in ultrathin films and nanowires. **David Ménard and Christian Lacroix’s** (Polytechnique Montréal) article “Spin Wave Resonance of Ferromagnetic Nanowire Arrays” presents a brief introduction to the experimental investigation of spin wave resonances of ferromagnetic nanowire arrays. Both of these works emphasize their relevance to the emergent field of magnonics, which is dedicated to the control of wave propagation in artificially nanostructured magnetic materials. Magnetization dynamics is also central



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The contents of this journal, including the views expressed above, do not necessarily represent the views or policies of the Canadian Association of Physicists.

Le contenu de cette revue, ainsi que les opinions exprimées ci-dessus, ne représentent pas nécessairement les opinions ou les politiques de l'Association canadienne des physiciens et physiciennes.

to an exciting new frontier of condensed matter physics which takes the approach of building unconventional pathways that link magnetization dynamics with cavity mechanics and cavity quantum electrodynamics (QED). Three articles highlight the advancement in this frontier. In “Spin Mechanics,” **Joseph Losby and Mark Freeman** (Univ. of Alberta) present a brief history, the current state, and future directions of spin mechanics, where Canadian physicists are making remarkable progress by developing cavity opto-mechanics, which couples spin angular momentum with macroscopic mechanical motion. **Can-Ming Hu** (Univ. of Manitoba) reviews the “Dawn of Cavity Spintronics” by tracing it back to some of the most courageous, inspiring, and seminal works in the history of spintronics, cavity QED and polaritons. In “Electronic transport in magnetic tunnel junction: a discussion of the electron-magnon-photon coupling” **Yang Xiao** (Nanjing Univ. of Aeronautics and Astronautics) and **Hong Guo** (McGill Univ.) describe a Green’s function approach to tunneling magnetoresistance and the electron-magnon-photon interaction relevant for understanding magnon polaritons in the strong

coupling regime. Finally, this issue closes with a description of “STT-RAM memory devices” by **Monika Arora et al.** (Simon Fraser University) focusing on a new magnetic device based on spin-transfer torque random access memory where the interaction between the spin polarized current and the localized magnetic moment of a ferromagnet can induce magnetization reversal.

We thank Michael Steinitz for the suggestion of this theme issue and all of the contributing authors who made it successful.

Martin Plumer, Memorial University of Newfoundland  
Can-Ming Hu, University of Manitoba  
Guest Editors, *Physics in Canada*

*Comments of readers on this Foreword are more than welcome.*

## LE MAGNÉTISME APPLIQUÉ

**A**lbert Fert (Orsay) et Peter Grünberg (Jülich) ont été reconnus par le prix Nobel de physique 2007 pour la découverte de la magnétorésistance géante, fondée sur des découvertes indépendantes remontant à deux décennies plus tôt. Dans l’industrie des disques durs cet effet fondamental qui comporte la diffusion d’électrons dépendante du spin dans des films ferromagnétiques minces a permis le développement de capteurs avec une sensibilité accrue et a favorisé l’accroissement de la capacité de stockage ([http://www.nobelprize.org/nobel\\_prizes/physics/laureates/2007/press.html](http://www.nobelprize.org/nobel_prizes/physics/laureates/2007/press.html)). La magnétorésistance géante est l’un des exemples les plus connus dans le domaine croissant de la spintronique, où le magnétisme d’un matériau sert à manier l’électronique des appareils à échelle nanométrique. Ce domaine en plein essor a revigoré la recherche sur les capteurs magnétiques et les mémoires, offrant des moyens prometteurs de production d’énergie, de stockage de données ainsi que de communication et de traitement de l’information.

La spintronique n’est qu’une des nombreuses voies de recherche examinées dans le présent numéro, qui traite de divers sujets en magnétisme appliqué. Toutes comportent deux facteurs importants : les caractères fondamentaux des matériaux magnétiques utilisés ainsi que la forme et les dimensions dans lesquelles ils sont fabriqués. La découverte de nouvelles applications du magnétisme dans les dernières décennies a été

stimulée à la fois par la synthèse de nouveaux matériaux et les moyens de fabriquer des nanoparticules, des films minces et des appareils orientés. La photolithographie mise au point pour les fabricants de semi-conducteurs est devenue un outil clé dans la conception et la fabrication d’appareils magnétiques. De nouvelles méthodes de dépôt de matériaux magnétiques en films minces, de quelques monocouches d’épaisseur, a amené la découverte de nouveaux phénomènes de surface et d’interface liés aux changements à la géométrie atomique d’une orbitale électronique.

Depuis quelques décennies, la recherche sur les applications des propriétés magnétiques des matériaux s’est aussi élargie grâce à une meilleure compréhension des interactions entre les propriétés magnétiques des matériaux et les autres, microscopiques et macroscopiques. Des méthodes de synthèse et de nanofabrication de nouveaux matériaux, exploitant la conjugaison du spin et d’autres degrés de liberté tels l’optique, l’électrique et le mécanique, ont fait exploser les activités de recherche.

Le présent numéro s’inspire des travaux présentés à divers ateliers récents sur le nord magnétique (<http://www.magnetic-north.mun.ca/>) et contient un petit échantillon décrivant huit activités choisies de recherche expérimentales et théoriques en magnétisme appliqué, surtout au Canada. Il ne se prétend pas une étude approfondie (voir aussi M.L. Plumer, J. van Ek, et

W.C. Cain, *La Physique au Canada* 67, 25 (2011)). L'espace de la revue étant limité, la majorité de ceux qui œuvrent dans ce domaine ne sont pas représentés ici. On espère qu'ils le seront dans de futurs numéros thématiques de *La Physique au Canada*. Les articles présentés servent aussi à compléter le numéro thématique de 2012 intitulé *Frustrated Magnetism* (magnétisme dit frustré) (vol. 68, n° 2).

Commençant par un article pédagogique («Bob the Builder and his electron shovel: Planning and constructing nanomagnets for jobs from drug delivery to electric car motors»), **Johan van Lierop et autres** (Univ. du Manitoba) montrent comment le magnétisme sert à diriger la «libération» d'atomes et de leurs électrons et à permettre ainsi la conception de systèmes à nanoparticules comme la libération de médicaments à cible définie. Suit l'étude de **Rogério de Sousa** (Univ. de Victoria), intitulée «The holy grail of multiferroic physics» (le saint graal de la physique multiferroïque), où il donne un exemple de couplage du spin et des propriétés ferroélectriques, mettant l'accent sur le  $\text{BiFeO}_3$ . Il décrit la théorie du mode de contrôle du magnétisme par champs électriques et place le  $\text{BiFeO}_3$  près du «saint graal» de la physique multiferroïque : la réalisation d'un élément ferromagnétique-ferroélectrique à température ambiante. Il est essentiel de comprendre la dynamique de la magnétisation pour l'appliquer aux appareils de connexion haute fréquence. Deux articles traitent de la physique fondamentale de cette dynamique. Dans «Instability Processes for Magnons in Ferromagnetic Nanostructures» (processus d'instabilité pour les magnons dans les nanostructures ferromagnétiques), **Michael Cottam et Zahra Haghshenasfard** (Univ. Western) décrivent les «ondes de spin» et une théorie des processus dynamiques non linéaires dans les films ultra-minces et les nanofils. L'article de **David Ménard et Christian Lacroix** (Polytechnique, Montréal), «Spin Wave Resonance of Ferromagnetic Nanowire Arrays» (résonance d'ondes de spin en réseaux de nanofils ferromagnétiques), présente une brève introduction de l'étude expérimentale des résonances d'ondes de spin en réseaux de nanofils ferromagnétiques. Ces deux travaux soulignent leur pertinence au domaine croissant de la magnonique, qui vise à contrôler la propagation des ondes des matières magnétiques nanostructurées artificiellement. La dynamique de la magnétisation est aussi au centre d'un nouvel horizon passionnant pour la physique de la matière condensée, consacré à des champs non traditionnels reliant cette dynamique à la mécanique de

cavité et à l'électrodynamique quantique de cavité. Trois articles soulignent les progrès dans cet horizon. Dans «Spin Mechanics» (la mécanique de spin), **Joseph Losby et Mark Freeman** (Univ. de l'Alberta) présentent une histoire brève, l'état actuel et les orientations futures de la mécanique de spin, où les physiciens du Canada font des progrès remarquables en élaborant l'opticomécanique de cavité, qui allie le moment angulaire du spin au mouvement mécanique macroscopique. **Can-Ming Hu** (Univ. du Manitoba) étudie la «Dawn of Cavity Spintronics» (l'aube de la spintronique de cavité) en remontant jusqu'à certains travaux des plus courageux, inspirants et marquants dans l'histoire de la spintronique, l'électrodynamique quantique de cavité et les polaritons. Dans «Electronic transport in magnetic tunnel junction: a discussion of the electron-magnon-photon coupling» (transport électronique dans la jonction de tunnels magnétiques: étude du couplage électrons-magnons-photons, **Yang Xiao** (Univ. d'aéronautique et d'astronautique de Nanjing) et **Hong Guo** (Univ. McGill) décrivent une approche à la tunnellation de Green, et l'interaction électrons-magnons-photons pertinente à la compréhension des polaritons de magnon dans un régime de couplage fort. Enfin, le présent numéro se termine par une description du transfert en court-circuit contrôlé des dispositifs de mémoire vive («STT-RAM memory devices») par **Monika Arora et autres** (Université Simon Fraser), qui mettent l'accent sur un nouvel appareil magnétique fondé sur la mémoire vive à transfert de couple du spin, où l'interaction entre le courant à spin polarisé et le moment magnétique localisé d'un élément ferromagnétique peut induire l'inversion de la magnétisation.

Nous remercions Michael Steinitz, d'avoir suggéré ce numéro thématique, et les divers auteurs qui ont contribué à en faire un succès.

Martin Plumer, Université Memorial de Terre-Neuve  
Can-Ming Hu, Université du Manitoba  
Rédacteurs honoraires, *La Physique au Canada*

*Les commentaires de nos lecteurs ou lectrices au sujet de cette préface sont bienvenus.*

*NOTE: Le genre masculin n'a été utilisé que pour alléger le texte.*

# BOB THE BUILDER AND HIS ELECTRON SHOVEL: PLANNING AND CONSTRUCTING NANOMAGNETS FOR JOBS FROM DRUG DELIVERY TO ELECTRIC CAR MOTORS

BY JOHAN VAN LIEROP, PALASH K. MANNA, ELIZABETH SKOROPATA, AND MICHAEL P. ROWE



The earliest known application of any magnetic material is the navigation compass in which naturally occurring lodestone or “leading stone” was used. The applications of magnetic materials are now widespread, including transformers, electric motors, loudspeakers, sensors, tapes (audio and video), floppy disc and hard disc media, giant magnetoresistance (GMR) reading heads for magnetic media, magnetic random access memory (MRAM) devices, permanent magnets, and carriers for targeted drug delivery. The magnetism of a material needs to be tailored for the intended application. For example, for a permanent magnet, materials with a large magnetization (response to an applied magnetic field) remanance (remaining magnetization when there is no applied field) and coercivity (magnetic field necessary to rotate the material’s magnetization) are preferable. While designing a transformer core, a magnetic material with a high permeability and a low remanance (e.g. soft iron and silicon steel) is desirable.

One might be wondering: What is the primary origin of magnetism in a magnetic material? It is the motion of electrons at the atomic scale which results in magnetism. The magnetic moment of an electron has two contributions: orbital and spin. For an atom with many electrons, the electrons of partially filled shells contribute to the magnetism. In a material, the mixing of electronic orbitals occurs due to the formation of energy bands or covalence, and sets the overall magnetic behaviour. The electrons of different atomic sites of a material interact with each other via an exchange interaction, which decides the overall nature of the magnetic configuration. Moreover, the exact form of the magnetic coupling between moments depends on the elements present and how those are arranged crystallographically. Let us consider the

examples of Fe and Fe<sub>3</sub>O<sub>4</sub>. In the case of pure Fe metal, the orbitals of its *d*-electrons are delocalized. But, the presence of O<sup>2-</sup> ions in Fe<sub>3</sub>O<sub>4</sub> [(Fe<sup>3+</sup>)tetrahedral(Fe<sup>3+</sup>,Fe<sup>2+</sup>)octahedral(O<sup>2-</sup>)<sub>4</sub>] localize the *d*-electron orbitals and alter the magnetism in comparison to the pure metal considerably. In Fe<sub>3</sub>O<sub>4</sub>, the octahedral Fe<sup>3+</sup> and Fe<sup>2+</sup> ions are coupled ferromagnetically (moments parallel to each other) via a double exchange mechanism; whereas, the Fe<sup>3+</sup> ions in the tetrahedral sites are coupled antiferromagnetically (moments antiparallel) to the octahedral sites through a superexchange interaction via the neighbouring O<sup>2-</sup> ions. Essentially, this is how one can think of a particular electronic configuration to get the desired magnetic property; somewhat similar to the usage of an “electron shovel” by “Bob the Builder”.

In this article, we shall concentrate particularly on magnetic nanoparticles and how they can be used individually at the nanoscale or cooperatively to make new bulk (macroscopic) magnets. Over the past hundred years, nanoparticle research has driven a more complete understanding of physics at the nanoscale, inspired new viewpoints on materials production and engineering, and enabled the realization of applications previously only imagined. Due to the extremely small size of nanoparticles (typically ~3–50 nm), a substantial fraction of the atoms that compose the particle reside at the surface (~60% for a 5 nm diameter iron-oxide nanoparticle). Surface atoms have broken coordination; their “frustrated” character is a product of an incomplete number of neighbouring atoms. The associated electronic surroundings, and the reduced symmetry, results in properties (magnetic and electronic) that differ substantially from the interior, well-coordinated “bulk-like” population. These nanoparticle surface atoms therefore behave in different and sometimes unexpected ways, leading to many compelling questions regarding the physics of nanoscale-material properties. Many interesting opportunities arise for making use of these nanoparticle surfaces that are irrelevant in a non-nanostructured systems due to the sparsity of surface atoms compared to those in the bulk. For example, meaningful surface functionalization can be conducted on nanoparticles to attach organic and

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## SUMMARY

**We discuss how understanding the physics of magnetism is used to direct the “pushing” of atoms and their electrons to make and enable novel applications.**

biological molecules for biomedical applications. In addition, the specialized reactivity of nanoparticles can be capitalized on to engineer new and fascinating materials.

The evolution of nanoparticle-based magnetism has been driven substantially by materials physics and chemistry in two ways: 1) Exploration of fundamental qualities of materials by the emergence of new, previously unattainable structures, compositions, and morphologies; and 2) The methodology of using nanoparticles as “building blocks” that offers reactivities substantially different from their bulk-form doppelgangers. It is important to note that this has led not only to new nanostructured macro-scale materials, but also much more effective means to synthesize bulk materials that are unfavourable or problematic to produce through traditional top-down approaches. Both 1) and 2) lay out novel bottom-up pathways to new physics by constructing electron configurations that enable novel and useful magnetic properties. We discuss briefly two areas of nanomagnets: First, using the archetypal iron-oxides for biomedical application, and second, a promising candidate for a rare-earth-free permanent magnetic material - manganese bismuth.

## NANOMAGNETS MADE FOR TARGETED DRUG DELIVERY: FROM NANOPARTICLE, TO COATING, TO DELIVERY AND DRUG RELEASE

### A Brief History

The work on targeted drug delivery was started by the founder of chemotherapy, Paul Ehrlich, who approximately 100 years ago postulated the concept of a “magic bullet” that would carry treatment to a target in the body<sup>[1–3]</sup>. Ehrlich’s goal was to find chemical substances that would have specific affinities for pathogenic organisms, and like a “magic bullet” would go directly to targeted cells<sup>[4]</sup>. In 1910, Ehrlich and his colleague Sahachiro Hata discovered that drug trial 606 (a synthetic organic compound containing arsenic) could treat syphilis infected laboratory rabbits<sup>[5,6]</sup>. This first magic bullet was later marketed as Salvarsan<sup>[5,6]</sup> and the research Ehrlich and his colleagues pioneered became a new area of science now known as “targeted drug delivery” - an interdisciplinary research area now comprising physics, chemistry, engineering, biology, and medicine.

### Advantages and Goals of Targeted Drug Delivery

The main advantage of a targeted approach is being able to minimize the exposure of healthy cells to any adverse side effects, permitting a more effective and efficient treatment. The success of a targeted delivery system is based on its capability to manipulate a drug molecule by the following criteria: 1) retain, 2) evade, 3) target, and 4) release<sup>[7,8]</sup>. Thus, the efficacy of the drug should be retained during the delivery system’s synthesis, processing and application. Once administered, the delivery system should be able to evade the body’s immunological defences and reach the targeted cells without

affecting healthy cells. Finally, the delivery system must have the capability to release the drug in a controlled manner<sup>[7]</sup>.

### Planning and Construction

#### *Part 1) Deciding on the drug carrier*

Of primary importance is to find a biocompatible carrier for the drug(s). Of the possible magnetic carriers that fit this requirement, the innate biocompatibility of iron-oxide nanoparticles make them the best candidate, currently. This biocompatibility arises from ferritin<sup>[9]</sup>, an iron-oxide nanoparticle that enables blood to be oxygenated by binding oxygen molecules to ionic iron stored by the nanoparticle. The United States Food and Drug Administration (FDA) and the European Commission (EC) have already approved iron oxide nanoparticles for use in clinical trials<sup>[10,11]</sup>. Examples are the recently introduced Fe-oxide nanoparticle-based magnetic resonance imaging (MRI) contrast agents Combidex, Feridex and Lumirem that are being used in clinical practice<sup>[11]</sup>.

#### *Part 2) Does the particle size and shape matter?*

Particle size and shape are very important considerations, especially with regards to nanoparticle functionality. Firstly, nanoscale sizes are necessary to pass inside a living animal without adverse effects, and then to safely penetrate membranes, such as cell walls and the blood brain barrier. It has also been observed that depending upon their size, nanoparticles can accumulate preferentially in different parts of the body. For example, larger particles (>1  $\mu\text{m}$ , including coating) accumulate in the liver and lungs, while medium-sized nanoparticles (10–300 nm) populate the bone marrow, spleen, liver and lymph nodes. Smaller nanoparticles (<10 nm) go preferentially to the kidney directly<sup>[11,12]</sup>.

The shape of the nanoparticles also plays an important role<sup>[13–16]</sup>. For example, non-spherical nanoparticles (rods, discs, etc.) are known to be more effective when targeting damaged cells compared to spherical nanoparticles<sup>[13–16]</sup>. A possible explanation for this is the difference in electric (zeta-potential) and magnetic field-gradients from different shapes, shown schematically in Fig. 1.

Comparing a spherical nanoparticle with a nanorod, the field gradient is uniform for a spherical shape, while a rod exhibits a strong axial field gradient at the ends of its long axis. Consequently, it is easier to affect nanorods with an external magnetic field<sup>[11]</sup>. Both the size and shape of the nanoparticle drug carrier need to be tailored to the intended target location.

#### *Part 3) Nanoparticle synthesis and surface functionalization*

The general design of a drug carrier is shown schematically in Fig. 2. Synthesis of the magnetic core, e.g.  $\text{Fe}_3\text{O}_4$  nanoparticles, can be done using a number of methods (co-precipitation, hydrothermal, sol-gel, microemulsion, and sonochemical synthesis<sup>[17]</sup>). The typical method for  $\text{Fe}_3\text{O}_4$  nanoparticles

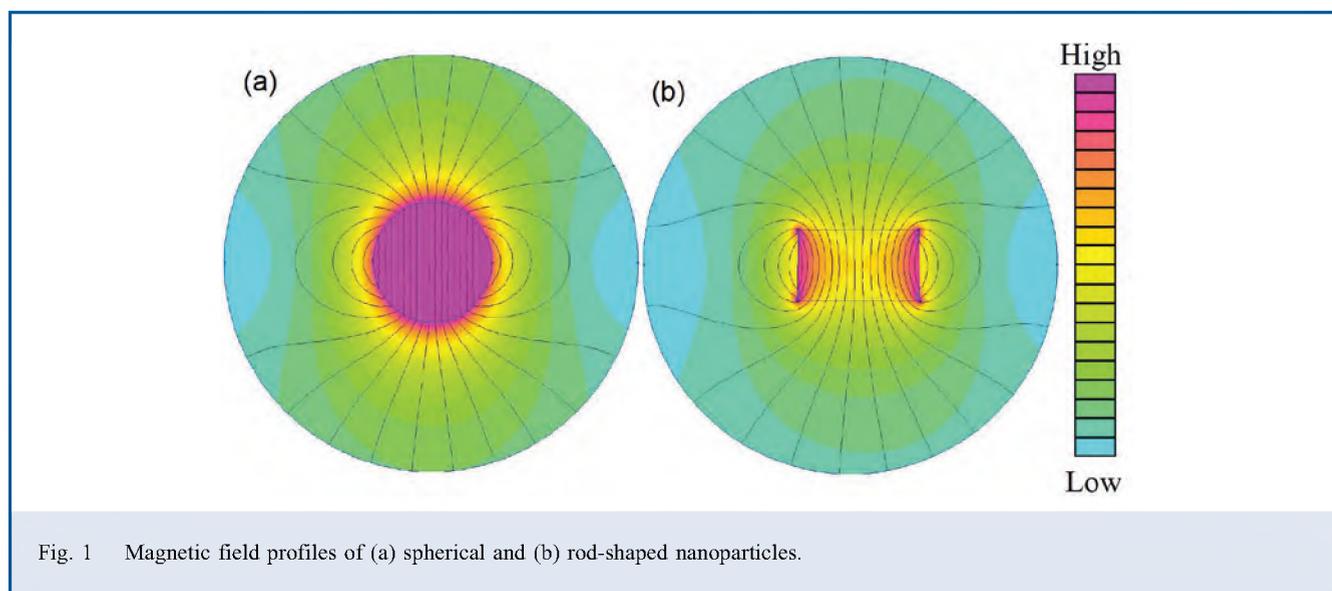


Fig. 1 Magnetic field profiles of (a) spherical and (b) rod-shaped nanoparticles.

synthesis is co-precipitation, pioneered by Massart<sup>[18]</sup> which is one of the best ways to prepare nanoparticles for drug delivery in gram-scale quantities.

A schematic of the co-precipitation synthesis procedure is shown in Fig. 3. In brief, in this method,  $\text{Fe}_3\text{O}_4$  nanoparticles are synthesized by mixing an alkaline solution (NaOH,  $\text{NH}_4\text{OH}$ , etc.) with a solution of  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  salts (1:2 molar ratio) in the pH range of 8–14. A number of factors determine the final nanoparticle size, such as reaction temperature, mixing rates of the base and salt solutions, the pH of the mixed base-salt solution, and the ratio of  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  salts<sup>[17,19]</sup>.

The co-precipitation reaction of  $\text{Fe}_3\text{O}_4$  proceeds via two stages: 1) nucleation, and 2) growth. The nucleation process is short-lived ( $\sim 2$  minutes)<sup>[19]</sup>. A recent report<sup>[19]</sup> shows that an unstable gel-like network structure is formed at this stage along with aggregates of  $\sim 2$  nm primary particles. These primary particles mostly consist of iron (hydr)oxide with a  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  ratio of  $\sim 0.55$ <sup>[19]</sup>. After a few more minutes, these aggregates start growing bigger to form spherical  $\text{Fe}_3\text{O}_4$  nanoparticles.

Nonspherical nanoparticles (rods, cubes, plates, rings, etc.) can be synthesized using methods like hydrothermal/solvothermal, vapor-phase, thermal decomposition, and polyol<sup>[16,17,20]</sup>. While the typical synthesis of non-spherical nanoparticles use template-based methods, a non-template based method such as hydrothermal is quite useful for a precise control over the shape of nanoparticles<sup>[16,17,20]</sup>. This method uses solutions of metal salts subjected to high vapour pressure and temperature (100–250 °C, typically)<sup>[17]</sup>.

Once synthesized, the nanoparticles are coated to prevent agglomeration and allow later attachment of drug molecules

via covalent and hydrogen bonds<sup>[10,11]</sup>. Some commonly used coating materials are carbohydrates (dextran), polymers (polyvinyl alcohol), proteins (albumin), gold and silica<sup>[10]</sup>.

The next step in the formation of a drug carrier system is the bonding of a multifunctional linker molecule to the coated nanoparticle surface (typically a bidentate organic molecule). This linker molecule is then used to attach drugs or active biomolecules to the surface of a nanoparticle structure via strong bonding interactions, like dative or hydrogen bonding. The linker molecules chemical functionalities are used to couple the iron-oxide nanoparticle (drug carrier) to the biologically active molecule, and include amines ( $-\text{NH}_2$ ,  $-\text{NHR}$ ,  $-\text{NR}_2$ ) to form amides with carboxylic acids ( $-\text{COOH}$ ), and aldehydes ( $-\text{CHO}$ ) forming imide with amines ( $-\text{NH}_2$ )<sup>[9]</sup>. The linker functionality is decided based on the corresponding chemical functionality of the binding site on the drug to be delivered. For example, folic acid is used to target folate receptors, and chlorotoxin when gliomas and neuroectodermal tumors need to be targeted<sup>[21]</sup>.

### Evading, Targeting and Releasing

The body's immune system presents the first impediment to the nanoparticle-based drug delivery system. In order to physically reach the target site, these nanoparticles are directed using physical (heat, light, magnetic field), chemical (site specific prodrugs) and biological (antibodies, peptides, proteins) means<sup>[7]</sup>. The final task is to release the drug at a prescribed rate<sup>[22]</sup>. It is often preferred to have a release mechanism governed by an external stimulus (i.e. heat or an alternating magnetic field). Poly (N-isopropylacrylamide) [p-NIPAAm] is one of the preferred polymers for controlled drug delivery because it exhibits a very sharp phase transition, known as lower solution critical temperature (LSCT), between 298–310 K. Below the LSCT, the polymeric chains are hydrophilic, and remain

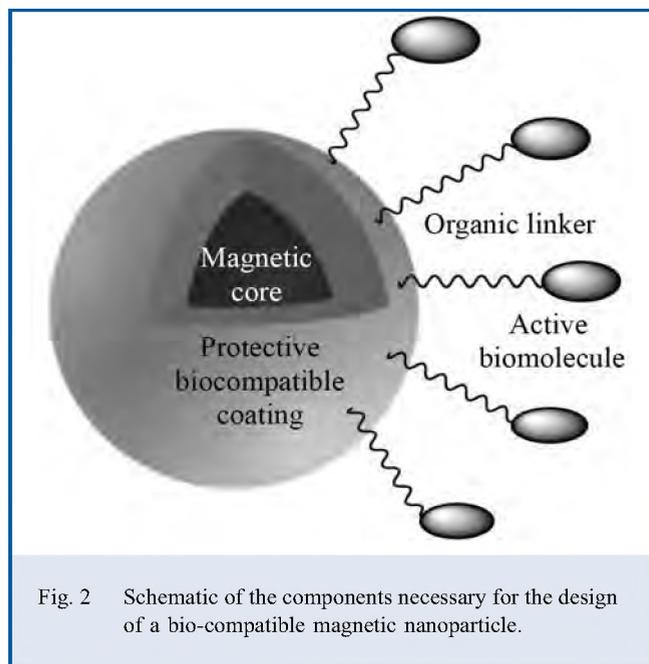


Fig. 2 Schematic of the components necessary for the design of a bio-compatible magnetic nanoparticle.

hydrated and swollen [21]. However, above the LSCT, the chains become hydrophobic and dehydrated. Therefore, if the final coating of the drug delivery nanoparticle is p-NIPAAm, a small amount of heat or an AC magnetic field (providing inductive heating in a manner similar to hyperthermia) [23], would trigger the release of the drug in the coating.

### NANOSTRUCTURED PERMANENT MAGNETS: MANUFACTURE AND DESIGN FROM THE BOTTOM-UP

The essential purpose of a permanent magnet is to produce a strong magnetic field without an additional expenditure of energy. The classic ‘refrigerator magnet’ is such a permanent magnet, as opposed to a solenoid which requires an electric current. To be a permanent magnet, a material must have 1) a large and stable magnetization, preferably large atomic moments, combined with 2) a single spatial alignment of their spin orientations (e.g., a uniaxial anisotropy). Shown in Fig. 4 is a typical response of the magnetic induction ( $B$ ) of a permanent magnet to an applied field ( $H$ ). The standard figure of merit for a permanent magnet is the energy product (abbreviated  $(BH)_{\max}$ ), which describes the maximum (magnetostatic) energy that the magnet can store.

To achieve the largest possible overall magnetization one needs the largest possible atomic moments. This calls for a metallic system to be used. Metal ions surrounded by non-metallic neighbours (such as oxygen-ions in the transition metal oxides) suffer quenched orbital moments as the 3d electrons are quite localized about the nucleus, and the associated “circulating currents” from the moving electrons are fragile and easily affected by the associated crystal field effects (due to Coulombic interactions between neighbouring atoms). Moving away from this super-exchange based magnetism, to exchange based magnetism,

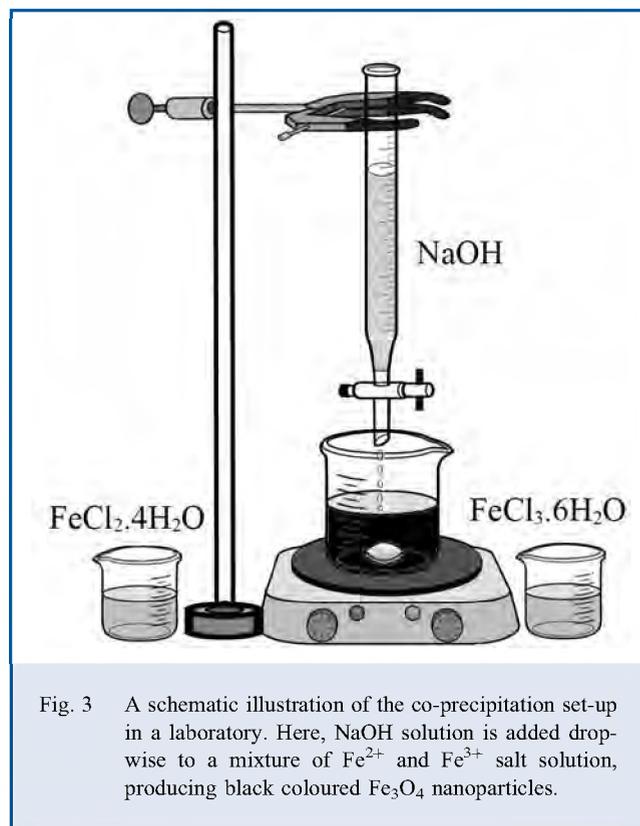


Fig. 3 A schematic illustration of the co-precipitation set-up in a laboratory. Here, NaOH solution is added dropwise to a mixture of  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  salt solution, producing black coloured  $\text{Fe}_3\text{O}_4$  nanoparticles.

with transition metal ions, in bands (metallic magnetism, like that of Fe metal discussed above) permits one to take advantage of the resulting delocalized electronic configuration about the atoms. Previously localized 3d electrons are pushed into a band that is superposed onto the 4s band, while crystal fields (charge distributions creating electric fields) enable this intermixing, and larger spin and orbital moments are accessible.

The directional dependence of the magnetic response (magnetic anisotropy) is essentially the reaction of the atomic moments in different crystallographic positions in a material when exposed to an external magnetic field. The spin part of the moments are coupled to the electronic orbital shapes and orientations (spin-orbit coupling) and the chemical bonding (facilitated by the bonding and antibonding of states near the bands) of the orbitals with the crystal field. Thus, to achieve an optimal magnetic anisotropy necessitates positioning the atoms and their electrons so as to generate the best possible anisotropy.

### A Brief History

The 20th century was a period of substantial advancement in the design and production of permanent magnets, which helped to drive numerous technological developments. Permanent magnets usefulness ranges from the trivial refrigerator magnet to the ubiquitous computer, to wind powered turbines, to electric motors [24,25]. Improvements hinged on the development of new and better materials (by exploring a variety of

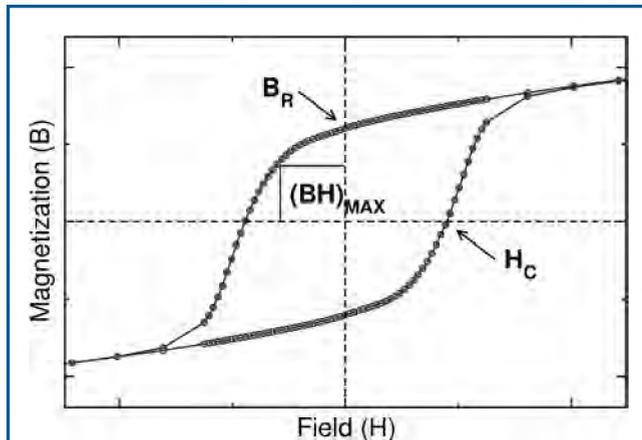


Fig. 4 Hysteresis loop describing the magnetic response of a typical permanent magnet to an applied field.

composition and structures) and by achieving control of the microstructure (e.g., grain size and morphology).

Fe-based steel alloys were the majority of permanent magnets in the first half of the 20th century. The tuning of the electrons' behaviour and resulting magnetism for these materials was limited by the understanding of quantum mechanics and magnetism at that time. Despite Fe atoms having what we now know to be a reasonably large moment, such magnets suffered low  $(BH)_{\max}$  values as the crystal field effects in these alloys are weak, resulting in low anisotropies. The first notable improvement in permanent magnet  $(BH)_{\max}$  was in 1931, with the discovery of Alnico. This family of metal alloys (based on aluminum, nickel, cobalt and iron) is an excellent example for the importance of both composition and microstructure in permanent magnets<sup>[26,27]</sup>. The transition metal ions are in special configurations that permit quite large spin moments, and their spin-orbit interactions with local neighbours permit

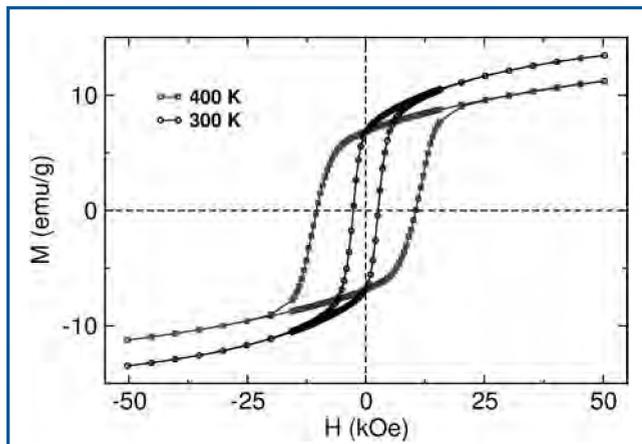


Fig. 5 Hysteresis loop of MnBi made from nanoparticles.

larger anisotropies. In addition, Alnico made as a mixture of nanometer-sized grains of Fe (or Fe/Co) surrounded by a weakly magnetic NiAl matrix (formed by a spinoidal phase separation during processing) permitted much larger  $(BH)_{\max}$  values. The early Alnicos ( $\sim 1$  MGOe) were improved to  $\sim 5.5$  MGOe in the 1930s<sup>[26,27]</sup>.

The 1960s ushered in the era of the strong permanent magnet.  $\text{SmCo}_5$  was the first compound discovered. Based on metallic Co, these magnets have an intrinsically large magnetization, where exchange coupling with the rare earth element Sm, which has a large unquenched orbital angular momentum, results in a huge intrinsic magnetic anisotropy. Refinements to these magnets resulted in  $(BH)_{\max}$  values up to 20 MGOe<sup>[28]</sup>. The high cost and the unpredictable supply of Co during the 1970s, due to geopolitics, re-energized the development of Fe-based magnets.

In 1982,  $\text{Nd}_2\text{Fe}_{14}\text{B}$  was discovered<sup>[29,30]</sup>. Fe, whose 3d electrons ferromagnetically coupled to the 4f electrons of Nd, results in both a large magnetization and a large anisotropy. A small amount of B provides a crystallographic stability, and additional Dy increases high temperature performance by increasing the magnetic ordering temperature. From the 1980s to 90s,  $\text{Nd}_2\text{Fe}_{14}\text{B}$  was studied extensively, and microstructure refinement (e.g. grain growth and orientation) led to the current optimal  $(BH)_{\max}$  of  $\sim 60$  MGOe<sup>[31]</sup>. The discovery of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  impacted many industries, and the excellent magnetic properties have led to  $\text{Nd}_2\text{Fe}_{14}\text{B}$  being the most widely used permanent magnet material to date.

Currently, history is repeating itself as the geopolitical climate causes concern over many rare-earth elements supply chains. Since 2009 with the arrival of the “rare-earth crisis”<sup>[32]</sup>, increasing research focus has been placed on finding new “rare-earth free” permanent magnets.

### Planning and Constructing Hard Magnets

The “top-down” approach used for magnet research and development of lodestones up through modern rare-earth permanent magnets has limitations with regards to materials combinations and microstructure control, and therefore what can be realized in overall magnetic properties. Researchers are turning to nanoparticles to address these technological boundaries. Inherent to their size, nanoparticles offer the direct control of composition and microstructure from the “bottom-up” in magnet constructions<sup>[25,33]</sup>. In particular, the coercivity will increase as the particle size is decreased, with an optimal size depending on the material (e.g.,  $\sim 10$  nm for Fe,  $\sim 20$  nm for cobalt-rich grains in Alnico). However, when the grains become too small, the energy required to reverse the magnetization may be overcome merely by the thermal energy. When this occurs, the nanoparticle becomes “superparamagnetic” (“super” since the entire magnetization of the particle acts together by comparison with the single atomic moments in a typical paramagnet, yet presents similar magnetization vs field behaviour) and the coercivity becomes zero. Achieving a

delicate balance of grain structure is necessary both in traditional “top-down” approaches, where particle size is controlled indirectly (e.g., by the nature of the alloying mechanisms, or post-synthesis processing like mechanical grinding), and in the “bottom-up” approach using nanoparticles. A considerable advantage of the “bottom-up” approach is the direct control of the grain size necessary for good performance.

#### **Making rare-earth-free permanent magnets using nanoparticles of MnBi**

The intermetallic alloy MnBi has been a highly sought “rare-earth free” permanent magnet for over 60 years<sup>[34]</sup>. When formed in the “low-temperature-phase” (LTP), MnBi has a very large magnetic anisotropy at room temperature that uniquely increases with increasing temperature due to the nature of subtle temperature-dependent changes in the atomic (crystalline) configuration that alter the crystal fields about the atoms. Because many commercially important applications of strong permanent magnets are above room temperatures, LTP-MnBi promises excellent performance at elevated temperatures for uses such as electric motors in cars, generators in turbines, and solenoids in aircraft (potentially replacing the heavy pneumatic control systems used currently). Because of this, substantial efforts by researchers around the world have been directed toward the formation, purification, and large-scale production of LTP-MnBi. However, producing the LTP form of MnBi has proven to be extremely difficult. This is due to two primary aspects of the constituent metals: 1) The peritectic interaction of molten Mn and Bi, and 2) The slow interdiffusion of Mn and Bi. Historically, these impediments to the successful synthesis of LTP-MnBi have retarded the subsequent understanding of the physics behind the magnetism in this compound. Approaches from mechanical grinding and ball milling, to arc melting and rapid solidification, have seen limited success. This necessitates novel approaches to overcome the materials challenges associated with LTP-MnBi.

We have turned to a “bottom-up” approach using a new wet chemical synthesis method because of these challenges. Fundamentally, nanoparticles are synthesized by the reduction of metal ions in the presence of a surfactant. However, the reduction potential of Mn is too high for such an approach to be practical, so an alternative method is needed. Using a manganese “ligated anionic element reagent complex” (Mn-LAERC)<sup>[35,36]</sup> to reduce bismuth ions, while simultaneously depositing Mn atoms at room temperature, produces nanoparticles of Mn, Bi and a ferromagnetic MnBi phase, which can then be conveniently annealed to form the desired LTP-MnBi. The hysteresis loops measured at 300 and 400 K show [Fig. 5] the suitability of MnBi nanoparticles for applications as hard magnets.

Importantly, new chemistries have been developed to access challenging metal alloys, in nanoparticle-sizes. Such advancements allow the physics of the nanoparticle magnetism to be investigated and understood, improving the state of the art for a critical magnetic material.

#### **CONCLUSIONS**

The present article provides an overview of the strategies involved in designing nanoparticle systems for targeted drug delivery and hard magnets. We have discussed how understanding and tuning the behaviour of atom’s electrons, the primary source of magnetism, are the tools necessary for creating materials suitable for an application. The study of nanomaterials has flourished because properties at the nanoscale can produce phenomena that are not otherwise accessible at bulk macroscopic dimensions. But, nanoscale-based magnets require a detailed understanding of the physics to enable the requisite control over atomic electron configurations to achieve the desired magnetism. Such mastery manifests in the laboratory as pushing electrons and atoms around, finally assembling them into nanoparticles, and beyond. From the applications view-point, for nanoparticle-based drug delivery, the amount of drug delivered to targeted cells is typically around 5%<sup>[8]</sup>, which points to the lack of understanding of all the actual mechanisms by which drug carriers interact with a body’s cells and organs. Moreover, all the steps involved in the delivery of any drug to the targeted cells are not well characterized for any particular nanocarrier and drug, currently. A plethora of reports are available, but a systematic approach to this challenge has yet to be developed. For permanent magnets, the use of nanoparticles has resulted in novel avenues towards material synthesis (such as with MnBi), the realization of hard/soft material combinations (to take advantage simultaneously of magnetization of one material and the anisotropy of another in one nanostructured magnet), and as a means to control directly the grain structure in traditional materials. Currently, the development of permanent magnets using a nanoparticle-based approach is the focus of substantial ongoing research, and is considered a promising route towards the next generation of permanent magnets.

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# THE “HOLY GRAIL” OF MULTIFERROIC PHYSICS

BY ROGÉRIO DE SOUSA

## THE CROSS-CORRELATION PROBLEM: IS MAGNETISM CONTROLLABLE BY ELECTRIC FIELDS?

What happens if a compass’ needle is held fixed in the presence of an external  $\mathbf{B}$  field? If the  $\mathbf{B}$  field is strong enough, the microscopic magnetic dipoles forming the magnet (Fig. 1) will reorient themselves within the material so that they get aligned parallel to  $\mathbf{B}$  (with the needle’s orientation remaining the same). It is this functionality that allows ferromagnetic materials to work as memory bits in a computer hard drive. A ferromagnet with  $\mathbf{M}$  pointing up can represent bit “1”, while  $\mathbf{M}$  pointing down can represent bit “0”. Writing “0” or “1” to a magnetic memory requires the application of a  $\mathbf{B}$  field that is stronger than the magnetic anisotropy of the material. In today’s computers this is achieved by running a large electric current to the hard drive write head <sup>[1]</sup> [See “Spin-based memory devices”, by Arora *et al.* in this issue].

We can also build an “electric compass” that responds to an external electric field  $\mathbf{E}$  in a similar way that the magnetic compass responds to  $\mathbf{B}$ . In this case we need to build the compass’ needle out of a ferroelectric material, the electric analog of a ferromagnet. Such a material consists of a collection of microscopic electric dipoles (formed by equal numbers of positively and negatively charged atoms), all aligned with each other, giving rise to non-zero electric polarization density  $\mathbf{P}$ . Similarly to the magnetic case, if the material is held fixed, a strong  $\mathbf{E}$  larger than the material’s electric anisotropy would be able to force a reorientation of  $\mathbf{P}$  inside the material. Ferroelectrics can also function as memories; in contrast to magnetic memories, the write operation can be achieved with an  $\mathbf{E}$  field as opposed to a  $\mathbf{B}$  field. This difference makes ferroelectric memories potentially faster, perhaps as fast as our current RAM, which use charged and discharged capacitors to represent each bit <sup>[2,3]</sup>.

### SUMMARY

Electric-field control of magnetism may bring bismuth ferrite ( $\text{BiFeO}_3$ ) closer to the “holy grail” ferromagnet-ferroelectric at room temperature.

If we make a *composite* compass needle with ferromagnetic and ferroelectric materials attached to each other, the compass would certainly respond to both  $\mathbf{E}$  and  $\mathbf{B}$  simultaneously. But what would happen if the needle is held fixed in the presence of a strong  $\mathbf{B}$  field? The answer is that for the overall majority of composite materials, the ferromagnet would reorient its  $\mathbf{M}$  to point along  $\mathbf{B}$ , but the ferroelectric wouldn’t care; its  $\mathbf{P}$  would remain along the original direction. Similarly, if we were to apply a strong  $\mathbf{E}$  instead of  $\mathbf{B}$ , the  $\mathbf{P}$  would reorient, but the  $\mathbf{M}$  wouldn’t change. The reason for the absence of cross-correlation between electric and magnetic states is because the interactions coupling them are very small; they arise either from relativistic effects (such as spin-orbit coupling) or from the dependence of magnetic interactions on the distance between magnetic ions (the exchange striction effect [“Spin mechanics” by Losby and Freeman in this issue]).



## MULTIFERROIC MATERIALS

One way around this problem is to obtain a material that displays both ferromagnetic and ferroelectric order within the same crystal structure and at the same temperature. In this case, a reorientation of one of the order parameters (either  $\mathbf{M}$  or  $\mathbf{P}$ ) would affect the material internally, perhaps forcing the other order parameter to change along. Then magnetism would be coupled to electricity, enabling a variety of applications. For example, we can imagine an ideal magnetic memory whose state could be written electrically (without the need for generating a  $\mathbf{B}$  field from a current pulse) and read magnetically. Such a memory would minimize Joule heating allowing the integration of the hard drive with the processor in personal computers <sup>[4]</sup>.

It turns out that a single crystal material with coexisting ferromagnetic and ferroelectric orders at room temperature has never been found and was never synthesized artificially in the laboratory. Its search is the subject of prolific research in the field of multiferroic materials – where the ferromagnet-ferroelectric at room temperature is often denoted the “holy grail” or “dream” material.

Multiferroic materials are defined as materials that possess at least two of the three ferroic or antiferroic orders at the same temperature: (Anti)ferromagnetism, (anti)ferroelectricity, and (anti)ferroelasticity <sup>[5]</sup> (See Fig. 1).

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Most multiferroic materials available to date combine antiferroic orders with ferroic ones. This includes one of the few materials who shows multiferroicity at room temperature, bismuth ferrite ( $\text{BiFeO}_3$  or BFO for short), a strong antiferromagnet-ferroelectric in bulk and thin-film forms. The overall majority of multiferroics are low temperature. For example, strained films of  $\text{EuTiO}_3$  become a strong ferromagnet-ferroelectric at  $T < 4$  K [6], and the family of rare earth manganites  $\text{RMnO}_3$  ( $R$  a rare earth atom such as Gd, Tb, Dy, . . .) display coexisting antiferromagnetism with ferroelectricity at  $T < 30$  K. The reason why multiferroicity is such a rare property is because magnetism and ferroelectricity tend to be mutually exclusive [7]. The usual mechanism for ferroelectricity is a Jahn-Teller crystal distortion associated with *empty* d orbitals (consider, e.g., the textbook ferroelectric  $\text{BaTiO}_3$  in which  $\text{Ti}^{4+}$  has no electrons in its d shell). In contrast, magnetism usually occurs in materials with *filled* d orbitals, such as in the transition metals Cr, Mn, Fe, Co, etc. For this reason, magnetoelectric multiferroics are rare.

Multiferroic materials can be classified in two types [8]. Type I multiferroics are the ones whose coexisting orders originate from independent mechanisms. For example, BFO becomes ferroelectric at  $T < 1093$  K, where it is well into the para-

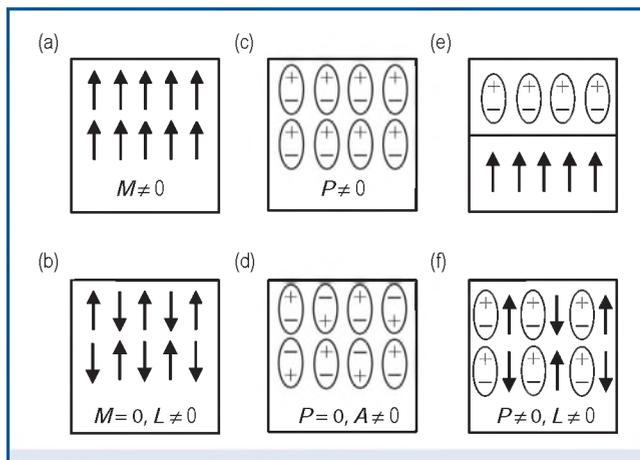


Fig. 1 (a) A ferromagnet described by order parameter  $\mathbf{M}$ , the magnetization. At  $T < T_c$   $\mathbf{M}$  becomes non-zero spontaneously (with external  $B = 0$ ). (b) An antiferromagnet with  $\mathbf{M} = 0$  and staggered order parameter  $\mathbf{L} = \mathbf{M}_1 - \mathbf{M}_2$  non-zero (here 1 and 2 refer to nearest-neighbor sublattices). (c) A ferroelectric described by order parameter  $\mathbf{P}$ , the electric polarization. At  $T < T_c$ ,  $\mathbf{P}$  becomes non-zero spontaneously (with external  $E = 0$ ). (d) An antiferroelectric with  $\mathbf{P} = 0$  and staggered polarization  $\mathbf{A}$  non-zero. (e) A compound material made of a ferroelectric attached to a ferromagnet. (f) A multiferroic material showing coexistence of ferroelectricity and antiferromagnetism in the same crystal phase.

magnetic phase; it becomes antiferromagnetic only at much lower temperatures (below 643 K). This indicates that the mechanism driving ferroelectricity is completely independent of the mechanism driving magnetism.

In contrast, type II multiferroics have one of its orders induced by the other one. For example, terbium manganite ( $\text{TbMnO}_3$ ) is a frustrated magnet that becomes a collinear-sinusoidal antiferromagnet at temperatures  $T < 41$  K; at  $T < T_{\text{lock}} = 28$  K its magnetic phase changes to a non-collinear spiral (a cycloid, see below). As it turns out, at exactly at  $T < T_{\text{lock}}$  the material also becomes ferroelectric [9]. This is not a coincidence;  $\text{TbMnO}_3$  is an example of a material with magnetically induced ferroelectricity. The origin of its ferroelectricity is a special kind of magnetic interaction called spin-current interaction [10]:

$$\mathcal{H}_{\text{SC}} = \sum_{\langle i,j \rangle} J_{\text{SC}} \mathbf{P} \cdot [\mathbf{R}_{ij} \times (\mathbf{S}_i \times \mathbf{S}_j)], \quad (1)$$

where the sum runs over all nearest neighbors  $\langle i,j \rangle$ , with  $\mathbf{S}_i$  and  $\mathbf{S}_j$  representing the spins of ions located at  $\mathbf{R}_i$  and  $\mathbf{R}_j$ , respectively, with  $\mathbf{R}_{ij} = \mathbf{R}_i - \mathbf{R}_j$  denoting their separation vector. When the spins are aligned parallel or antiparallel to each other (collinear phase) the vector product in Eq. (1) is always zero, and the spin-current interaction has no effect. However, in a non-collinear spiral phase each non-zero  $\mathbf{E}_{\langle i,j \rangle} = -J_{\text{SC}} \mathbf{R}_{ij} \times (\mathbf{S}_i \times \mathbf{S}_j)$  acts as an internal electric field that transforms the originally paraelectric material into a ferroelectric (Note how Eq. (1) can be written as  $\mathcal{H}_{\text{SC}} = -\mathbf{P} \cdot \sum_{\langle i,j \rangle} \mathbf{E}_{\langle i,j \rangle}$ , with  $\mathbf{E}_{\langle i,j \rangle}$  of magnetic origin). This generates a spontaneous  $\mathbf{P}$  that is controllable by an external magnetic field: applying a  $B$  field perpendicular to the spin spiral plane forces the spins to form a spiral in a different plane, rotating  $\mathbf{P}$  by  $90^\circ$  [9].

While type II multiferroics can be viewed as the ideal material to search for strong coupling between magnetism and ferroelectricity, their multiferroicity usually occurs at low temperatures, and their secondary order parameter ( $\mathbf{P}$  for magnetically induced ferroelectricity) is quite weak. This does not make type II multiferroics attractive for applications. For example, in  $\text{TbMnO}_3$  the largest  $P$  is less than  $0.1 \mu\text{C}/\text{cm}^2$ . In contrast, the type I multiferroic BFO has room temperature multiferroicity with  $P = 100 \mu\text{C}/\text{cm}^2$  (among the largest  $P$  of all ferroelectrics).

## ELECTRIC-FIELD CONTROL OF MAGNETISM IN BFO

Can we control magnetism with an external  $E$  field in type I multiferroics? The answer is a definite yes as shown by many experiments in bulk and thin-film BFO. The key mechanism is once again the spin-current interaction Eq. (1). When BFO becomes antiferromagnetic at  $T < 643$  K, its  $\mathbf{P}$  is already quite close to the maximum value of  $100 \mu\text{C}/\text{cm}^2$ , pointing along one of the eight cube diagonals of the perovskite unit cell (Fig. 2a). Antiferromagnetism sets in in the presence of a very strong  $\mathbf{P}$ ,

and the spin-current interaction drives an instability towards a spiral magnetic state. In other words, in BFO the spin-current interaction has the inverse effect that it has in  $\text{TbMnO}_3$ : Here it causes spin frustration instead of ferroelectricity. This leads to an inhomogeneous magnetic state, with order parameters depending on position <sup>[11–13]</sup>:

$$\mathbf{L}(\mathbf{r}) = L_0 \left[ \sin(\mathbf{q} \cdot \mathbf{r} + \phi_0) \hat{\mathbf{q}} + \cos(\mathbf{q} \cdot \mathbf{r} + \phi_0) \hat{\mathbf{P}} \right], \quad (2a)$$

$$\mathbf{M}(\mathbf{r}) = M_0 (\hat{\omega}_{\text{AFD}} \times \mathbf{q}) \sin(\mathbf{q} \cdot \mathbf{r}), \quad (2b)$$

with amplitudes  $L_0 = 4.1 \mu_{\text{B}}/\text{Fe}$  and  $M_0 = 0.09 \mu_{\text{B}}/\text{Fe}$  <sup>[14]</sup>. Thus the antiferromagnetic order parameter  $\mathbf{L}$  forms a spiral of the cycloid type (wavevector  $\mathbf{q}$  in the same plane as the spins), with  $\mathbf{M}$  displaying sinusoidal order along a single direction perpendicular to the cycloid plane (the antiferrodistortion vector  $\hat{\omega}_{\text{AFD}}$  describes a staggered rotation of oxygen octahedra in the perovskite cells;  $\hat{\omega}_{\text{AFD}}$  can point parallel or antiparallel to  $\mathbf{P}$ ). Both order parameters average out to zero at macroscopic length scales larger than the cycloid wavelength  $2\pi/q = 620 \text{ \AA}$ .

A key feature is that the cycloid’s wavevector  $\mathbf{q}$  is “tied” to  $\mathbf{P}$  so that the spin-current energy Eq. (1) is minimized. As a result,  $\mathbf{q}$  is always perpendicular to  $\mathbf{P}$ . This dependence of  $\mathbf{q}$  on  $\mathbf{P}$  is central to all experimental demonstrations of electric control of magnetism in BFO. Applying external  $E > 3.5 \times 10^4 \text{ V/cm}$  switches  $\mathbf{P}$  from one cube diagonal to the other, forcing the cycloid plane to change accordingly (Fig. 2b). This effect was demonstrated in pure bulk BFO using neutron diffraction measurements <sup>[15]</sup>. In addition, it enabled  $E$ -field

control of ferromagnetism in a junction formed by CoFe (a room temperature ferromagnet) and BFO. Switching BFO’s  $\mathbf{P}$  domains by  $180^\circ$  was shown to switch the CoFe’s  $\mathbf{M}$  domains by  $180^\circ$ , a remarkable effect whose origin is not yet completely understood <sup>[16,17]</sup>. A similar control of exchange bias (a shift of magnetic hysteresis used in hard drive write heads) was demonstrated in junctions formed by  $\text{LaMnO}_3$  and BFO <sup>[18]</sup>. Based on these remarkable experiments, one may be inclined to believe that the only way to control magnetism in a type I multiferroic such as BFO is to switch  $\mathbf{P}$  from one equilibrium direction to the other (Fig. 2b). Actually, our research has found that this is not the whole story. A key development was our realization that BFO’s cycloid state makes it much more “visible” with optics <sup>[19]</sup>. When we shine light on BFO, the optical electric field produces vibrations of  $\mathbf{P}$ . Since the spins are confined to the plane of  $\mathbf{P}$  and  $\mathbf{q}$ , these vibrations generate magnetic excitations, the so called spin waves or magnons [See “Instability processes for manganese in ferromagnetic nanostructures” by Cottam and Haghshenasfard in this issue]. As shown in Fig. 3, there are two kinds of magnons: The ones that are within the cycloid plane (tangential to the cycloid), and the ones that are perpendicular to the cycloid plane. We call these cyclons (denoted by  $\phi$ ) and extra-cyclons ( $\psi$ ), respectively.

The cycloid breaks translation symmetry along the  $\mathbf{q}$  direction, so that the spin waves are not simple plane waves like  $e^{i\mathbf{k}\cdot\mathbf{r}}$ ; they are in fact Bloch states, i.e., linear combinations of plane waves with higher harmonics. As a result, an optical excitation with wave vector  $\mathbf{k}$  is capable of exciting cyclon and extra-cyclon modes at  $\mathbf{k} + n\mathbf{q}$  where  $n$  is an integer. In other words,

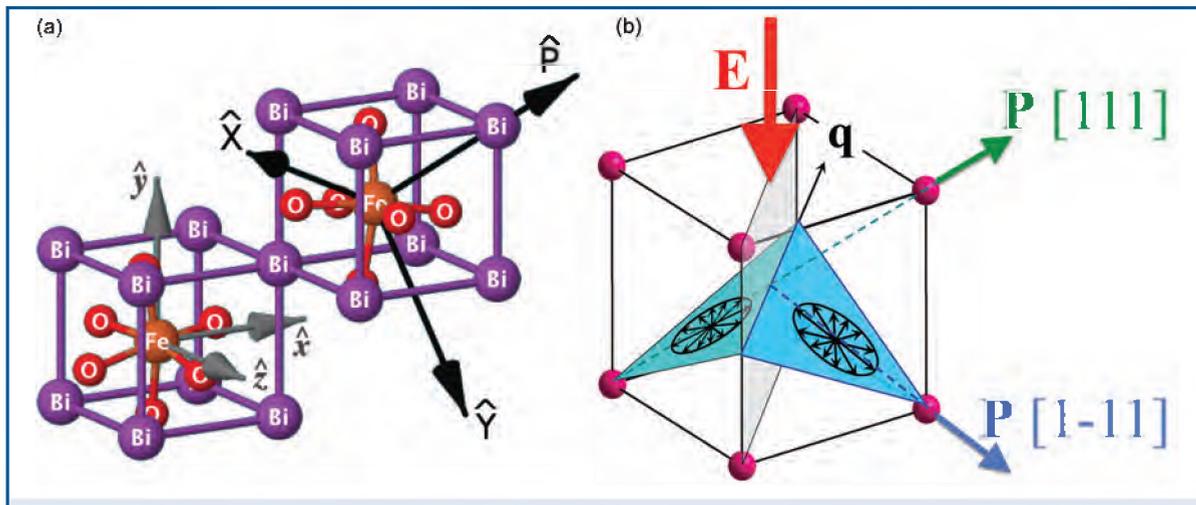


Fig. 2 (a) Crystal lattice of room temperature multiferroic  $\text{BiFeO}_3$  (BFO). The ferroelectric moment  $\mathbf{P}$  arises from the ionic displacement of cations (Fe, Bi) relative to anions (O). Due to electric anisotropy,  $\mathbf{P}$  points along one of the eight cube diagonals of the perovskite unit cell. (b)  $E$ -field control of magnetism by switching  $\mathbf{P}$ . In BFO the Fe spins are ordered antiferromagnetically with a weak ferromagnetic moment ( $L \gg M > 0$ ).  $\mathbf{L}$  forms a cycloidal spiral with wavelength  $2\pi/q = 620 \text{ \AA}$ . The plane of the cycloid is tied to  $\mathbf{P}$ . Therefore, when  $\mathbf{P}$  is switched with an external  $E$  field, the cycloid plane is forced to change.

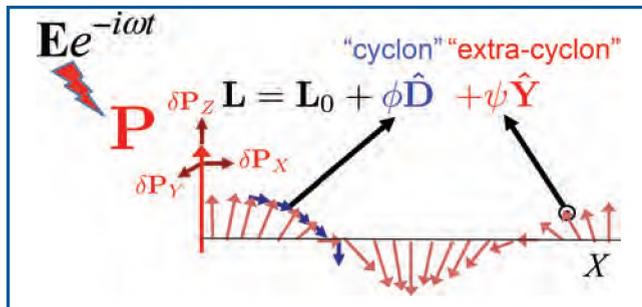


Fig. 3 Magnetic excitations of the spin cycloid. An oscillatory electric field (e.g., light) vibrates  $\mathbf{P}$ , producing in plane spin fluctuations (cyclons  $\phi$ ) and out of plane fluctuations (extra cyclons  $\psi$ ).

light scattering is able to emit and absorb magnons with wave vectors  $\mathbf{k}' = \mathbf{k} + n\mathbf{q}$ , giving rise to a series of optical resonances that “map out” the magnon dispersion relations. Indeed, Raman scattering experiments in bulk BFO reveal the presence of two distinct series of optical resonances: The cyclons at frequency  $\omega_\phi(nq) \propto |n|$  and the extra-cyclons with frequency  $\omega_\psi(nq) \propto \sqrt{1+n^2}$ , with  $n$  integer<sup>[20]</sup>. Later it was shown that the modes split in the presence of magnetic anisotropy<sup>[21]</sup> and external  $B$  field<sup>[22]</sup>. These optical experiments are much more sensitive than neutron scattering measurements; while neutron scattering requires large bulk samples, optical scattering can be done in much smaller samples, including gated devices and thin films.

### A NEW TYPE OF MAGNETIC CONTROL IN MULTIFERROICS: $E$ -FIELD CONTROL WITHOUT SWITCHING $P$

This led us to try an experiment. Using Raman scattering, we tracked the frequency of the cyclonic magnons as a function of an external  $E$  field. The result was quite surprising<sup>[23]</sup>: The magnon frequencies displayed a hysteresis loop as a function of  $E$  that was quite different from the  $P$  vs.  $E$  ferroelectric loop. Remarkably, some of the magnon frequencies shifted by as much as  $5 \text{ cm}^{-1}$  without switching  $P$ . Such a shift is considered gigantic, in view of the fact that it is  $10^5$  times larger than previous measurements of  $E$ -field magnon shifts<sup>[24]</sup>.

Our interpretation of this result was that BFO possessed an additional interaction energy coupling  $E$  fields to spins. Using microscopic theory, we were able to show<sup>[25]</sup> that BFO’s magnetic anisotropy energy is quite sensitive to an applied  $E$ -field, leading to the following energy density,

$$\mathcal{H}_E = -\frac{\xi'}{4} \mathbf{E}_\perp \cdot \left[ (L_Y^2 - L_X^2) \hat{X} + 2L_X L_Y \hat{Y} + 2\sqrt{2}L_Z \hat{L} \right], \quad (3)$$

where  $\mathbf{E}_\perp$  is the component of the  $E$  field perpendicular to  $\mathbf{P}$ , and  $\mathbf{L}$  is the antiferromagnetic order parameter in cgs units. The coupling energy  $\xi'$  was measured to be  $\xi' = 1/(2 \times 10^4 \text{ V/cm})$ , a value anomalously large for a magnetoelectric effect. In addition,  $\xi'$  was shown to scale with material properties as<sup>[25]</sup>.

$$\xi' \propto \frac{\Delta_{\text{SO}}^2 P}{\Delta_{\text{gap}}^2}, \quad (4)$$

where  $\Delta_{\text{SO}}$  is the spin orbit splitting of the 6p orbitals of bismuth, and  $\Delta_{\text{gap}}$  is BFO’s band gap energy. Hence, the large  $\xi'$  stems from the large values of  $\Delta_{\text{SO}}$  and  $P$ . Both are among the largest in nature: Bi has the largest spin-orbit splitting of all non-radioactive atoms of the periodic table; and BFO has one of the largest values of  $P$  of all ferroelectrics. Therefore, the coexistence of two phases (ferroelectricity and antiferromagnetism) acts to amplify a particular property (magnetic anisotropy as a function of  $E$  field).

Under the application of an external  $E$  field, the interaction (3) will compete against the usual ( $E = 0$ ) magnetic anisotropy energy, giving rise to the  $E$ -field phase diagram shown in Fig. 4. It leads to the prediction that an external  $E$  field along particular directions in the plane perpendicular to  $P$  can convert the cycloid into a homogeneous antiferromagnet ( $\mathbf{L}$  independent of  $\mathbf{r}$ ) with the direction of  $\mathbf{M}$  and  $\mathbf{L}$  controllable by the particular direction that  $\mathbf{E}_\perp$  is applied. We predict that a minimum  $E = 9 \times 10^4 \text{ V/cm}$  is required to unwind the cycloid<sup>1</sup>.

Our prediction of  $E$ -field control of magnetism without switching  $P$  is yet to be realized experimentally. Such a demonstration would open up a pathway for  $E$ -field control of magnetism that avoids charge displacement and energy dissipation associated to the relaxation of  $P$  into another direction (switching  $P$  dissipates  $5 \text{ J/m}^2$ )<sup>[26]</sup>. In BFO, the weak magnetization  $\mathbf{M} \propto \hat{Z} \times \mathbf{L}$  is tied to  $\mathbf{L}$ . Thus our predicted mechanism allows the electrical switching of  $\mathbf{M}$  from a sinusoidal state with zero spatial average to a homogeneous state with non-zero  $\langle \mathbf{M} \rangle$ . This effect converts an  $E$ -field pulse into a magnetic pulse. By combining BFO with another magnetic material (as done in<sup>[16,17]</sup>), we can envision the writing of data in a magnetic memory element using an  $E$ -field pulse in an insulator instead of the usual current pulse in a metal.

1. An important point is that  $P$  can be switched by the external  $E$ -field, changing the effective direction of  $\mathbf{E}_\perp$  in Fig. 4 (note that Fig. 4 assumes  $P \parallel [111]$  at all magnitudes of  $\mathbf{E}_\perp$ ). To avoid switching, one can apply the  $E$ -field with the largest component along the  $[111]$  direction. For example, using  $\mathbf{E} = E[\cos(30^\circ)\hat{Z} - \sin(30^\circ)\hat{X}]$  allows control of magnetism without changing  $P$ , at the expense of having  $\mathbf{E}_\perp = E/2$ . Using  $\xi' = 1/(2 \times 10^4 \text{ V/cm})$  we get that a minimum  $E = 0.9 \times 10^5 \text{ V/cm}$  is required to induce the homogeneous state, a value that falls in the practical range.

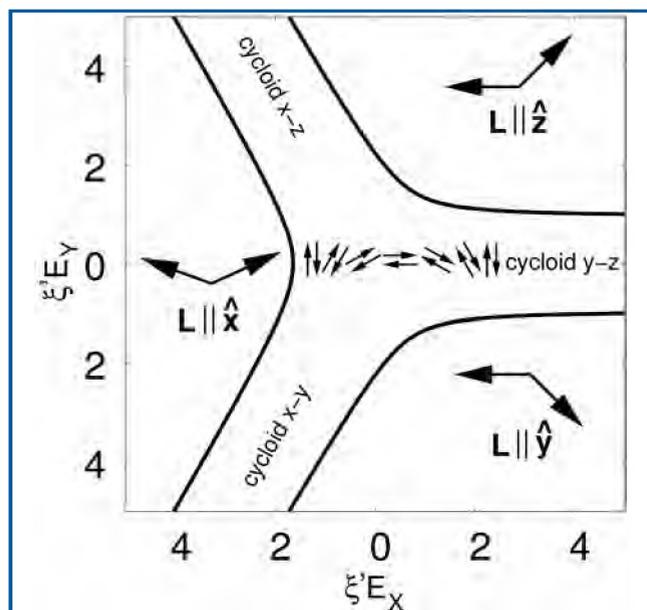


Fig. 4 Predicted phase diagram for BFO as a function of an external electric field [25].  $E$  fields of the order of  $1/\xi' = 2 \times 10^4$  V/cm applied along certain directions in the plane perpendicular to  $P(\hat{X}, \hat{Y})$  plane in Fig. 2a) are capable of unwinding the spin cycloid, converting BFO into a homogeneous antiferromagnet with canted ferromagnetic moment that does not average out over macroscopic length scales. The directions of  $L$  and  $M$  are controllable by the direction of  $E$ .

### CHALLENGE FOR FUTURE RESEARCH: CAN WE MAKE KNOWN MULTIFERROICS CLOSER TO THE “HOLY GRAIL” FERROELECTRIC-FERROMAGNET?

Despite all these amazing effects, BFO still falls short of being the holy grail of multiferroic physics. Its ferromagnetic moment is sinusoidal in bulk samples, with a quite small amplitude ( $M_0 = 0.09\mu_B/\text{Fe}$ ). The challenge for future

research is to figure out a way to increase  $M_0$  in BFO and related structures.

One possibility is to apply strain, or to combine strain with applied  $E$  fields. Recent experiments in thin-film samples of BFO show that the cycloid is unwound in the presence of large epitaxial strain [27]. The origin of this effect is thought to be due to additional magnetic anisotropy, but no microscopic theory has been carried out to confirm this scenario. Indeed, strain was shown to transform  $\text{EuTiO}_3$  into a strong ferromagnet-ferroelectric at low temperatures [6]. Who knows whether there exists a magical region in BFO's strain- $E$  field phase diagram where  $M_0$  is amplified. Perhaps this is wishful thinking, but BFO has given us so many surprises that we feel enticed to speculate.

Another promising direction is the exploration of the proximity effect. When BFO is interfaced with a strong ferromagnet such as CoFe [16,17] its magnetic order is subject to a strong local magnetic field that can unwind the cycloid [22] and increase  $M_0$  for BFO's Fe spins close to the interface. The length scale for such a proximity effect has never been measured or calculated. Such a length scale would characterize an interface “holy grail” with strong  $P$  and  $M$ .

Finally, there exists an exciting effort to synthesize new materials closely related to BFO. Thin films of  $\text{Bi}_2\text{FeCrO}_6$  (BFCO) were shown to be a strong ferroelectric and perhaps ferrimagnetic at room temperature [28].

The search for the “holy grail” ferromagnet-ferroelectric at room temperature is at full steam, either by synthesizing new materials or by modifying existing ones. While we may never find it, we have already discovered one thing: that searching for it brings out remarkable phenomena in material science and condensed matter physics.

### ACKNOWLEDGEMENTS

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# INSTABILITY PROCESSES FOR MAGNONS IN FERROMAGNETIC NANOSTRUCTURES

BY MICHAEL G. COTTAM AND ZAHRA HAGHSHENASFARD

An understanding of the magnetization dynamics, both linear and nonlinear, in ordered magnetic materials such as ferromagnets is of fundamental interest and also has applications for various high-frequency and switching devices in the expanding fields of spintronics and magnonics. Here we describe some nonlinear processes in ultrathin films and nanowires, where the fundamental excitations of the systems, known as spin waves or magnons, are strongly influenced by their spatial confinement in the nanosystem and can be driven into a decay instability by application of a microwave-frequency electromagnetic wave above a high-power threshold level.

## INTRODUCTION

A description of the wave-like fluctuations in unbounded ferromagnets (i.e., where boundary effects are negligible) in terms of “spin waves” is well known and given in most solid-state physics and magnetism textbooks<sup>[1,2]</sup>. When the quantum-mechanical nature of the spin operators is taken into account, the excitations are called “magnons”, by analogy with phonons as the quantized lattice vibrations in a solid. It is often helpful to picture magnons schematically as in Fig. 1 in terms of arrays of precessing spin vectors, where there is a small change of phase (related to the wave vector) from any one spin to a neighbouring spin. In this semi-classical viewpoint the precession of a spin vector takes place due to the torque from an effective magnetic field that incorporates all the magnetic interactions with other spins as well as any applied magnetic field. In simple cases (such as at low temperatures compared with the Curie temperature  $T_C$ ) the angle of precession is small, meaning that the component of the spin vector along the direction of net magnetization remains approximately constant.

### SUMMARY

The nonlinear magnetization dynamics in ferromagnetic nanostructures are studied through the parametric instabilities of the interacting magnons in thin films and nanowires under microwave pumping.

The dispersion relation of the magnons, which gives the angular frequency  $\omega(\mathbf{k})$  of precession in terms of the wave vector  $\mathbf{k}$ , depends on the nature of the interactions. These arise mainly from (a) the short-range exchange interactions, which are quantum-mechanical in nature and are due to the overlap of wave functions on neighboring atoms, and (b) the long-range magnetic dipole-dipole interactions as in classical electromagnetism. If a Hamiltonian formalism is employed, the contributions to the energy from these terms<sup>[1–3]</sup> are, respectively, proportional to  $J(r_{12})\mathbf{S}_1 \cdot \mathbf{S}_2$  and  $\mu_B^2[\mathbf{S}_1 \cdot \mathbf{S}_2 - 3(\mathbf{S}_1 \cdot \hat{\mathbf{r}}_{12})(\mathbf{S}_2 \cdot \hat{\mathbf{r}}_{12})]/r_{12}^3$ , where subscripts 1 and 2 label spin operators at different atomic sites at a distance  $r_{12}$  apart connected by unit vector  $\hat{\mathbf{r}}_{12}$ . The interaction strength  $J$  before the exchange term is important typically only between nearest neighbours, whereas the weaker dipolar terms (with  $\mu_B$  denoting the Bohr magneton) have a more complicated directional dependence and fall off slowly like  $1/r_{12}^3$ .

A simple calculation of the magnon frequency, applicable for the one-dimensional (1D) system in Fig. 1 with the assumption that only exchange effects occur, is given, for example, in the book by Kittel<sup>[1]</sup>. This is based on using the torque equation of motion for each spin vector and seeking travelling-wave solutions for the fluctuating components. The final result is that  $\omega$  increases as the 1D wave vector  $k$  increases, being proportional to  $SJ(ka)^2$  at small wave vector such that  $ka \ll 1$ , where  $a$  is the distance between spins and  $S$  is the spin quantum number.

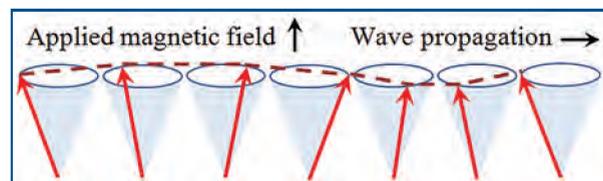


Fig. 1 Schematic illustration of a spin wave (or magnon), taking for simplicity a long line of spin vectors (red arrows), undergoing precession about the direction of net magnetization, defined by the applied magnetic field. One complete wavelength of propagation is depicted, where the dashed line joining the heads of arrows is drawn as a guide to the eye to highlight the wave-like character.



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This result would be modified if effects due to dipolar terms and an applied magnetic field were included [2,3].

A general consequence of the competing interactions is that in reciprocal space, when a Fourier transform is made to a wave-vector representation, the exchange terms dominate at medium and large wave vectors in the Brillouin zone, but the dipolar terms are important at small enough wave vectors. Typically in bulk ferromagnets the dipolar terms need to be included for wave vectors less than about 1/100 of the Brillouin zone boundary value, which is relevant for experimental techniques such as ferromagnetic resonance (FMR) and Brillouin light scattering (BLS) that probe the so-called magnetostatic and dipole-exchange regimes [2,3].

### INTERACTING MAGNON GAS

The magnons, when treated in the simplest linear-wave approximation can be shown to behave as bosons, and the number of thermally-excited magnons with energy  $\hbar\omega(\mathbf{k})$  is described by the Bose-Einstein distribution function. In reality the magnon states are not exact eigenfunctions of the Hamiltonian, and consequently the magnons constitute a weakly interacting boson gas. In the semiclassical spin-wave picture, the origin of the magnon-magnon interactions is associated with the role of the finite angle of spin precession in changing the longitudinal spin projection. Quantum mechanically the spin operators, which are analogous to the orbital angular momentum operators, do not satisfy the boson commutation relationships, and a mathematical transformations between spin operators and boson operators has to be applied [2,3].

The Hamiltonian for the interacting magnon gas of a ferromagnet, in the notation of second quantization, can be expressed as

$$H = \sum_{\mathbf{k}, l} \omega_l(\mathbf{k}) b_{\mathbf{k}, l}^+ b_{\mathbf{k}, l} + H^{(3)} + H^{(4)} + \dots \quad (1)$$

in leading order (at temperatures well below  $T_C$ ), apart from a constant term. Here  $b_{\mathbf{k}, l}^+$  and  $b_{\mathbf{k}, l}$  are the creation and annihilation operators, respectively, for a magnon of wave vector  $\mathbf{k}$  and branch  $l$ . For a bulk (effectively unbounded) material we have only  $l = 1$ , but this will not generally be so for nanostructures. The first term on the right of Eq. (1) has a form similar to that for the treatment of a simple-harmonic oscillator in quantum mechanics. The next two terms,  $H^{(3)}$  and  $H^{(4)}$ , describe the leading-order three-magnon and four-magnon interaction processes, respectively. The first of these involves operator products like  $b_{\mathbf{k}, l}^+ b_{\mathbf{k}-\mathbf{k}', l}^+ b_{\mathbf{k}', l}$  and its Hermitian conjugate, which represent magnon splitting (i.e., a magnon is annihilated and two magnons are created) or the corresponding confluence. The last term in Eq. (1) involves products of four boson operators, e.g., two creation and two annihilation operators as for a pair of magnons scattering off one another to produce two other magnons with different wave vectors. It can be shown that the three-magnon processes are due to magnetic dipole-dipole

interactions, whereas four-magnon scattering has contributions coming from both the exchange and dipolar interactions [2,3].

### MAGNONS IN NANOSTRUCTURES

As mentioned, the magnons for a simple bulk ferromagnet in three dimensions are characterized by a 3D wave vector  $\mathbf{k}$  and the branch label  $l$  is single-valued. By contrast, in magnetic nanostructures, where one (or more) of the spatial dimensions is of order tens or hundreds of nanometres, the magnons are spatially confined and are required to satisfy boundary conditions at the surfaces or interfaces. In a thin film, for example, the magnons are characterized by a 2D wave vector in the directions of translational symmetry parallel to the surfaces. For the direction perpendicular to the surfaces, the magnons may either take a standing-wave form with a quantized value for the third wave-vector component, or they may be localized with amplitude decaying away from one or both surfaces. Likewise in a nanowire there is a 1D wave vector along the length and standing-mode behaviour or localization in the other two directions.

An example is given in Fig. 2 showing the calculated dispersion relations for the lowest magnon branches in a Permalloy ( $\text{Ni}_{80}\text{Fe}_{20}$ ) nanowire stripe with rectangular cross section 50 nm by 10 nm and in a longitudinal applied magnetic field of 0.202 T. The frequencies, which were obtained using a microscopic dipole-exchange theory [4] in which magnon interactions are ignored, are plotted versus the 1D wave vector in the small  $|\mathbf{k}|$

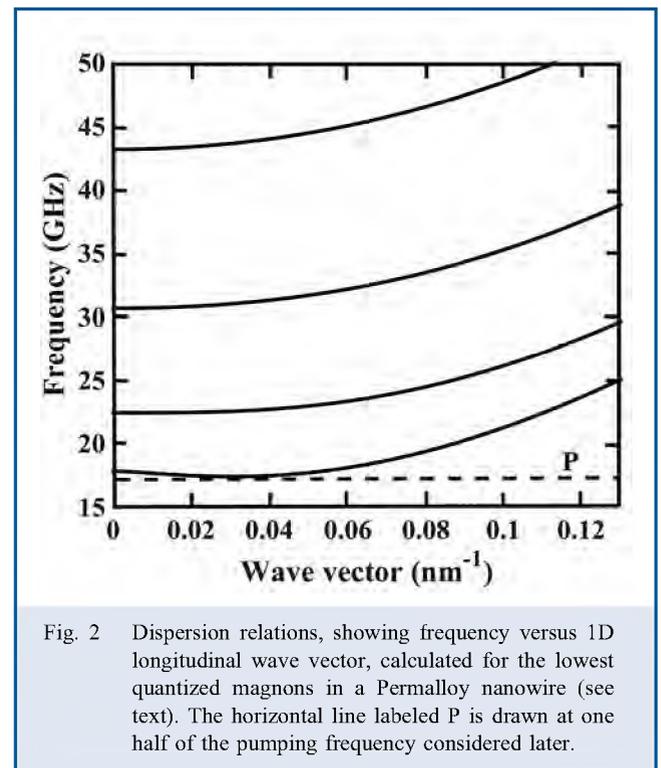


Fig. 2 Dispersion relations, showing frequency versus 1D longitudinal wave vector, calculated for the lowest quantized magnons in a Permalloy nanowire (see text). The horizontal line labeled P is drawn at one half of the pumping frequency considered later.

regime accessible by FMR and BLS measurements. The initial dip for some branches, which is more pronounced for the lowest branch and has been confirmed experimentally, is due to the dipolar interactions competing with the exchange that eventually dominates at larger  $|\mathbf{k}|$ .

### MAGNON INSTABILITIES UNDER MICROWAVE PUMPING

Typically FMR experiments are carried out at relatively low power levels; an oscillating magnetic field at microwave frequency is applied to a ferromagnet in a direction transverse to the magnetization direction. The microwave field can couple linearly to the oscillating magnetic moment of a magnon such that there is a resonant absorption of energy when a match is achieved (e.g., by scanning the static applied field) between the microwave frequency and the precessional frequency of the magnon [1]. Measurement of the FMR linewidth can yield information about the magnon damping (or reciprocal lifetime). This is long established for macroscopically large samples, but for nanostructures such as nanowires the experimental [5] and theoretical [6] studies are quite recent.

For bulk samples it was noticed that, when the signal power was increased in FMR experiments, the absorption strength for the main resonance reached saturation (instead of increasing further) and a subsidiary resonance appeared at higher frequency [7]. Subsequently these nonlinear effects with perpendicular microwave pumping were explained by Suhl [8] in terms of parametric instabilities involving the three- and four-magnon processes, respectively. They are now known as the first-order and second-order Suhl processes, respectively. An analogous instability under parallel microwave pumping was later identified by Schlömann and others [9]. The three types of processes are depicted schematically in Fig. 3; there are several reviews (mainly for macroscopic samples) giving details [2,3,10].

The outcome in all three processes is the production of a pair of magnons with wave vectors  $\mathbf{k}$  and  $-\mathbf{k}$  of equal magnitude, implying that they have the same frequency. Parallel pumping (Fig. 3a) relies on the fact that the dipolar interactions cause the spin precession to be elliptical rather than circular. Hence the parallel (or longitudinal) components of the spin vectors, which are coupled to the pumping field, fluctuate resulting in the excitation of a magnon pair. The first- and second-order Suhl processes (Figs. 3b and 3c) involve the excitation initially of one (or two) uniform-precession magnons, meaning modes with  $\mathbf{k} = 0$ , followed by the production of the magnon pair via the  $H^{(3)}$  and  $H^{(4)}$  interaction terms. From considerations of energy conservation it follows that the angular frequency of each magnon produced in the parallel pumping and first-order Suhl processes is  $\frac{1}{2}\omega_p$ , whereas in the second-order Suhl process it is  $\omega_p$ .

In a nanowire, however, the absence of wave-vector conservation in the directions perpendicular to its length gives two

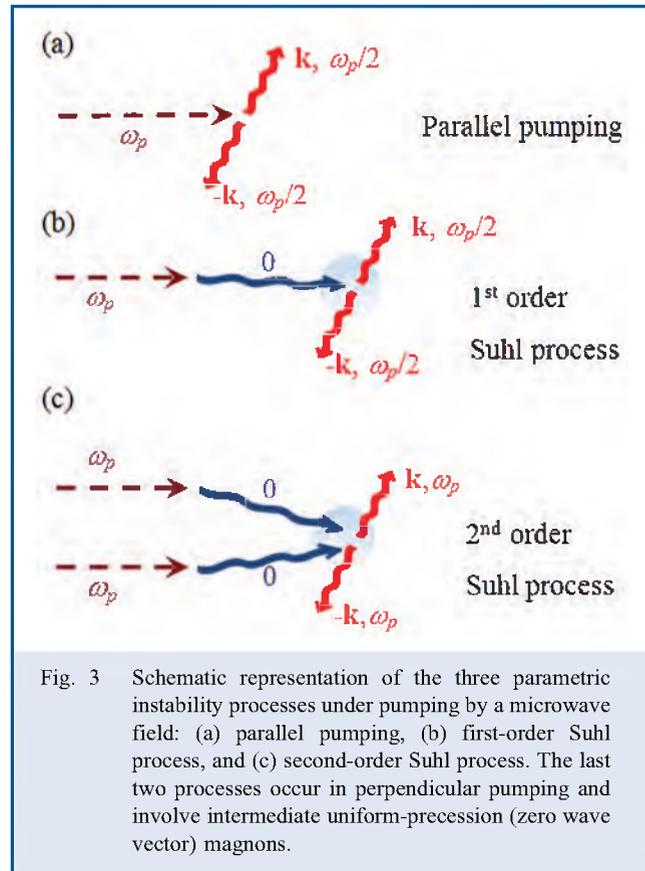


Fig. 3 Schematic representation of the three parametric instability processes under pumping by a microwave field: (a) parallel pumping, (b) first-order Suhl process, and (c) second-order Suhl process. The last two processes occur in perpendicular pumping and involve intermediate uniform-precession (zero wave vector) magnons.

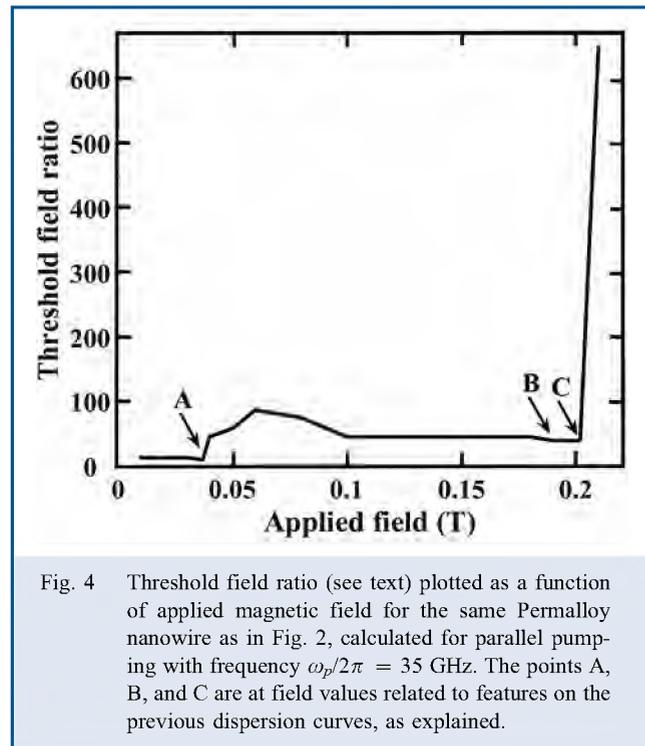


Fig. 4 Threshold field ratio (see text) plotted as a function of applied magnetic field for the same Permalloy nanowire as in Fig. 2, calculated for parallel pumping with frequency  $\omega_p/2\pi = 35$  GHz. The points A, B, and C are at field values related to features on the previous dispersion curves, as explained.

distinctive features from the macroscopic case: the interaction processes involve a “mixing” between different magnon branches, and there are strong density-of-states effects for the magnons due to the spatial confinement. When the threshold strengths of the pumping field for the onset of an instability in any magnon branch are calculated (using techniques analogous to those for ultra-thin films<sup>[11,12]</sup>), we obtain results as in Fig. 4 for the same Permalloy nanowire considered in Fig. 2. This shows the dimensionless threshold field ratio (conventionally defined as the threshold field amplitude divided by the FMR half-linewidth in magnetic field units) plotted against the applied field for parallel pumping. Referring to the dispersion curves, the horizontal line P in Fig. 2 is drawn at half of the pumping frequency, which corresponds to production of the parametric magnons. With an applied field of 0.202 T, for which Fig. 2 is drawn, the line P coincides with the minimum in the lowest magnon branch. When the applied field is scanned up (or down) in value, the line P moves down (or up) relative to the dispersion curves. For fields above 0.202 T the line does not intersect with any magnon branch, and so the instability threshold rapidly increases. This explains the special point labeled C in Fig. 4. For lower applied field values there may in general be one or more intersection points, and so the decay is allowed. For nanostructures (as in this example) certain features on the discrete spectrum become emphasized, by contrast with the smooth behaviour (the so-called “butterfly” curve) found for

macroscopic samples<sup>[2,3]</sup>. Thus we may associate points labeled B and A in Fig. 4 as corresponding to when line P coincides with the  $\mathbf{k} = 0$  magnons of the lowest and next-lowest branches, respectively. Other structural features can be attributed to density-of-states effects for the quantized magnons.

## CONCLUSION

It is of great interest currently to extend the work on magnon instabilities to other types of magnetic nanostructures and to their arrays (as in magnonic crystals). Also, recent experiments have reported the observation of a Bose-Einstein condensation (BEC) in a macroscopic magnon gas at room temperature<sup>[13]</sup> when driven far from equilibrium by an intense microwave pumping field. A macroscopic theoretical interpretation<sup>[14]</sup> was subsequently developed by utilizing the form of the three- and four-magnon interaction terms. Investigation of the possible occurrence of a magnon BEC in a magnetic nanostructure with spatially-confined magnons is an intriguing topic.

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# SPIN WAVE RESONANCE OF FERROMAGNETIC NANOWIRE ARRAYS

BY DAVID MÉNARD AND CHRISTIAN LACROIX

Spin waves in ferromagnetic materials exhibit a large variety of field-tunable dispersion relations, permitting the manipulation of microwaves in solids. While magnetic oxides, such as ferrites and garnets, have traditionally been used for such purposes<sup>[1]</sup>, an increasing interest has recently been dedicated to magnetic wave propagation in artificially-nanostructured magnetic materials. This emerging research field, called magnonics, seeks to exploit magnetic wave phenomena in order to process information at the nanoscale<sup>[2–4]</sup>.

Here we are concerned with magnonic materials consisting of nanowires, made of ferromagnetic metals electroplated in nanoporous alumina membranes<sup>[5–7]</sup>. By combining metallic and ferromagnetic nano-inclusions in a dielectric template, one can exploit various charge and spin transport phenomena, along with spin and charge density waves, to achieve magnetic and dielectric responses not found in nature.

## EFFECT OF DIPOLAR INTERACTIONS ON FERROMAGNETIC RESONANCE

Ferromagnetic resonance (FMR) generally refers to the collective resonance modes of strongly coupled spins in ferromagnets. Unlike the magnetic resonance of paramagnetic electrons or of nuclear spins, FMR is often shape-dependent and strongly anisotropic. This behavior is due to the strong anisotropic coupling between the elementary magnetic moments in ferromagnets, which results in effective internal fields, related to the crystallographic axes, mechanical stresses or sample shapes<sup>[8]</sup>. For a specimen with rotational symmetry, magnetized along the symmetry axis, the ferromagnetic resonance frequency (in rad/s) is

$$\omega = \gamma\mu_0(H_0 + H_{eff}), \quad (1)$$

### SUMMARY

We present a brief introduction to the spin wave resonance of ferromagnetic nanowire arrays, emphasizing their relevance for the emerging field of magnonics.

where  $\gamma$  is the gyromagnetic ratio,  $\mu_0$  is the vacuum permeability,  $H_0$  is the external applied field and  $H_{eff}$  is the effective uniaxial anisotropy field. For soft magnetic materials, dominated by the long-range dipolar interaction between the magnetic moments, the effective field is

$$H_{eff} = \left(\frac{1 - 3N_z}{2}\right)M_s, \quad (2)$$

where  $M_s$  is the saturation magnetization and  $N_z$  is the component of the diagonal demagnetizing tensor parallel to the magnetization<sup>[6]</sup>. Note that  $N_x + N_y + N_z = 1$ , where  $N_x$  and  $N_y$  are the other two orthogonal components of the diagonal demagnetizing tensor.

Demagnetizing effects, arising from dipolar interactions, lead to shape dependent FMR characteristics, related to the value of  $N_z$  in Eq. (2). Figure 1 shows the expected behavior for a longitudinally magnetized CoFeB wire ( $N_z = 0$ ), a CoFeB sphere ( $N_z = 1/3$ ) and a thin CoFeB film magnetized perpendicular to the plane ( $N_z = 1$ ). The offset of the linear FMR characteristic is a measure of the effective anisotropy field, associated with dipolar interactions.

In soft magnetic nanowire arrays, the shape-dependent demagnetization of the individual wires is modified by the inter-wire dipolar interactions. This leads to an effective demagnetizing tensor, which is a function of the geometrical parameters of the array (wire length, diameter and spacing) and of the saturation magnetization of the wires<sup>[6]</sup>. This is illustrated in Fig. 1, where the resonance field for a film of densely-packed vertical wires (perpendicular to the film surface) magnetized parallel to the wires exhibit an effective demagnetizing tensor somewhere between that of a wire and a thin film.

Over the years, we have verified that, provided there are no other contributions to the magnetic anisotropy, the ferromagnetic resonance characteristics of these arrays can be tailored by adjusting their geometrical parameters during the fabrication process<sup>1</sup>. Interestingly, with proper choice of geometric parameters, an array of ferromagnetic wires

1. This has been generally observed in several Ni, NiFe and CoFeB samples, with the exception of the smaller diameter wires (around 20 nm), for which a surface magnetic anisotropy starts to contribute to the FMR response.



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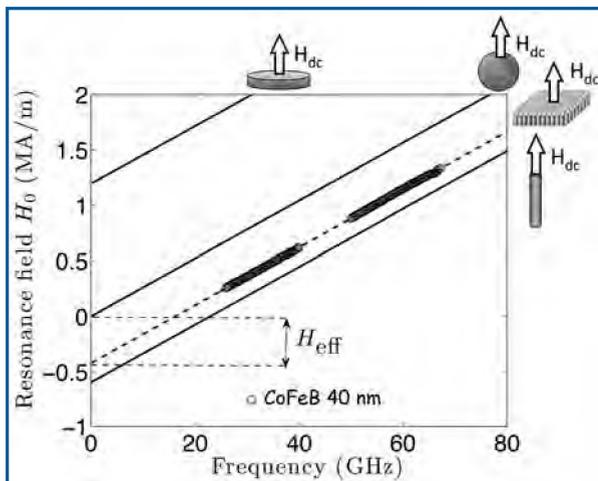


Fig. 1 Ferromagnetic resonance field as a function of frequency, for different sample shapes: wire (axial field), sphere, uniform film (magnetized out-of-plane) and 40-nm-diameter CoFeB nanowire array. The material, an alloy of CoFeB, is characterized by  $M_s = 1200$  kA/m and  $\gamma = 1.92 \times 10^{11}$  rad/(s.T). The open circles are the measured data of the array. The dashed line is a fit, using Eq. (1) with 0 by  $M_s = 1200$  kA/m and  $H_{\text{eff}} = 422$  kA/m, in agreement with the dipolar field calculated from the parameters of the array [6].

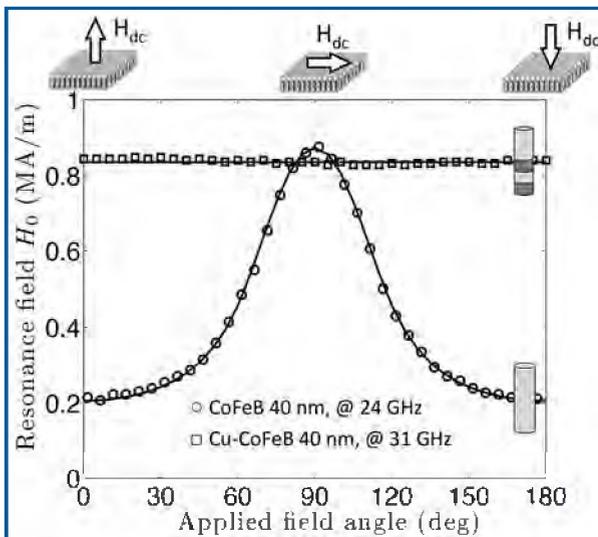


Fig. 2 Angle-dependent resonance field of a 40-nm diameter CoFeB nanowire array (circles) and a 40-nm diameter multilayered Cu-CoFeB nanowire array (squares). The solid lines are fits, using Eq. (29) from Ref. [6], with  $H_{\text{eff}} = 422$  kA/m and  $\gamma = 1.92 \times 10^{11}$  rad/(s.T) for the uniform array and  $H_{\text{eff}} = 0$  kA/m and  $\gamma = 1.86 \times 10^{11}$  rad/(s.T) for the multilayered array.

could be forced to be isotropic, as if it was a sphere! This is demonstrated by the angle-dependent FMR measurements in Fig. 2. In this example, we have used multilayered nanowires, alternating Cu and CoFeB layers, to gain even more flexibility to adjust the effective demagnetizing factor. While the uniform composition wires exhibit the characteristic bell-shaped curve expected from an out-of-plane uniaxial anisotropy, the multilayered nanowire arrays display an FMR field independent of the direction of the applied field.

## MAGNONIC MATERIALS

The control over the FMR characteristics of magnetic materials is an important step towards the realization of magnonic devices. Magnonics relies on the propagation of spin waves in man-made periodic structures to transport and process information signals. The relatively short wavelength of the spin waves, on the order of 100 nm in the low-GHz frequency regime, as compared to several cm for EM waves, holds promise for nanoscale devices. While other fields of research, such as plasmonics, also seek to exploit short wavelength excitations in solids, what sets magnonics apart is its larger variety of spin wave dispersions and the fact that these are tunable using an external magnetic field. For example, a magnetic field can be used to modify dynamically the band structure of a magnonic crystal [9]. In this respect, the possibility to reconfigure the remanent magnetic state (no applied field) of ferromagnets, is of great interest for the design of reprogrammable devices, an important theme of magnonic research [Other aspects of spin waves are also covered in the following articles also in this issue: “Dawn of Cavity Spintronics” by Hu, “Instability Processes for Magnons in Ferromagnetic Nanostructures” by Cottam and Haghshenasfard, “Electronic transport in magnetic tunnel junction: a discussion of the electron-magnon-photon coupling” by Guo and Xiao and “The ‘holy grail’ of multiferroic physics” by de Sousa].

Ferromagnetic nanowire (FMNWs) arrays, exhibiting significant hysteresis, are potential candidates for self-biased reprogrammable magnonic devices. If not magnetically saturated, the FMNWs arrays can be modelled by considering the systems as two magnetically-uniform antiparallel arrays, strongly coupled by dipolar interactions [10,11]. In other words, each nanowire has a uniform magnetization, which points either up or down, thus creating two embedded sub-arrays. The distribution between up and down wires can be adjusted using minor hysteresis cycles. It is worth mentioning that this feature would be very difficult to achieve, if not impossible, in conventional ferrites and garnets.

Figure 3 presents the frequency dependence of the effective complex permeability of a FMNWs array, measured at four different applied fields. The four fields correspond to four distinct magnetic states along the lower branch of the hysteresis curve. As the field is swept from  $-5$  kOe to  $5$  kOe ( $1$  kOe =  $79.6$  kA/m), the nanowires randomly reverse, gradually modifying the resulting dipolar fields. The component of the scalar effective permeability, presented in Fig. 3c, are associated with

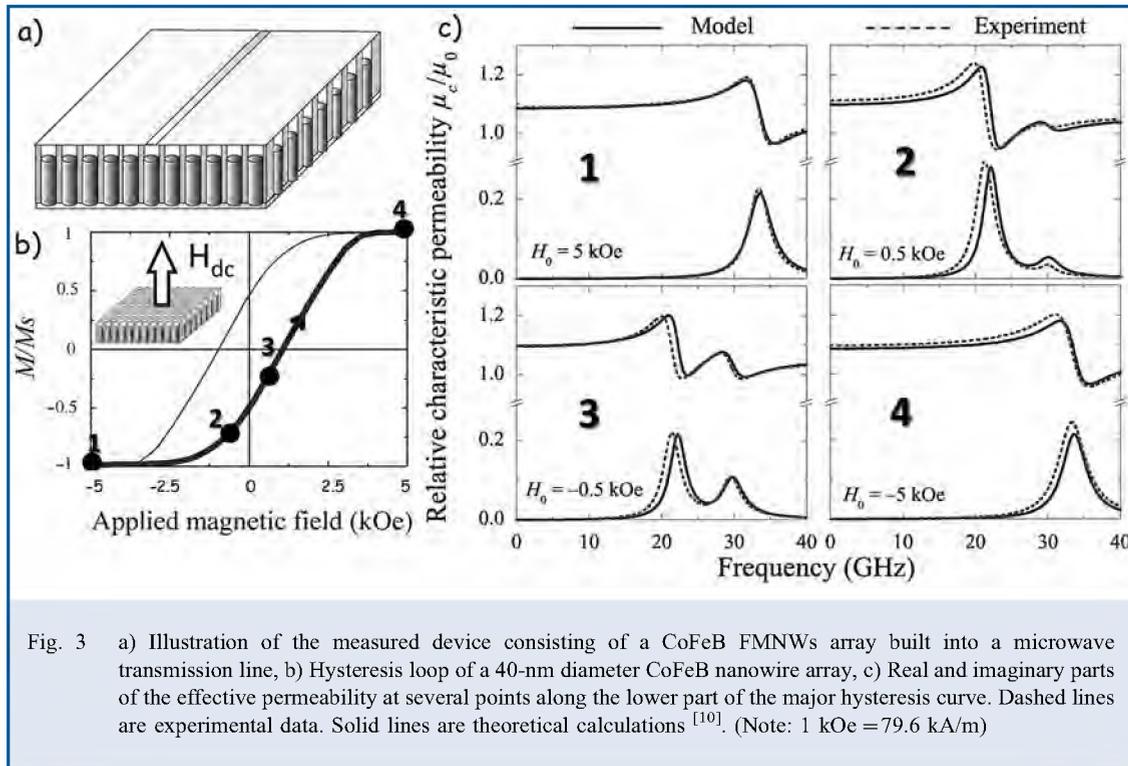


Fig. 3 a) Illustration of the measured device consisting of a CoFeB FMNWs array built into a microwave transmission line, b) Hysteresis loop of a 40-nm diameter CoFeB nanowire array, c) Real and imaginary parts of the effective permeability at several points along the lower part of the major hysteresis curve. Dashed lines are experimental data. Solid lines are theoretical calculations<sup>[10]</sup>. (Note: 1 kOe = 79.6 kA/m)

the microwave magnetic field, which is perpendicular to the static applied field,  $H_0$ . It is complex due to magnetic damping, and exhibits the characteristic dissipation (imaginary part) and dispersion (real part) of a resonant response. The solid line is the calculated response, based on the simple dipolar model, presented earlier, but applied to the two sub-arrays and including the mutual coupling between the arrays<sup>[10]</sup>.

At saturating fields (points 1 and 4), all magnetic moments are oriented in the same direction, corresponding to a single resonance. At lower field (points 2 and 3), two resonance peaks are observed, associated with the normal modes of the coupled sub-arrays, as detailed in Ref. [10]. As indicated by the relatively good agreement between the data (dotted line) and the model (solid line), the response is generally well described using two coupled magnetic oscillators, with resonance characteristics depending on the relative distribution of the wires between the parallel and antiparallel directions.

## CLOSING REMARKS

In this brief introduction to one aspect of magnonics research, we have shown that the microwave response of ferromagnetic nanowire arrays can be surprisingly well accounted for by a

simple model, assuming a periodic array of single-domain cylindrical ferromagnets, exhibiting bistable hysteresis, and mutually coupled by dipolar interaction. The model leads to quantitative expressions for the effective anisotropy field as a function of the material and geometrical parameters of the arrays<sup>[6]</sup>, which can be used as design rules to engineer their properties. However, this increased design flexibility is provided at the cost of higher microwave losses, as compared to state-of-the-art ferrites and garnets. Microwave losses originate from the damping of the precessing magnetization and are related to the linewidth of the imaginary part of the effective permeability. Understanding and reducing the microwave losses, along with demonstrating spin wave propagation in FMNWs-based magnonic waveguides is an active research field in our group.

## ACKNOWLEDGEMENTS

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# SPIN MECHANICS

BY JOSEPH E. LOSBY AND MARK R. FREEMAN

## SPIN MECHANICS TIMELINE

Electrons carry charge, magnetic moment, mass, and mechanical (spin and orbital) angular momentum. Intensive investigation of the interplay between magnetism and charge transport, or *spin electronics* has tremendously enriched our fundamental understanding of magnetic materials and enormously expanded the horizons for magnetic devices and applications.<sup>1</sup> An analogous opportunity exists in the merging of magnetism and mechanical motion, or *spin mechanics*. These include the deflection of mechanical objects due to angular momentum transfer via magnetic torques, magnetic gradient force interactions, or strains induced through magnetostrictive effects. The idea that electrons carry a mechanical angular momentum became evident a century ago through the results of magneto-mechanical experiments seeking to determine the origin of magnetism, and mechanical implementation followed alongside the historical advancement of magnetism.

A series of events closely tied to the development of spin mechanics is shown in the timeline, Fig. 1. Perhaps the earliest known practical application of a ‘spin mechanical’ device by humans is through navigation thousands of years ago by use of the magnetic compass<sup>[1]</sup>. The discovery that the long axis of a thinned piece of lodestone always orients in the north-south direction (which we know now is due to a torque induced on the magnetization in the needle by Earth’s magnetic field) had a profound effect on our history with the use of the compass in seafaring. Predating our history, many organisms have acquired magnetoreceptive abilities that grant the ability to follow and align to small changes in Earth’s field. The simplest of them, magnetotactic bacteria, synthesize internally a linear chain of nano-sized magnetite particles that are dipolar-coupled to effectively form a compass needle, which passively allows them to migrate with Earth’s field to depths with favourable oxygenation conditions<sup>[2]</sup>. Below, we spotlight a few developments along the (incomplete) timeline shown in Fig. 1. The timeline also includes key 20th century

### SUMMARY

A brief history, the current state, and future directions of *spin mechanics* are presented.

advances in magnetism having a huge bearing on the development of spin mechanics.

Ampère, in the early 1820s, hypothesized that the magnetic field of a ferromagnetic body was produced by persistent ‘molecular currents’<sup>[4]</sup>. Rowland, in the 1870s, confirmed that the mechanical rotation of electrostatically-charged disks generates magnetic fields, using an ultrasensitive torsion-fibre compass capable of measuring field changes of order 1 nT<sup>[5]</sup>. O.W. Richardson later suggested that a relationship should exist between the magnetization (or magnetic moment) and mechanical angular momentum in a ferromagnet (1908)<sup>[6]</sup>. He proposed a mechanical experiment involving a piece of iron suspended on a torsion string, which would experience a twist as the ‘magnetic atoms’ in the iron imparted a mechanical angular momentum as they switched their ‘axis’ from one direction to another along the direction of the string. S.J. Barnett, while pondering the origin of Earth’s magnetic field, suggested that a ferromagnet with no net moment should become magnetized upon mechanical rotation (inverse to Richardson’s proposal) and indicated preliminary experimental success of his theory (1909)<sup>[7]</sup>. In 1915 he published his results on what is now known as the Barnett effect<sup>[8]</sup>.

In the same year, Einstein and de Haas announced their findings, believing they had confirmed the existence of the Ampèrian molecular currents<sup>[9]</sup>. Their experiment was similar to what was proposed by Richardson, while adding a key gain in sensitivity by changing the applied field (and switching the magnetization) at the mechanical resonance frequency of the torsion balance. At the time, it was believed that the electron’s orbital angular momentum was solely responsible for the change in the amplitude of twist of the mechanical resonator. The ratio of magnetic moment  $m$  to angular momentum  $L$ , when calculated for a classical electron orbit or current loop, is  $m/L = -e/2m_e$ , where  $m_e$  is the electron mass and  $-e$  its charge (the ratio  $e/m_e$  was well known from the classic J.J. Thomson experiment), was the experimental constant sought (also known as the gyromagnetic ratio). Einstein and de Haas’ result matched the classical gyromagnetic ratio reasonably well, within 10% error.

1. See articles in this issue by M. Arora *et al.* for an overview of spin torque transfer memory devices and H. Guo *et al.* for a theoretical description magnetic tunnel junction physics, which play a key part in spintronics device applications.



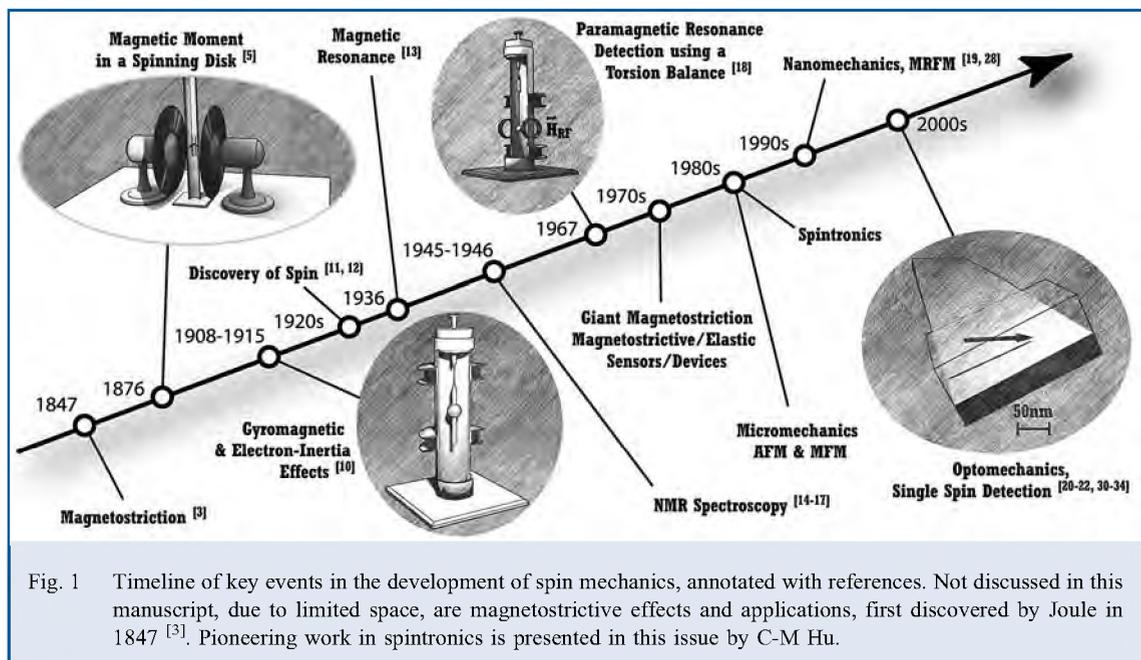
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Curiously, later experiments seeking to reproduce the Richardson and Einstein-de Haas experiment all arrived at a gyromagnetic ratio of around  $m/L = -e/m_e$ , a factor of two larger than predicted [10]. This ‘anomaly’ brought into question the accepted value. Although the intimate association between angular momentum and ferromagnetism existed, it was not due to the persistent molecular currents. The reason would not be known until the discovery of ‘the spin’ and the formulation of quantum mechanics in the 1920s. The intrinsic magnetic moment of the electron is predominantly responsible for the magnetization in ferromagnets.

The gyromagnetic studies by Richardson, Barnett, and Einstein-de Haas, and others make up the earliest of spin mechanical measurements which preceded the development of the spin in 1925 [11,12]. A Rev. Mod. Phys. article published by Barnett in 1935 provided a detailed summary of the classical viewpoint, and a chronology of the first century of thought and experimentation on the subject dating back to Ampère and Weber [10].

Magnetic resonance is, at its core, a spin-mechanical effect: a magnetic dipole mis-aligned to a local magnetic field would not precess if not for its intrinsic mechanical angular momentum (this key physical distinction relative to electric dipoles is not emphasized to physics undergraduates). Electron spin resonance was first observed by Gorter through a calorimetric method [13], and then by Rabi with molecular beams [14]. Nuclear magnetic resonance (NMR) spectroscopy through electromagnetic induction was demonstrated by Zavoisky [15], Purcell *et al.* [16], and Bloch [17] independently, and laid the foundations for powerful methods now used throughout science and medicine. Alzetta, Ascoti, Gozzini and co-workers in 1967 performed a pioneering demonstration of electron paramagnetic resonance detection

using a torsion balance to record an ‘Einstein-de Haas torque’, foreshadowing the much later resurgence of spin mechanical detection [18]. The same group would revisit this work in a highly miniaturized geometry in 1996 [19].

The advancements made in semiconductor device manufacturing from the 1960s brought about the miniaturization of micro-electromechanical devices. The atomic force microscope (AFM), using a micro-cantilever with a sharp tip to probe surface forces at nanoscale resolution, was developed in the early 1980s. Soon after, AFM tips were evolved to incorporate magnetic material. In magnetic force microscopy (MFM), the interaction is through the magnetic gradient forces between the sample and the tip, causing a mechanical deflection of the cantilever. Gradient force detection of magnetic resonance has been developed to sensitivity equivalent to a fraction of an electron spin, or tens of protons [20].

## MODERN SPIN MECHANICS

Richardson/Barnett/Einstein-de Haas effects scale-up in import for small systems with tiny moments of inertia and high angular rotation speeds. The response of a nanoscale magnet can change qualitatively, depending upon whether the structure is anchored or free to rotate. By 2005, Kovalev, Bauer, and collaborators, along with Chudnovsky and collaborators, were analyzing the expected consequences of the effects of rotation on magnetism in nanostructured and quantum systems [21,22]. Remarkable recent experiments have leapfrogged all the way to inelastic electron tunneling spectroscopy of strongly coupled spin-phonon modes in a single-molecule magnet / carbon nanotube hybrid system [23; theory in 24]. The mechanisms of angular momentum transfer between microscopic magnetic moments

and their mechanical hosts are thinly understood. Chudnovsky would note in 2004 that “the problem of spin-lattice interactions is almost as old as the quantum theory of solids” [25]. The concept of phonon angular momentum was introduced as recently as 2014 [26].

A modern Richardson/Einstein-de Haas experiment is described through Fig. 2a [27]. Thin magnetic films (or small structures) are affixed to micro- or nanomechanical resonators while external fields induce magnetic torques that are transferred to a mechanical degree of freedom, in this case the flexural mode

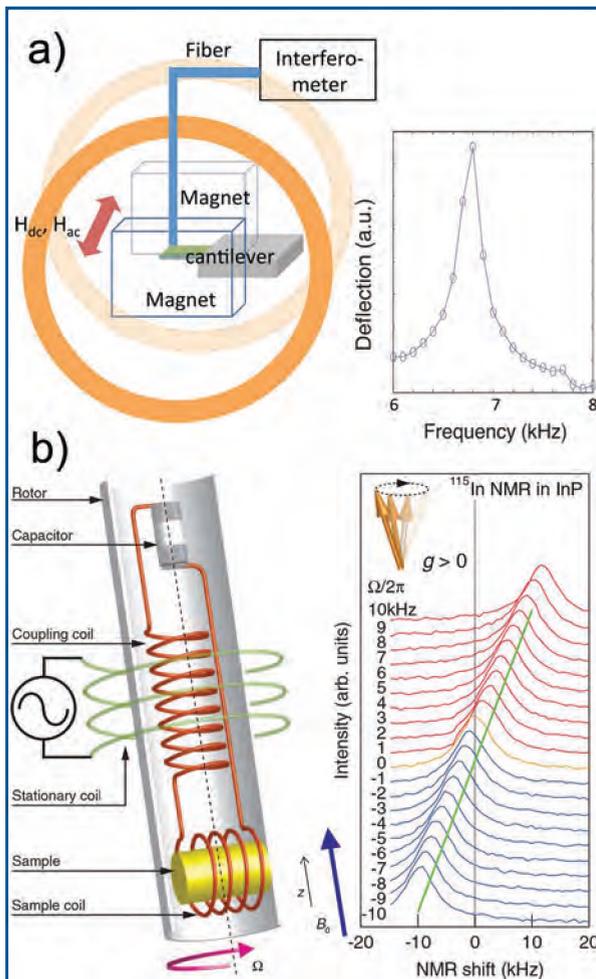


Fig. 2 a) Instrumental schematic of a micromechanical Richardson/Einstein-de Haas effect driven by  $H_{ac}$  at the fundamental flexural mode of the cantilever (frequency sweep shown on the right of the panel) while under bias by  $H_{dc}$ . (Ref. [27], Copyright 2013, The Japan Society of Applied Physics). b) Coil-spinning method for inducing Barnett fields for readout via NMR (Ref. [29], Copyright 2014, IOP Publishing). The NMR frequency shifts for the  $^{115}\text{In}$  nuclei in InP with angular rotation velocity is shown on the right.

of a microcantilever [28]. The applied AC ‘dither’ field is at the mechanical resonance frequency (frequency sweep, right side of Fig. 2a) and deflections down to the sub-nanometer can be detected using sensitive optical interferometric methods.

In Fig. 2b, a schematic is shown of a recent experiment which observed Barnett fields through NMR using a ‘coil spinning’ technique [29]. The apparatus consists of a sample coil and a coupling coil, both spinning within a stationary coil connected to an NMR spectrometer. Through mutual induction the RF field from the stationary coil is received by the coupling coil and transferred to the sample coil, inducing the NMR signal. The Barnett field is proportional to the angular frequency  $\Omega$ , and modifies the applied field  $B_0$ , resulting in NMR frequency shifts. This is shown in the resonance spectra for  $^{115}\text{In}$  nuclei under various sample rotation speeds (Fig. 2b, right).

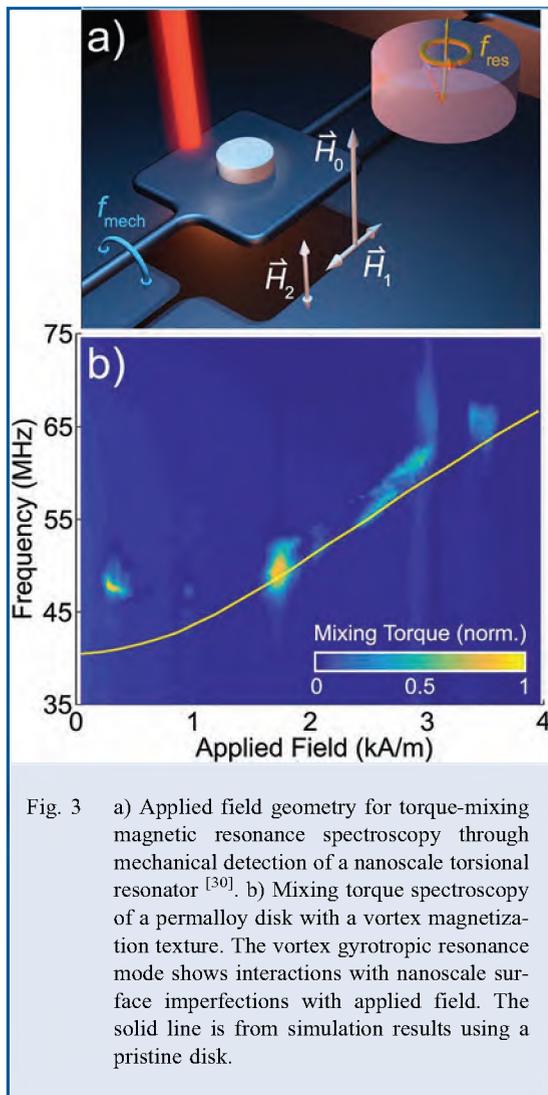
A recently developed torque method for magnetic resonance spectroscopy is shown in Fig. 3a [30]. The method permits direct detection of the transverse component of precessing dipole moments (inset), and parallels the conventional approach to NMR, where this is detected inductively. Here, a mesoscopic magnetic sample is attached to a nanomechanical torsional resonator and placed under bias by the static field  $H_0$ .

The RF field  $H_1$  (at frequency  $f_1$ ) drives the precession of the moments at  $f_{res}$ . An additional RF field  $H_2$  (at  $f_2$ ) cooperates with  $H_1$  to generate sum and difference frequency ‘torque-mixing’ components proportional to the magnetic resonance amplitude. By applying  $f_2$  and  $f_1$  such that their difference is the mechanical mode  $f_{mech}$  of the torsional resonator, the magnetic resonance can be read out with high sensitivity. Spectroscopy is performed by sweeping  $f_2$  and  $f_1$  together while maintaining the  $f_{mech}$  difference.

An example of torque-mixing resonance spectroscopy is shown in Fig. 3b for a Permalloy disk ( $\text{Ni}_{80}\text{Fe}_{20}$ , 15 nm thick and 2  $\mu\text{m}$  in diameter). Such a structure holds a low-field vortex magnetization state, with a core pointing out of plane to the disk surface. The lowest order magnetic resonance mode of the vortex texture is that of a precession of the core about an equilibrium. With applied field, the equilibrium of the core is ‘pushed’ towards the edge of the disk and its precession frequency is blue-shifted, as seen in the figure. The core, with a high exchange energy density, can probe the magnetic landscape. The ‘dropouts’ seen in the evolution of the magnetic resonance signal with applied field are due to pinning events as the core interacts with nanoscale grain boundaries inherent in Permalloy, and also observable as Barkhausen transitions in the net magnetization [31,32]. The micromagnetic simulation results for a ‘pristine’ disk is shown overlaid.

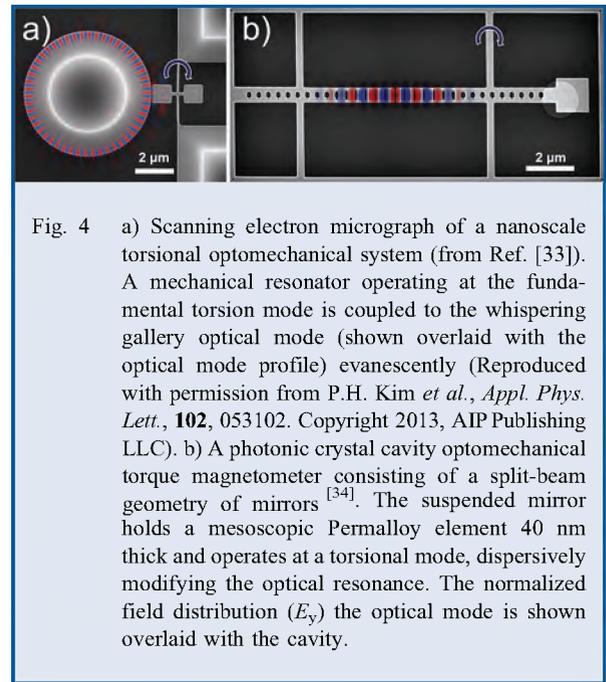
## CAVITY TORSIONAL OPTOMECHANICS

Most of the spin-mechanical phase space between millions-of-Bohr-magneton objects and single spin systems remains unexplored but is now accessible, owing to advances in related, enabling technologies. Experimental capabilities for detecting



nanomechanical motion have been revolutionized by the development of *cavity optomechanics*. In these systems a micro- or nanoscale mechanical resonator is embedded in a high finesse optical cavity. A dispersive coupling of the mechanical modulation with the cavity results in an optical resonance frequency shift, which is detected with extremely high sensitivity. Displacements of a nanostructure corresponding to a small fraction of the diameter of a proton have been measured.

A significant advance in torsional nanomechanics has been achieved through coupling to an optical whispering gallery mode in a silicon microdisk, as presented in Fig. 4a<sup>[33]</sup>. Light is coupled into the microdisk using a single-mode tapered fiber. The optical field profile from simulation is overlaid on the scanning electron micrograph. The motion of the torsional resonator interacts with evanescent fields, modulating the effective index of refraction (and thus resonance frequency) of the optical mode. Mechanical deflections corresponding to torques down to the  $10^{-20}$  Nm scale have been reported. The



earliest implementation of a photonic crystal cavity optomechanical torque magnetometer is shown in Fig. 4b<sup>[34]</sup>. In this scheme, a magnetic element is placed at the end of a suspended structure serving as an optical ‘mirror’, which can operate mechanically at the torsional mode. The suspended mirror is optically coupled to an anchored mirror receiving light from an optical fiber. To minimize radiation losses, the periodic holes defined in the structures are tapered to the dimension of the gap between the two mirrors (optical field profile shown below). With an applied AC magnetic field, the resonating mechanical structure dispersively causes a frequency shift of the optical mode.

## CONCLUSION

The magnetism sub-discipline of spin mechanics is at an exciting stage. Direct experimental insights into the behaviour of spin-rotation coupling in a wide variety of materials is key to a fuller basic understanding of magnetism. Resonant detection of spin angular momentum opens the door to physics not yet explored, such as the timescales associated with the Richardson/Einstein-de Haas effect. The coherent coupling of spin and motion potentially leads to mechanical control of magnetism for applications. Numerous other benefits of spin mechanics will be powerful new mechanical tools for the experimental magnetician’s kit, complementary to existing methods, including fully broadband optomechanical labs-on-a-chip for analysis (magnetometry and resonance spectroscopy) of structures from magnetic nanodevices to nanoparticles.

The fourth international workshop on spin mechanics will be held on February 20–25, 2017 in Lake Louise, Alberta.

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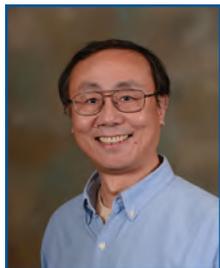
tute for Nanotechnology. The authors also thank David Fortin for the timeline design and 3d renderings (Fig. 1 and Fig. 3a), Fatemeh Fani Sani for micromagnetic simulation (Fig. 3b), and the respective authors for contributing material used in this manuscript.

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# DAWN OF CAVITY SPINTRONICS

BY CAN-MING HU



## HEROES OF SPINTRONICS

**H**eroes are not always stars. This we know from the movies, but it is also true in the community of physicists. In the field of spintronics, my heroes are Robert Silsbee and Mark Johnson. In 1979, Robert H. Silsbee, the 50-year old Cornell University professor on his sabbatical leave at the University of Paris-Sud, published an article in *Physics Review B* with the title “*Coupling between ferromagnetic and conduction-spin-resonance modes at a ferromagnetic-normal-metal interface*”<sup>[1]</sup>. It revealed two new physical characteristics of a spin current. (1) through the microwave excitation of ferromagnetic resonance (FMR), a spin current can be generated in a ferromagnetic metal, which will flow into an adjacent normal metal. (2) Such a spin current pumped by FMR impacts the spin dynamics in the metal via the exchange interaction. Several decades later, from these two effects came Spin Pumping<sup>[2]</sup> and Spin Torque<sup>[3]</sup>, two seminal concepts of contemporary magnetism. Today, every conference on spintronics has celebrated talks on spin pumping. However, Silsbee *et al.*'s ground breaking paper has only been cited about 100 times in four decades. Many students of today studying spin pumping have never read that paper, and some have never even heard of it. The same thing has happened in the history of cinematography. In an era when moviegoers celebrate blockbusters like “*Star Wars*”, few of us remember the epic “*2001, A Space Odyssey*”, a ground breaking work of art produced by Stanley Kubric in 1968, which enlightened George Lucas.

Kubric directed only 16 movies in his life time. He was too meticulous to endure anything but a masterpiece. So was Silsbee, who published only 82 papers. His 1979 paper on spin pumping<sup>[1]</sup> demonstrated optical injection and detection of spin current. That work inspired Silsbee's vision of electrical spin injection and detection, in which a spin current would be generated by a battery and detected by an electrometer. Twenty years later, that vision became

the main theme of spintronics<sup>[4]</sup>. But by then, it was a bold idea. The giant magneto resistance effect (awarded the 2007 Nobel Prize) would be discovered nine years later<sup>[5]</sup>, and the word “spintronics” did not exist. So in 1980, when Silsbee led his PhD student Mark Johnson to explore electrical spin injection into metals, it was not a race. It was a courageous lonely journey into a no man's land, as research in physics can often be.

Johnson's adventure in Ithaca working on spin injection was a scientific odyssey reminiscent of the epics of Homeric heroes. His achievement came after multiple years of failure. It shows that truly original work demands courage more than ideas. The best way to appreciate Johnson and Silsbee's originality and courage is to read their 1985 *PRL* paper<sup>[6]</sup> in comparison with a paper published by Jedema *et al.* in 2002 in *Nature*<sup>[7]</sup>. Silsbee predicted that spin accumulation was inversely proportional to sample volume, but in 1980, there was no clean room at Cornell University for making nano-devices. So Johnson started by developing his own lithography for making small samples. The next challenge was in the measurement. Even in the smallest sample he made for spin injection (where all three dimensions are the order of 100  $\mu\text{m}$ ), the signal was only a few picovolts. To measure it, Johnson designed a special bridge circuit, and used it together with a SQUID voltmeter and a lock-in to beat down noise. The third major obstacle was the spurious magnetoresistance effect in his device, which hampered his progress for years until he invented (together with Andras Janossy) the non-local detection method which measured spin diffusion instead of sending a current directly from the injector to the detector. Finally, to conclusively verify the spin signal, he and Silsbee introduced the Hanle effect<sup>[8]</sup> from atomic physics into condensed matter physics. By using a magnetic field to control spin precession, the Hanle effect became the compass that guided his courageous adventure in spin transport<sup>[6]</sup>.

Decades later, nonlocal detection combined with the Hanle effect would become the norm of performing spin injection and detection experiments. This was neatly shown in Nature's 2002 reproduction of the spin injection experiment<sup>[7]</sup>. As Silsbee predicted, by shrinking the device size from micrometers to nanometers, Johnson's picovolt spin signal detected at cryogenic condition in 1985 was enhanced by four orders of magnitude, so that in 2002 it was measured at room temperature. This shows that

### SUMMARY

**An emerging field of cavity spintronics connects some of the most exciting modern physics, such as quantum information and quantum optics, with one of the oldest sciences on earth, magnetism.**

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spintronics is a nano science. Today, with the great advancement in nanotechnologies, spin current is not only routinely measured in the labs by students, but it is commercially used in new storage devices [see the article “*STT-RAM Memory Devices*”, by Arora *et al.*]. In nano-structured magnetic devices, spintronic effects are often so large, so important, and so useful, that they are transforming the old science of magnetism, and thereby innovating our information and communication technology<sup>[9]</sup>. As will be highlighted in this article, the advancement of spintronics is now merging with the development of cavity techniques used in the field of quantum physics<sup>[10–13]</sup>.

## STARS AND INNOVATORS IN CAVITY QUANTUM ELECTRODYNAMICS

In 2012, the Royal Swedish Academy of Science decided to award the Nobel Prize in Physics to Serge Haroche and David Wineland. They developed ingenious trap<sup>[10]</sup> and cavity<sup>[11]</sup> techniques to measure and manipulate particles in quantum states. Their techniques allow the fundamental interaction between light and matter to be studied in its most elementary form in the quantum regime. Reaching this regime has generated the field of cavity QED<sup>[12]</sup>, and opened the door to a new era of using coherent quantum effects for quantum information processing<sup>[13]</sup>.

Innovative condensed matter physicists are often inspired by atomic physics. In a paper published in 2004 in *Nature*<sup>[14]</sup>, Schoelkopf and his team at Yale University showed how to take cavity QED from Haroche’s atomic world to a solid-state system, by replacing the atoms with a superconducting qubit. Reading Schoelkopf’s paper, some of us working on spintronics immediately had the idea of using a spin two-level system in magnetic materials to couple with photons in the microwave cavity. Doing so would propel the research in magnetization dynamics into a completely new regime of quantum coherent spin-photon coupling, merging spintronics with circuit QED to advance both fields. In 2010, before any experimental pioneers set their footprints on the new land, theoreticians prepared a map of quantum physics<sup>[15]</sup> for the dream world of Cavity Spintronics.

## SETTLERS OF THE CAVITY SPINTRONICS

In a theoretical paper published in *PRL*<sup>[15]</sup>, Michael Flatté and his student at the University of Iowa analyzed the interaction of a nanomagnet with a single photonic mode of a cavity in a fully quantum-mechanical treatment. Their result predicted an exceptionally large quantum-coherent magnon-photon coupling which reaches the strong coupling regime (which means the coupling strength exceeds the dissipation of the coupled system).

Three years later in 2013, the German group of Hans Huebl and Sebastian Goennenwein at the Walther-Meißner-Institut published in *PRL* the first experimental result on magnon-photon coupling<sup>[16]</sup>. They demonstrated how to use microwave transmission experiments to measure at 50 mK the strong

coupling between magnons in a yttrium iron garnet (YIG) and microwave photons in a superconducting coplanar microwave resonator. Huebl is an expert in quantum microwave devices, and Goennenwein is a driving force of spin mechanics. Other Viking explorers arrived at the Newfoundland of cavity spintronics from very different galaxies of physics.

In the galaxy of superconducting device and quantum computing, Yasunobu Nakamura at the University of Tokyo has been a star since he published in 1999 the paper “*Coherent control of macroscopic quantum states in a single-Cooper-pair box*” in *Nature*<sup>[17]</sup>. That was the first demonstration of a practical solid-state qubit which employed the macroscopic quantum coherence. Such a superconducting qubit was what Schoelkopf later used in his circuit QED experiments. In another galaxy, Schoelkopf’s young colleague Hong-Xing Tang at Yale University is a rising star of nano-electromechanical systems and quantum optics. Via the wormhole of quantum coherence, both Nakamura and Tang entered the field of cavity spintronics, setting their feet on the soil of the magnons in magnetic materials.

Both of their studies of magnon-photon coupling were published in 2014, showing how to tune the coupling strength. In Nakamura’s paper<sup>[18]</sup>, the Tokyo team used a variable-sample method. Their experiment was performed at cryogenic temperatures in the quantum regime where the average number of thermally or externally excited magnons and photons was less than one. The experiment of Tang’s group, in contrast, was performed at room temperature. In their paper<sup>[19]</sup>, the Yale team used a variable cavity method to show interesting dynamic features such as classical Rabi-like oscillations, magnetically induced transparency, and the Purcell effect. Comparing both papers, alerted readers may notice that the question arises regarding the distinction between the quantum and classical regime of magnon-photon coupling. That’s the point to which we will return in the next section.

All of these pioneering works done in Germany, Japan, and the USA were performed by measuring microwave spectra of coupled magnet-cavity systems. The vision of Silsbee has taught us that the highway of spintronics is spin transport<sup>[6]</sup>. Building this highway for cavity spintronics requires developing an electrical method to detect the magnons coupled with photons. Here come the Canadian settlers.

For decades in the community of semiconductor physics, electrical detection of charge dynamics has been extensively used<sup>[20]</sup>. Since 2004, our group has set out to expand this technique to study spin dynamics in ferromagnetic metals<sup>[21,22]</sup>. By then, it was nearly a no man’s land. But through a decade of effort by many spintronics groups worldwide, this branch of magnetism is now booming with diverse methods available<sup>[23]</sup>. In the paper entitled “*Spin Pumping in Electrostatically Coupled Magnon-Photon Systems*”<sup>[24]</sup>, which was published in 2015 as a *PRL* Editor’s Suggestion, Lihui Bai and Michael Harder *et al.* at the University of Manitoba used the tool of spin pumping to

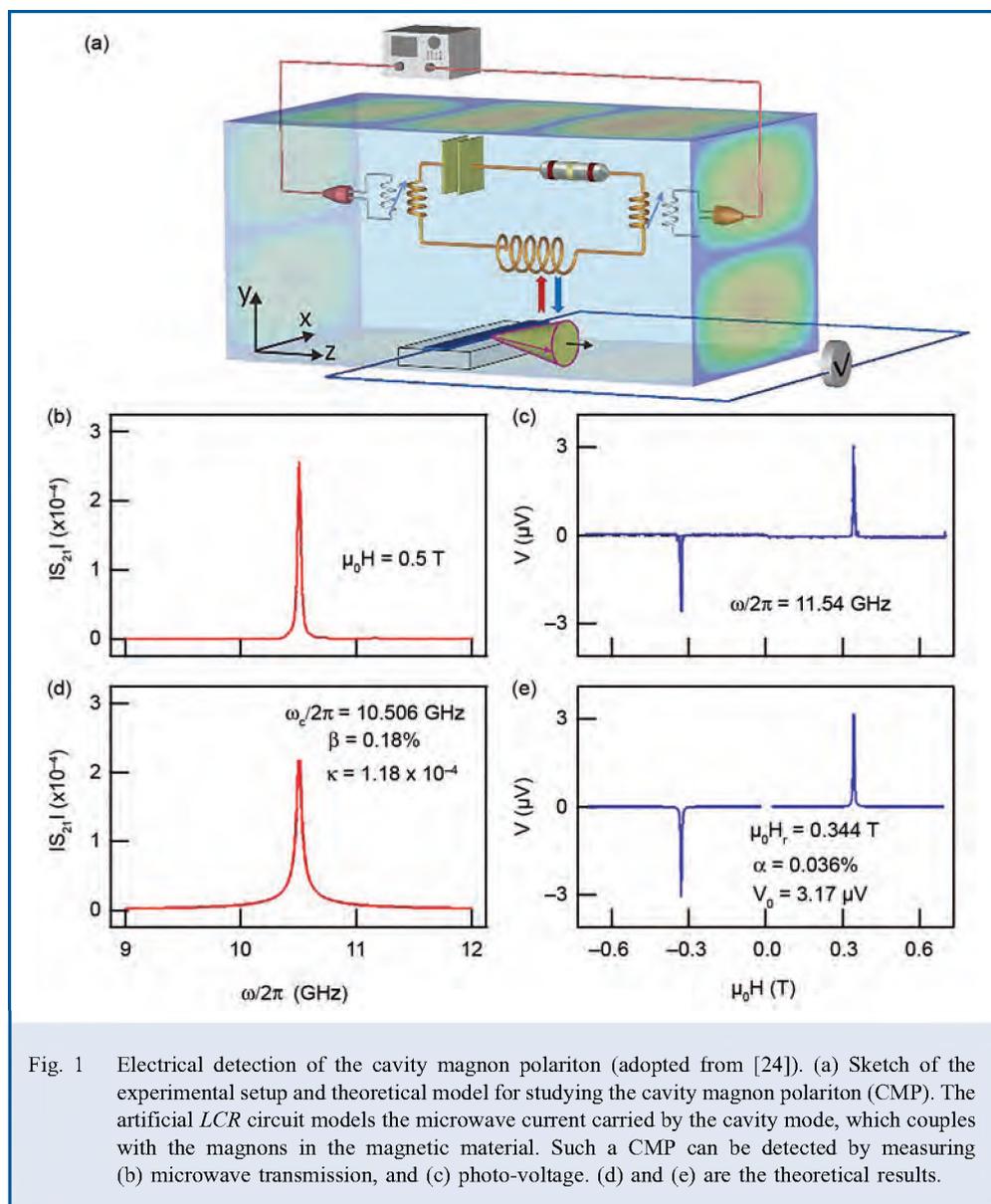
study the magnon-photon coupling. This was achieved by designing a special microwave cavity as schematically shown in Fig. 1. This set-up enables both microwave transmission measurement of the cavity, as well as microwave photo-voltage measurements of the ferromagnet. Setting in the cavity a bilayer device of YIG/Pt fabricated by the group of John Xiao at the University of Delaware, the microwave photo-voltage measured in Pt probes the spin current generated by the FMR in YIG. This enables studying the impact of magnon-photon coupling on the spin transport [25].

Not only that, in contrast to previous studies guided by the theory of quantum strong coupling [15], the Manitoba-Delaware collaboration did not follow the quantum map. Instead, a concise theory was developed showing that the magnon-photon

coupling can be described on the classical footing of electrodynamics [24]. This gives cavity spintronics an alternative classical map.

### QUANTUM OR CLASSICAL PHYSICS, THIS IS THE QUESTION

Initial interest in cavity spintronics was based on a quantum perspective [15]. Via the quantum strong coupling of magnons and photons which generates entangled states of spin orientation and photon number, quantum information can be easily transferred between the light and the magnet via Rabi oscillations [25]. Such quantum entangled states require cryogenic conditions, because the interaction of magnons with phonons through spin-orbit coupling limits the dephasing time at room temperature [15]. That was one of the reasons that the



magnon-photon coupling experiments were initially performed at extremely low temperatures.

Tang *et al.*'s experimental result came as a big surprise. Not only did they demonstrate that the ultrastrong coupling regime can be reached at room temperature, but they also observed directly in the time domain up to 10 cycles of microwave oscillations induced by the magnon-photon coupling. Something must be happening beyond the scope of the quantum map, but the origin of classical magnon-photon coupling was not clear.

That mystery was solved by the Manitoba-Delaware collaboration<sup>[24]</sup>, which singled out the classical origin of magnon-photon coupling: the phase correlation between FMR and the cavity resonance due to classical electrodynamics. Quantum coherence stems from entangled states evolving according to Schrodinger's equation, but Maxwell's equations of macroscopic electromagnetic fields also contain classical coherence. The close resemblance between Schrodinger's equation and Maxwell's equations indicates that the magnon-photon coupling can be either modeled as the quantum coherence of the entangled spin-photon states<sup>[15]</sup>, or be described as the classical coherence of macroscopic electromagnetic fields<sup>[24]</sup>. In light of the classical map<sup>[24]</sup> of the cavity spintronics, an intriguing question arises of how to properly distinguish the quantum and classical regimes for the coupled magnon-photon system. New experiment is designed to search for exclusive quantum features<sup>[26]</sup>. In modern physics, probing the quantum superposition principle at the borderline to classical physics has been a powerful driving force<sup>[10,11]</sup>. Now, cavity spintronics adds new fuel to this engine.

## THE RENAISSANCE OF CAVITY POLARITONS

The classical map<sup>[24]</sup> also leads to another insight. It shows that the eigenvector of the coupled magnon-photon mode is a linear combination of the rf magnetic field and rf magnetization. This is by definition the magnon-polariton<sup>[27]</sup>. Such a new insight links cavity spintronics with the physics of cavity polariton which is an exciting frontier of semiconductor research.

A polariton is an optical effect arising when light couples to a material that has a macroscopic polarization or magnetization. This concept was developed in 1951 by the 32-year-old Chinese physicist Kun Huang<sup>[28,29]</sup>. It was so fundamental that it soon became the "basic knowledge" of solid-state textbooks, which ubiquitously explains the interaction between electromagnetic waves and elementary excitations in materials such as phonons, excitons, and magnons<sup>[27]</sup>.

A renaissance placing the polariton at the frontier of semiconductor research started in 1992 when C. Weisbuch *et al.* published an article<sup>[30]</sup> in *PRL*, showing that the strong coupling of the exciton and cavity photon in a semiconductor microcavity leads to the formation of a cavity exciton polariton, a half-light, half-matter bosonic quasi-particle. Since then, research in that frontier has led to remarkable breakthroughs in

both basic and applied research, such as the discoveries of Bose-Einstein condensation<sup>[31]</sup> and superfluidity<sup>[32]</sup> of cavity exciton polaritons at standard cryogenic temperatures, the room-temperature polariton parametric scattering driven by a polariton condensate<sup>[33]</sup>, and the development of the electrically pumped cavity polariton laser with unsurpassed properties based on the physics of coherent strong coupling<sup>[34]</sup>.

So far, experiments on cavity polaritons are mainly performed in semiconductor materials at optical frequencies, utilizing the strong coupling of excitons with photons<sup>[30-34]</sup>. Now, the classical map of cavity spintronics reveals a new type of cavity polariton: the cavity magnon polariton<sup>[24]</sup> that is based on magnetic materials operating at microwave frequencies. Soon, the strong analogies between the polariton physics of the two different systems may merge the studies of cavity exciton polaritons with the growing interest in cavity magnon polaritons. This may not only lead to a better understanding of the fundamental physics of strong coupling between magnons and photons, but along such an adventure in basic research, new microwave and spintronic applications that are beyond our imagination will emerge.

## CONCLUSION AND FUTURE PERSPECTIVES

In summary, advances in magnetism, nanotechnology, and light-matter interaction have created a new frontier of condensed matter research studying cavity spintronics. Via the quantum physics of spin-photon entanglement on the one hand, and via the classical coherence of electrodynamics on the other, this frontier merges the progress in spintronics with the advances in cavity QED and cavity polaritons. This brief article (with a more comprehensive version posted at arXiv:1508.01966) is focused on reviewing the root of this frontier by tracing it back to some of the most courageous, inspiring, and seminal work in the history of spintronics, cavity QED and polaritons.

Looking forward from the Canadian perspective, the development of cavity spintronics may benefit from the remarkable progress made by Canadian physicists and engineers, in the closely related fields of cavity optomechanics (developed by Mark Freeman, John Davis, Paul Barclay, Jack Sankey, and Aashish Clerk *et al.*, see the article "*Spin Mechanics*" by Losby and Freeman), quantum magnetism (studied by Chris Wiebe and Bruce Gaulin *et al.*), and miniaturized microwave circuits (invented by Lot Shafai and Greg Bridges *et al.*). With the wonderful twilight appearing in the dawn sky of cavity spintronics, perhaps an enjoyable way of imagining its future is listening to the song<sup>[35]</sup>:

*I am the dawn, I'm the new day begun  
I bring you the morning, I bring you the sun  
I hold back the night and I open the skies  
I give light to the world, I give sight to your eyes  
I am the sky and the dawn and the sun*

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# ELECTRONIC TRANSPORT IN MAGNETIC TUNNEL JUNCTION: A DISCUSSION OF THE ELECTRON-MAGNON-PHOTON COUPLING

BY YANG XIAO AND HONG GUO

One of the most useful spintronics phenomena [1] is the tunnel magnetoresistance (TMR) observed in magnetic tunnel junctions (MTJs). An MTJ is a tunnel structure where two ferromagnetic layers (FM) sandwich a thin insulating barrier. The tunneling current  $I_{\uparrow\uparrow}$  is large when magnetic moments of the two FM layers are in parallel configuration (PC,  $\uparrow\uparrow$ ), and  $I_{\uparrow\downarrow}$  is small when they are antiparallel (APC,  $\uparrow\downarrow$ ). Due to this binary nature, MTJs have become the elementary unit of the magnetic random access memory (MRAM) technology [2,3]. From a practical point of view, extensive research has focused on producing MTJs having a large TMR ratio [4-6] which is defined as  $(I_{\uparrow\uparrow} - I_{\uparrow\downarrow}) / I_{\uparrow\downarrow}$ ; improving switching capability between PC and APC using advanced techniques based on spin transfer torque [7], and improving the material properties etc.

Being very sensitive to external magnetic field, MTJs have been used as field sensors, e.g., read sensors in hard drives [4-6]. Due to suitable energetics, MTJs have recently been applied in microwave sensing [8] and even microwave imaging by phase-sensitive detection techniques [9]. Spintronics-based microwave technology is a very exciting new direction of nanotechnology whose principle is totally different from the conventional radar approach. When a magnetic system (e.g., an MTJ) is subjected to microwave radiation, complicated spin dynamics may occur which influences spin-polarized charge transport in the system, and microwave sensing is achieved by electrical detection of the changes of the transport signal. Microwave rectification [10-12], e.g. the generation of a DC electric current by magnetization dynamics, is such a transport phenomenon characterized by charge or spin currents. It is now generally accepted that several physical mechanisms including spin rectification [11], spin pumping [10], spin torque diode effects [12],

etc., can co-exist in a device to produce the observed radio-frequency sensing data in metal spintronics.

Fig. 1 shows a typical model of MTJs where the left/right leads are FM metals (for instance Fe) and the device region is a very thin insulating tunnel barrier (for instance YIG). In an MTJ, electrons are driven to quantum mechanically tunnel through by an external bias voltage  $V$ . In a microwave rectification experiment, a static magnetic field  $\vec{H}_{ext}$  is applied to induce spin precession around it. The precession is eventually damped out by various relaxation processes in the material. A microwave field with wave vector  $\vec{k}$  can be applied to deflect the spins from the direction of  $\vec{H}_{ext}$  and to maintain a stable spin precession by overcoming the damping processes. Since resistance oscillates with the orientation and magnitude of the magnetization due to various physical mechanisms, the oscillating current and oscillating resistance produce an AC voltage that has a DC component across the sample. Such a rectification was experimentally demonstrated in Ref. [13]. Reversely, by detecting the DC signal, the device acts as a microwave sensor.



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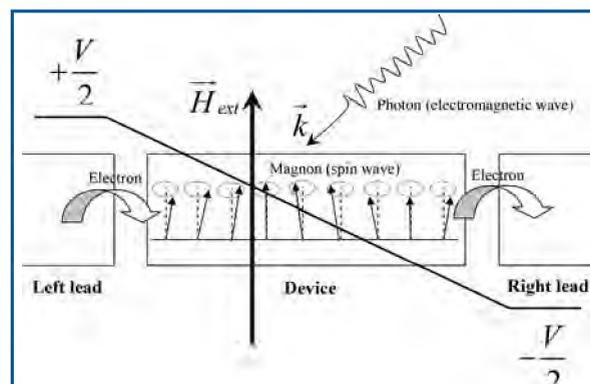


Fig. 1 Theoretical model of an MTJ. Two leads are biased with a voltage  $V$ . The external magnetic field  $H_{ext}$  and a microwave are applied. The spin wave is shown in central region.

## SUMMARY

We present a pedagogical discussion on electron transport in magnetic tunnel junctions under the electron-magnon-photon interaction.

In the device model of Fig. 1, conduction electrons, precessing magnetic moments, and electromagnetic fields are all present<sup>1</sup>. The collective motion of the magnetic moments is a spin wave and its quantize version is a magnon. Similarly, the quantum of the electromagnetic field is a photon. In principle, quantum transport in such systems involves interactions between electrons, magnons and photons, and the outcome can be quite complicated depending on the coupling strengths between each pair of them. It is the purpose of this article to present a pedagogical discussion of this coupling and its implication to quantum transport. Our discussion is summarized from the outcome of rigorous mathematical derivations using the Keldysh nonequilibrium Green's function (NEGF) formalism<sup>[14]</sup>, which is summarized elsewhere<sup>[15]</sup>.

The rest of this article is organized as follows. The next section presents a device model as the example for discussion. In the section entitled “*Boson Assisted Transport Processes*”, the well-known inelastic tunneling and boson-assisted tunneling are discussed. Depending on the coupling strength of magnon-photon interaction, weak coupling and strong coupling regimes are recognized and discussed in the sections entitled “*Weak Coupling*” and “*Strong Coupling*” respectively. Finally, the section entitled “*Perspective*” presents a short conclusion and discussion on future perspectives.

## THE DEVICE MODEL

The Hamiltonian of the device model in Fig. 1 can be written in the following form,

$$H = H_\alpha + H_d + H_t \quad (1)$$

where  $H_\alpha = \sum_{\alpha,k} \epsilon_{\alpha,k} d_{\alpha,k}^\dagger d_{\alpha,k}$  is the Hamiltonian of the left and right leads of the device ( $\alpha = L, R$ ),  $k$  indicates the quantum states of the leads,  $d_{\alpha,k}^\dagger$  ( $d_{\alpha,k}$ ) are the creation (annihilation) operators of electrons in lead  $\alpha$ , and  $\epsilon_{\alpha,k}$  is the energy of the electrons. The simplest form of the Hamiltonian for the central region of the device (see Fig. 1) is,

$$\begin{aligned} H_d = & \sum_e \epsilon_e c_e^\dagger c_e + \sum_p \epsilon_p a_p^\dagger a_p + \sum_m \epsilon_m b_m^\dagger b_m \\ & + \sum_{e,p} g_{ep} c_e^\dagger c_e [a_p^\dagger + a_p] + \sum_{e,m} g_{em} c_e^\dagger c_e [b_m^\dagger + b_m] \\ & + \sum_{m,p} g_{mp} [a_p^\dagger b_m + a_p b_m^\dagger], \end{aligned} \quad (2)$$

where the first three terms represent energies of bare electrons, photons and magnons; the last three terms represent electron-

photon, electron-magnon and magnon-photon interactions.  $c_e^\dagger$  ( $c_e$ ),  $a_p^\dagger$  ( $a_p$ ) and  $b_m^\dagger$  ( $b_m$ ) are the creation (annihilation) operators of electron, photon and magnon with eigen-energy  $\epsilon_e$ ,  $\epsilon_p$  and  $\epsilon_m$ , respectively.  $g_{ep}$ ,  $g_{em}$  and  $g_{mp}$  represent the coupling strength of electron-photon, electron-magnon and magnon-photon interactions. Here the electron-electron interaction is neglected for simplicity. Finally, the central region of the device is coupled to the leads by the Hamiltonian  $H_t$  in the familiar form<sup>[14]</sup> of  $H_t \sim d_k^\dagger c_e$ . In the above model, the left and right leads play the role of source and drain for electrons traversing the central region.

The electric current flowing from the left lead to the device can be derived by the standard Green's function theory<sup>[14,16]</sup>,

$$J_L = \frac{e}{\hbar} \int \frac{dE}{2\pi} \text{Tr}(\Sigma_L^< G^> - \Sigma_L^> G^<), \quad (3)$$

where  $e$  and  $\hbar$  are elementary charge and reduced Planck constant.  $\Sigma_L^>$  is the lesser/greater self-energy of the leads which reflects the electron scattering rates from the leads to the central part of the device.  $G^>$  is the lesser/greater Green's function of the device which describes the electron/hole density matrix. The physical meaning of Eq. (3) is clear:  $\Sigma_L^< G^>$  and  $\Sigma_L^> G^<$  represent the forward and backward tunnelling current and thus the difference constitutes the net current in the left lead. The Green's function  $G$  is the most important quantity in our theory which can be calculated by a perturbation-like series expansion<sup>[17]</sup>,

$$\begin{aligned} G(t-t') = & \sum_{n=0}^{\infty} \frac{(-i)^{n+1}}{n!} \int_{-\infty}^{\infty} dt_1 \cdots \int_{-\infty}^{\infty} dt_n \\ & \times \langle \phi | T c(t) V(t_1) \cdots V(t_n) c^\dagger(t') | \phi \rangle, \end{aligned} \quad (4)$$

where  $V(t)$  is the various interactions such as those appearing in Eq. (2),  $|\phi\rangle$  is the ground state,  $T$  is time-ordering operator. Although the Green's function consists of infinite terms in general, we shall only consider the lowest order terms. The  $n = 0$  term in Eq. (4) is the Green's function in the absence of any interaction; the  $n = 2$  and  $n = 4$  terms will be emphasized in the sections which follow.

For simplicity of the discussion, we shall consider a quantum dot model for the center part of the device having one energy level  $\epsilon_e$ , photons with a single energy  $\epsilon_p$ , and a single mode in the magnon spectrum. As a result, the summations over the quantum indices in Eq. (2) are dropped. In addition, the left/right leads and the lead-device coupling are described by interaction-free electron reservoirs. For more details of the calculation of  $J_L$ , we refer interested readers to Ref. [18].

1. The model in Fig. 1 is somewhat different from an usual MTJ which has non-magnetic spacer where magnons are excited at the proximity region between the ferromagnetic electrodes and the spacer. To focus on magnon-related tunneling physics while avoiding complications of proximity effect, here we consider a magnetic insulator as the spacer. This does not affect the tunneling nature of the usual MTJ.

**BOSON-ASSISTED TRANSPORT PROCESSES**

Since magnons and photons are bosons, we start by discussing quantum tunneling in MTJ assisted by these boson fields. It has been well understood, both theoretically and experimentally, that boson-like particles can enhance electron transmission [19]. From a theoretical point of view, substituting the interaction  $V = g_{ep}c^\dagger c[a^\dagger + a] + g_{em}c^\dagger c[b^\dagger + b]$  of Eq. (2) into Eq. (4), the  $n = 2$  terms of the Green's function reflect electron scattering by the one-boson processes (magnon or photon) with the physical mechanism depicted in Fig. 2(a,b). Fig. 2(a) is for the simple case of excitation where an electron enters the central device region from the left lead, it absorbs a boson (e.g.,

magnon or photon), gets excited to high enough energy that allows it to exit to the right lead. For this situation, direct tunneling is clearly impossible at zero external bias. Fig. 2(b) is for the bias situation where direct tunneling is possible but can be further assisted by emitting bosons to open up more transmission channels for exiting the device. This process leads to the well-known inelastic tunneling spectroscopy [20] (IETS). The boson-assisted processes depend on boson frequency and wave vector, hence the assisted tunneling spectra can be used to detect the frequency (energy) of the bosons: IETS has already been employed to detect the mode frequency of phonons and magnons in a number of experiments [21]. Fig. 2(d) and (e) show inelastic current ( $I_{ine}$ ) arising from the

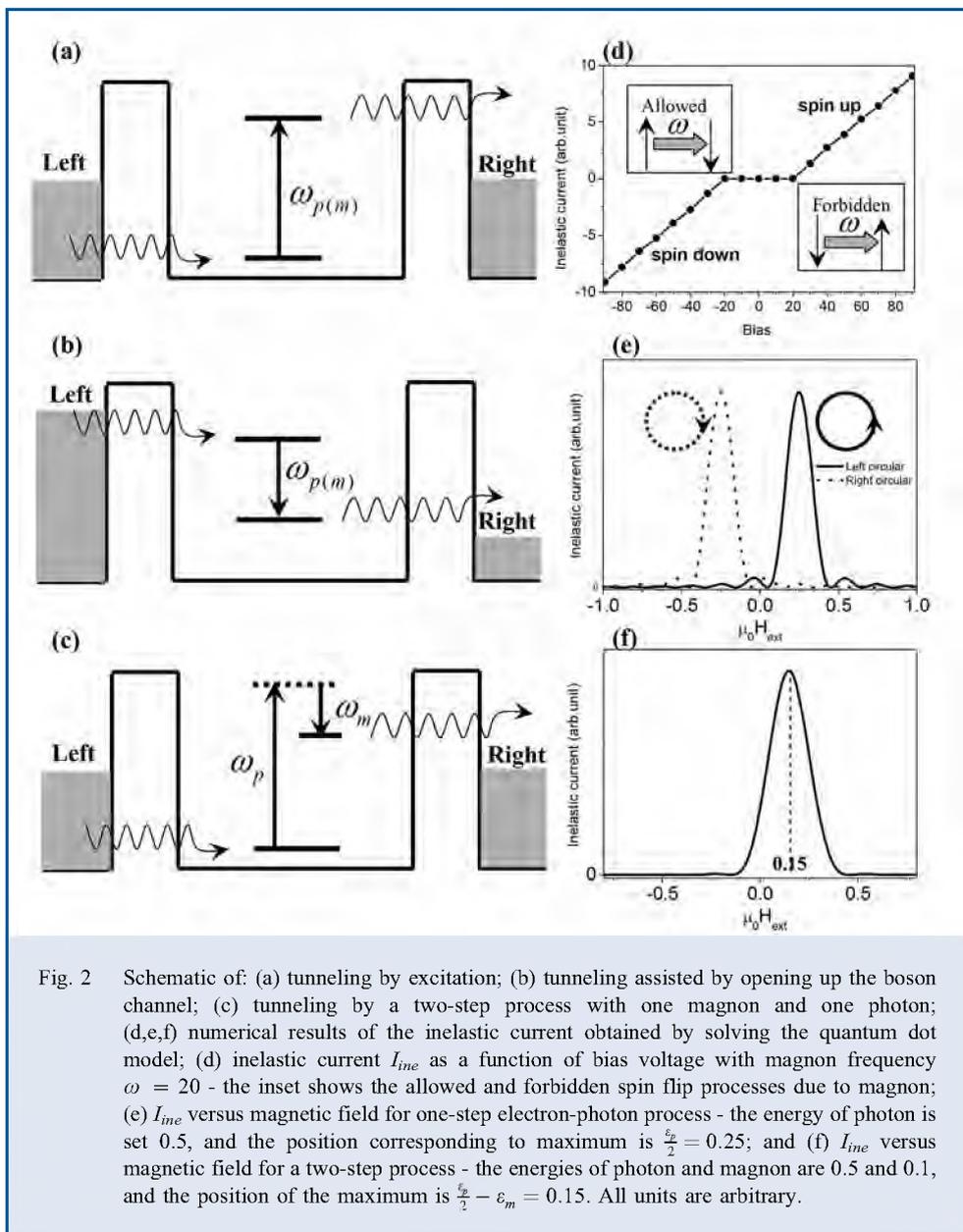


Fig. 2 Schematic of: (a) tunneling by excitation; (b) tunneling assisted by opening up the boson channel; (c) tunneling by a two-step process with one magnon and one photon; (d,e,f) numerical results of the inelastic current obtained by solving the quantum dot model; (d) inelastic current  $I_{ine}$  as a function of bias voltage with magnon frequency  $\omega = 20$  - the inset shows the allowed and forbidden spin flip processes due to magnon; (e)  $I_{ine}$  versus magnetic field for one-step electron-photon process - the energy of photon is set 0.5, and the position corresponding to maximum is  $\frac{\varepsilon_p}{2} = 0.25$ ; and (f)  $I_{ine}$  versus magnetic field for a two-step process - the energies of photon and magnon are 0.5 and 0.1, and the position of the maximum is  $\frac{\varepsilon_p}{2} - \varepsilon_m = 0.15$ . All units are arbitrary.

magnon- or photon-assisted tunneling. The numerical curves were obtained by calculations of the quantum dot model. In IETS, below a threshold voltage only direct tunneling can occur due to the quantum nature of the boson. Above this threshold voltage, the assisted tunneling starts to contribute to the current, see Fig. 2(d). The value of the threshold voltage gives a direct measure of the boson energy or frequency. The IETS of magnon or photon can be made possible by varying the magnetic field instead of the bias voltage, as shown in Fig. 2(e). Moreover, due to the fact that magnon or circularly-polarized photon holds one spin angular momentum, the tunneling current is spin polarized when bias voltage or magnetic field is changing, as shown in Fig. 2(d) and (e).

The processes in Fig. 2(a) and (b) involve absorption or emission of a single boson. For the MTJ device in Fig. 1, there are two kinds of bosonic particles, magnon and photon. It is interesting to understand how the two bosonic particles influence electronic transport together. In particular, for the microwave sensing with MTJs, electron-magnon, electron-photon and magnon-photon couplings occur at the same time. In general, the coupling strength varies with the specific details of the MTJ device and material. Depending on the coupling strength of the magnon-photon interaction, the device can be characterized as being in the “weak coupling regime” or “strong coupling regime”.

## WEAK COUPLING

The direct coupling between magnon and photon, i.e. the parameter  $g_{mp}$  in Eq. (2), is usually very small and thus can be omitted [22]. This is the weak coupling regime. To first order ( $n = 2$ ) of the electron-boson coupling strength, one obtains magnon-assisted tunneling and/or photon-assisted tunneling respectively- the well-known physics was discussed in the last section (Fig. 2(a) and (b)).

The second order treatment can be worked out by the Green's function formalism to reveal a two-step sequential tunneling process. The basic idea is to consider the  $n = 4$  terms in Eq. (4). The  $n = 4$  terms consist of three terms describing electron scattering with two magnons, with two photons, and with one magnon plus one photon. Apart from the two-boson nature, the former two terms have nothing new compared with the simple physics described in the last section. The last term, shown in Fig. 2(c), depicts where the incoming electron first absorbs a photon and then emits a magnon. Based on quantum dot calculation shown in Fig. 2(f), one could see that  $I_{me}$  of such a two-step sequential process is on resonance at the magnetic field determined by the frequency difference between the magnon and photon. The reverse process is theoretically allowed but is not dominant for low-intensity microwave fields. Although such a two-step photon-magnon process has not been observed experimentally so far, its *phonon* counter-

part – the two-step photon-phonon process, has been subjected to extensive investigations both theoretically and experimentally in the semiconductor literature [15].

## STRONG COUPLING

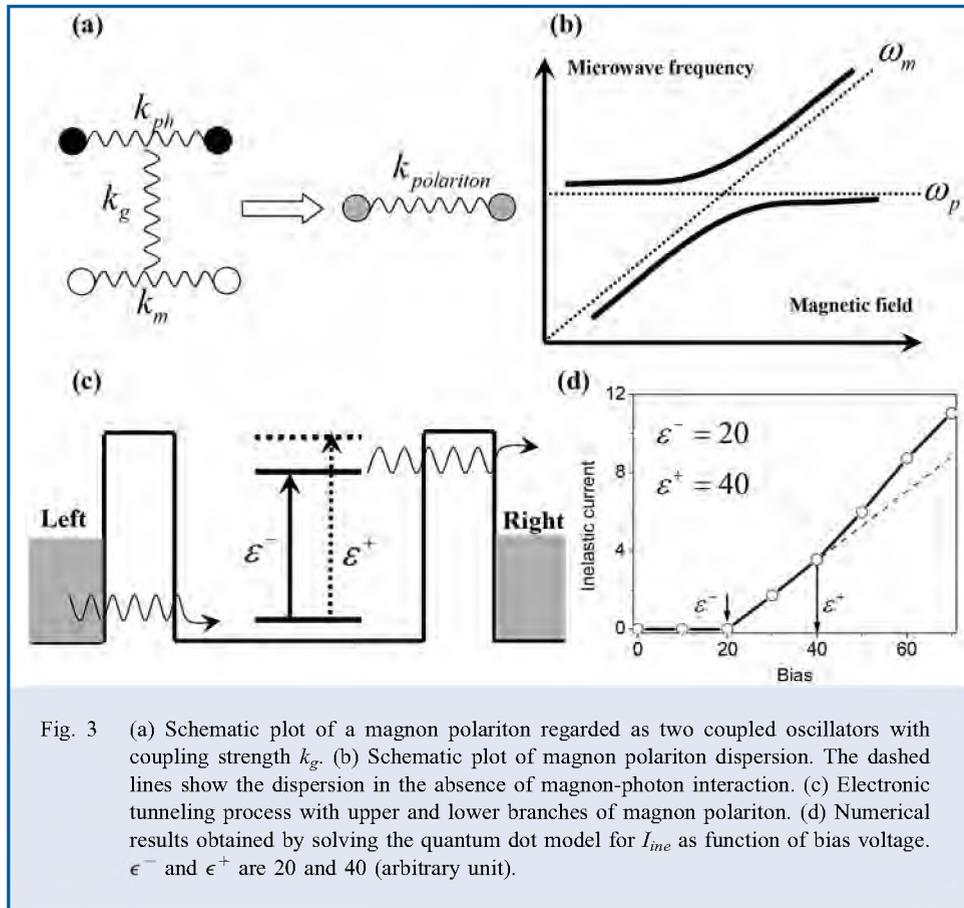
A strong coupling between magnon and photon is perhaps the most interesting situation. As mentioned above, for a long time the direct coupling between magnon and photon has been neglected. Experimentally, this was due to the achievable quality factor (Q) of cavity and low-spin density of magnetic materials which lead to very small coupling  $g_{mp}$ . Thanks to advances in fabrication techniques of high-Q cavity and pure single-crystalline magnetic insulator YIG, strong coupling via magnetic dipole between photon and magnon has been realized recently [23–26]. The well-established systems – consisting of the cavity and ferromagnetic resonance (FMR) set-up, enable strong and even ultra-strong coupling with strength up to a few GHz. Such a coupled system is usually called magnon polariton. Recently, magnon polariton has been observed experimentally at both ultralow temperature (0.01 K) and room temperature [23–26]. The co-existence at low and high temperatures has led one to consider the quantum and classical nature of the processes [see the article “Dawn of cavity spintronics” by C.M. Hu in the same issue].

For strong coupling, the theoretical treatment of Eq. (2) is more complicated than that for weak coupling since all three coupling parameters must be included. Note that the coupling strength of electron-photon/magnon can be  $\sim 100$  meV while the magnon-photon coupling can be up to  $\sim 0.01$  meV, hence the magnon-photon coupling can still be treated perturbatively. A qualitative picture can be obtained as follows. We first solve the magnon and photon Hamiltonian  $H_{mp} = \epsilon_p a^\dagger a + \epsilon_m b^\dagger b + g_{mp} [a^\dagger b + ab^\dagger]$  with the Bogoliubov transformation  $a = A \cos \theta + B \sin \theta$  and  $b = B \cos \theta - A \sin \theta$ . The Hamiltonian is then diagonalized,  $H_{mp} = \epsilon^+ A^\dagger A + \epsilon^- B^\dagger B$ , by adjusting the parameter  $\theta$ . Substituting the above transformation into the remaining terms of Eq. (2), we obtain a reduced polariton Hamiltonian,

$$H_d = \epsilon_e c^\dagger c + \sum_{d=A,B} \{ \epsilon^\pm d^\dagger d + g_{e\pm} c^\dagger c [d^\dagger + d] \}, \quad (5)$$

where  $d = A(B)$  are operators for upper(lower) branches of polariton with eigen-energy  $\epsilon^\pm$  and interaction strength  $g_{e+} = g_{ep} \cos \theta - g_{em} \sin \theta$  and  $g_{e-} = g_{ep} \sin \theta + g_{em} \cos \theta$  respectively.

The polariton Hamiltonian Eq. (5) indicates that the magnon-photon interaction produces magnon polariton with an upper and a lower branch schematically shown in Fig. 3(a) where, roughly, the photon, magnon and magnon polariton are thought of as harmonic oscillators. The dispersion of upper and lower branches, i.e.,  $\epsilon^\pm$ , are shown in Fig. 3(b). Due to formations of the magnon polariton, the electron-magnon and electron-photon interaction strengths are renormalized to give



the interaction strengths between the electron and upper/lower branches of magnon polariton.

Having understood the elementary excitations in the device scattering region, new features of electron tunneling are expected due to the presence of magnon polariton. First, from the Bogoliubov transformation, we have  $[A, A^\dagger] = 1$  and  $[A, B^\dagger] = 0$ , which indicates that polariton obeys bosonic statistics. Consequently, a new tunneling behavior is expected, i.e., polariton-assisted tunneling in MTJs where electron transitions take place for both the upper and lower branches as shown in Fig. 3(c). Therefore, as seen in Fig. 3(d) which plots the numerical curves obtained by solving the quantum dot model,  $I_{ine}$  will be enhanced at both  $\epsilon^+$  and  $\epsilon^-$  as bias voltage increases. Second, the energy of a polariton can be tuned by the external magnetic field and microwave frequency. Such tunability adds extra degrees of freedom into electronic transport in addition to bias and gate voltage used in conventional devices. Third, an asymmetry appears in the tunneling current for the upper and lower branches. Based on Eqs. (3), (4) and (5), the inelastic tunneling current is proportional to the square of electron-boson coupling strength ( $n = 2$ ). Due to different strengths for coupling to the upper

and lower polariton branches, the tunneling current develops an asymmetric structure. This feature could be used to detect the existence of magnon polariton in transport measurements. Further details of these transport features will be presented elsewhere<sup>[15]</sup>.

## PERSPECTIVE

In this short article we have presented a paralogical discussion of the tunneling physics induced by the electron-magnon-photon interaction which is realized in microwave-irradiated MTJ devices. For the two-step tunneling, an important task is to make proper connections between theoretical results and experimental measurements. For magnon polariton, there is a need for a theoretical framework to calculate charge current and spin current in a strong coupling regime. Recently, spin current observed in a spin-pumping experiment in the strong coupling regime has been reported by Bai *et al.*<sup>[23]</sup>. In theory, the inclusion of a magnon-photon interaction produces new self-energy terms which make the time-dependent problem more difficult to solve. Another important question is how spin current varies when nonclassical states of photons are used. If a Fock state or squeezed state of photon is prepared

in a magnon polariton experiment successfully, the quantum nature of magnon polariton may be recognized without ambiguity. A new theoretical development is desired to predict the transport of spin current arising from such a nonclassical light. We wish to report these developments in the near future.

## ACKNOWLEDGEMENTS

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# STT-RAM MEMORY DEVICES

BY MONIKA ARORA, TOMMY MCKINNON, BRETT HEINRICH, EROL GIRT, CIARAN FOWLEY, EWA KOWALSKA, VOLKER SLUKA, AND ALINA MARIA DEAC

Over the past decades, the amount of digital information is increasing tenfold every five years. According to a report prepared by International Data Corporation (IDC) in 2014, the total amount of digital data generated globally will reach 44 ZB (1 ZB =  $10^3$ , EB =  $10^6$ , PB =  $10^{12}$ GB) by 2020 <sup>[1]</sup>. Hard drives are the most inexpensive devices used to store digital information that is infrequently accessed and stored for a long time. Hard drives, like magnetic tapes, have large storage capacity, however they are physically larger in size and slower in speed than the solid-state drives (SSD). Moreover, they have movable parts, which makes them more prone to damage and read/write errors.

As of now, there are three main types of solid-state semiconductor storage devices: static RAM (SRAM), dynamic RAM (DRAM), and flash memory. These are charge based solid-state electronic random access memories (RAMs) and each one of these has some merits and demerits. DRAM is being used as the main memory in all forms of modern computing devices. It is comprised of a single MOSFET (Metal-oxide semiconductor field-effect transistor) and a capacitor, which needs to be frequently refreshed as the capacitor leaks and the DRAM forgets its state. SRAM does not need to be refreshed. It is composed of 4–6 transistors, which makes SRAM much faster but requires more chip space. Flash memories have a very high density but comparatively low write speeds and endurance <sup>[2,3]</sup>. In this context, endurance means the number of read/write cycles a memory cell can go through before degradation occurs. Recently, in August 2015, Samsung introduced the world's largest solid state flash memory having 16TB storage capacity packed in a 2.5" case <sup>[4]</sup>.

## SUMMARY

The interaction between spin polarized current and local magnetic moment is studied in magnetic nanopillars for the use in future solid state STT-RAM memory devices.

The demand for improved memory has led to the emergence of new memory types. It was recently discovered that the interaction between the spin polarized current and the localized magnetic moment of a ferromagnet (FM) can induce magnetization reversal <sup>[5,6]</sup>. This effect is known as spin transfer torque (STT) and has been used to develop novel STT-RAM solid state memory devices. Spin transfer torque is mostly studied in nanopillars that consist of two ferromagnetic (FM) layers separated by a thin non-magnetic layer <sup>[6]</sup>. The first FM layer, the reference layer (RL), is used to create a spin-polarized current which then passes through the non-magnetic (NM) layer without a significant change in polarization and interacts with the second FM layer, the free layer (FL). This interaction exerts a spin torque on the magnetic moment of the free layer (FL) through a transfer of angular momentum from the polarized current to the FL magnetization. The device resistance depends on the relative orientation of the magnetic layers (parallel low resistance, and antiparallel high resistance), giving rise to giant magnetoresistance, GMR, if NM is metallic, or tunnel magnetoresistance, TMR, if NM is insulator <sup>[7–9]</sup>. If the polarized current density is large enough  $> 10^6$  A/cm<sup>2</sup>, the spin torque will induce magnetization reversal in the FL <sup>[6]</sup>.

STT-RAM is a non-volatile random-access magnetic memory (it retains its information when power is turned off) that suffers no degradation over time and has no moving parts <sup>[10]</sup>. It is also much faster than flash memory <sup>[11]</sup>. In STT-RAM, information is recorded by inducing magnetization reversal in the FL. GMR or TMR is then used to detect the magnetization direction of the FL <sup>[12,13]</sup>. In high frequency electronics impedance matching is extremely important. Although the signal for the GMR devices is smaller than that of the TMR devices, impedance matching of the GMR devices with the circuit is much easier to achieve due to their significantly lower resistance <sup>[14]</sup>. Use of TMR devices for microwave sensing is discussed in the article “Electronic transport in magnetic tunnel junction: a discussion of the electron-magnon-photon coupling” by Hong Guo and Y. Xiao.

Recently, there has been a lot of industrial effort to develop STT-RAM due to its high recording density, fast write/read speed (a few ns), unlimited endurance,



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excellent scalability and potential of low power consumption<sup>[15]</sup>. One of the main difficulties in achieving this goal is that, the critical current density needed to reorient the magnetization is at present too high. For this reason, finding ways to minimize the critical current is the focus of intense research in both industrial and academic circles. In July 2015, Avalanche technology has announced the availability of its high-speed, non-volatile, 32/64Mbit STT-RAM magnetic memory<sup>[16]</sup>. Other companies working on STT-RAM include Everspin, IBM, Intel, IMEC, FUJITSU, GRANDIS, Hynix, Crocus Technology<sup>[17]</sup>, and Spin Transfer Technologies<sup>[18,19]</sup>.

In the macrospin approximation, the critical current required for spin-transfer reversal from P to AP and from AP to P state is given by<sup>[20]</sup>

$$I_c = -\left(\frac{2e}{\hbar}\right) \frac{\alpha M_s V_{FL}}{g(\theta)p} H_{eff} \quad (1)$$

where  $M_s$ ,  $\alpha$ , and  $V_{FL}$  are the saturation magnetization, intrinsic Gilbert damping constant, and volume of the FL, respectively,  $p$  is the spin polarization of the current collinear with the RL magnetization, and  $g(\theta)$  is a pre-factor depending on the relative angle between the RL and the FL. The effective field acting on the perpendicularly magnetized FL,  $H_{eff} = \mp H_k \pm 4\pi M_s + H_{app} + H_{dip}$ , has contributions from magnetic anisotropy field  $H_k$ , demagnetizing field  $4\pi M_s$ , applied field  $H_{app}$ , and the dipolar field from the reference layer  $H_{dip}$ .

In this paper, we have designed a RL having a synthetic antiferromagnet (SAF) structure to minimize the dipolar interaction,  $H_{dip}$ , between the RL and the FL and hence reduce  $H_{eff}$ . We are not aware of any investigations of devices with SAF layer consisting solely of Co/Ni multilayers. Most research to date has used a combination of Co/Pd, Co/Pt, Co/Ni and CoFe layers in SAF to increase the anisotropy<sup>[20–23]</sup>.  $I_c$  decreases in FL's with perpendicular magnetic anisotropy<sup>[24]</sup>. To minimize  $I_c$  we used FL with a Co/Ni multilayer structure. Co/Ni multilayers have perpendicular anisotropy, low damping  $\alpha$ , and high spin polarization  $p$ <sup>[24,25]</sup>, which from Equation 1 are desirable for low  $I_c$ .

## EXPERIMENTAL DETAILS

The magnetic multilayer films are deposited on Si(001) wafers by magnetron sputtering in a high vacuum deposition system with a base pressure of  $7 \times 10^{-8}$  Torr. The Si wafers are covered with a 100 nm SiO<sub>2</sub> layer to electrically isolate the wafer and metallic films. The sputtering parameters and the thicknesses of the individual layers are varied to optimize the magnetic properties of the (111) textured SAF/Cu/FL multilayer film structures. The SAF consists of two FM layers, FM1 and FM2, antiferromagnetically coupled across a Ru spacer layer of thickness 0.4 nm. FM1 is composed of  $4 \times [\text{Co}(0.2)/\text{Ni}(0.6)]/\text{Co}(0.4)$ , FM2 is  $\text{Co}(0.4)/3 \times [\text{Ni}(0.6)/\text{Co}(0.2)]/\text{Ni}(0.6)/\text{Co}(0.6)$ , and the FL is  $4 \times [\text{Co}(0.2)/\text{Ni}(0.6)]$  (thicknesses are in nm).

3 nm of Cu is deposited as a spacer to decouple the SAF and the FL. To maximize the GMR effect in our structures, a thin Co layer is deposited on both sides of the Cu spacer layer. Ta(3 nm)/Cu(30 nm) are used as a bottom contact. The Ta/Cu bilayer structure also helps set up the (111) growth orientation for Co/Ni multilayers. For corrosion protection, the sample is covered by Ta(3 nm)/Ru(7 nm). The full STT MRAM structure is shown in Fig. 1a.

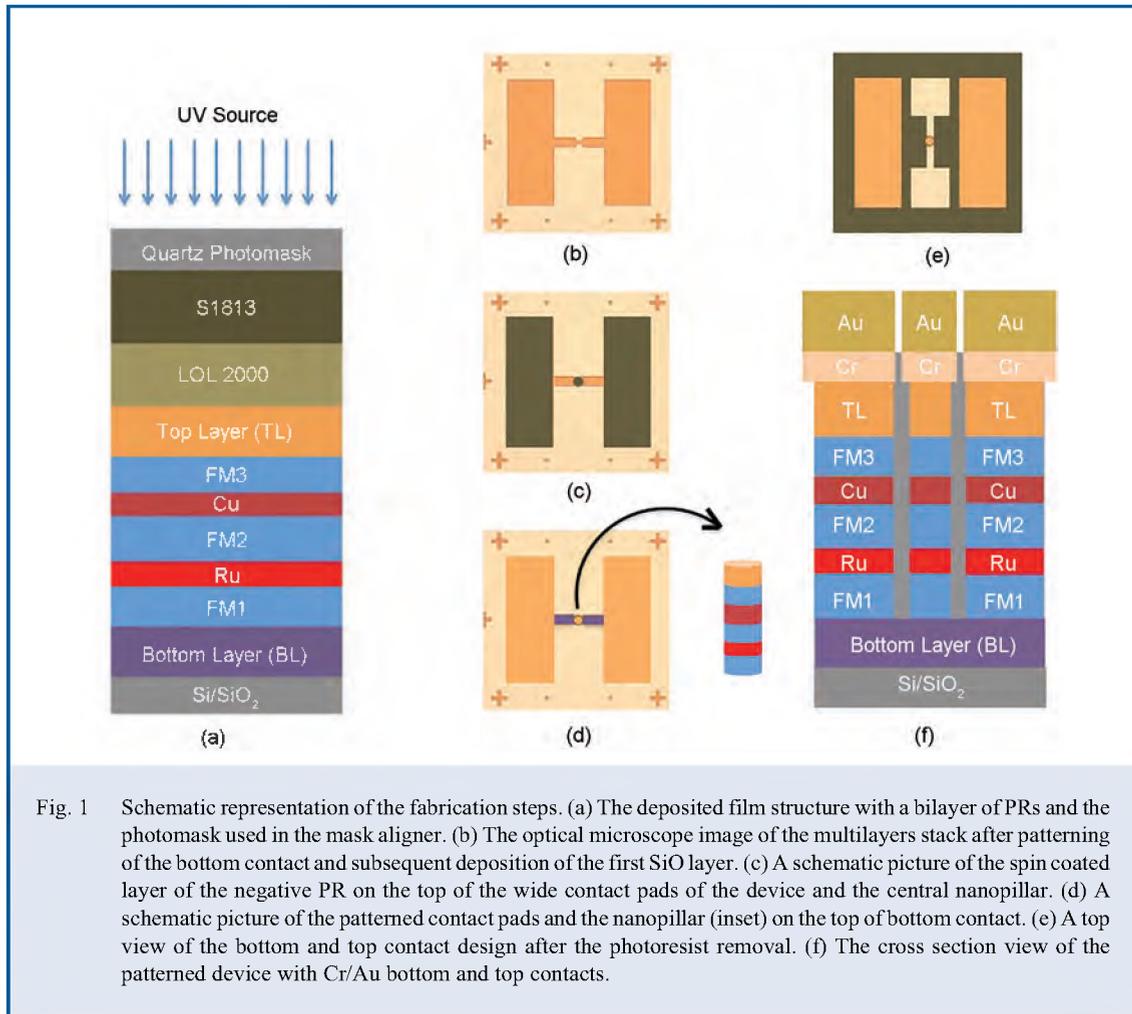
The sputtered films are cleaned in an ultrasonic acetone wash followed by isopropanol rinse then blown dry in N<sub>2</sub>. The films are coated with a bilayer of photoresist (PR) LOL2000 (200 nm) and S1813 (1.3  $\mu\text{m}$ ) using a vacuum spin coater. The substrate is baked to drive out the excess solvent from the PRs. LOL 2000 is not UV sensitive and its role is to help complete liftoff of S1813. The sample with a photomask (Fig. 1a) is then loaded into the UV exposure tool and exposed. The films are developed in MF-319 and rinsed in de-ionised water. The areas not protected by the PRs are etched until the Si/SiO<sub>2</sub> substrate in an ion-milling tool using Ar<sup>+</sup> ions. SiO (70nm) is deposited by electron beam evaporation to fill up the etched portion of the structure and electrically isolate the individual devices. Samples were soaked in 1165 remover (NMP-based) and placed in an ultrasonic bath to liftoff the unwanted photoresist. A single patterned device image taken by an optical microscope is shown in Fig. 1b.

After cleaning the samples, a negative photoresist maN-2403 (300 nm) is used to coat the patterned films. E-beam lithography (EBL) is used to expose the wide side contact pads (200  $\times$  50  $\mu\text{m}$ ) of H-shaped devices and the central circular area of diameter 200 nm Fig. 1c. Any unexposed resist is removed with maD-525 developer. The sample is then etched using Ar<sup>+</sup> ions until the Cu bottom layer, used as an electrical contact between the contact pads and the nanopillar. A 40 nm layer of SiO is deposited by thermal evaporation. This is shown in Fig. 1d, where the inset figure shows the 3D structure of the nanopillar. Acetone and 1165 are again used for PRs liftoff.

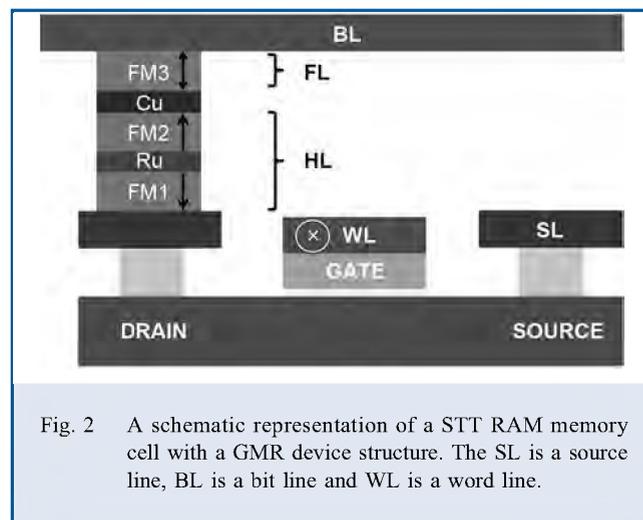
We again spin coat the bilayer of PRs on the top of the sample surface. UV light is used to expose the wide contact pads of the H device and the top contact area for the 200 nm nanopillar between the contact pads. The developed pattern is shown in Fig. 1e, where the olive green area represent the PRs. The device structure obtained after the deposition of Cr(5nm)/Au(125nm) layers on the top of sample surface and photoresist liftoff is presented in Fig. 1f (cross section).

Resistance of the nanopillar is measured using standard microwave probes. The current direction was set so that for positive current, electrons flow from SAF to FL. The probe station was capable of applying over 1 T field normal to the film surface.

A memory cell of a STT-RAM is composed of a GMR (or TMR) structure device, a transistor, a word line (WL), a bit line (BL), and a source line (SL) as shown in the Fig. 2. The BL and



WL are orthogonal to each other and this is indicated by the “×” sign. Each GMR device in a memory cell is connected in series to a transistor that controls the magnitude of current that passes through the GMR/TMR device. The transistor is controlled by the WL voltage that is adjusted for both read and write operations so that a current can pass through the transistor. During a read operation a small voltage difference is applied between the BL and SL. This voltage difference causes a current density that is significantly lower than that required for reversal of the free layer to flow through the GMR/TMR device. The magnitude of current depends on the relative orientation of the magnetic layers in the GMR/TMR device: a parallel alignment corresponds to low resistance and large current (a “0” state), and an antiparallel alignment to high resistance and low current (a “1” state). During a write operation a large voltage difference is applied between the BL and SL to generate a current density large enough to reverse the direction of the magnetization of the FL. The torque on the magnetic moment of the FL is proportional to the



current density flowing through the multilayer, and it changes sign when the current is reversed. Therefore, the magnetization of the FL can be reversed either parallel or antiparallel, with respect to HL, by changing the current direction from BL to SL.

## RESULTS AND DISCUSSION

Magnetic measurements are performed on the continuous film before patterning. The measurements revealed perpendicular magnetic anisotropy ( $2K_u/M_s > 4\pi M_s$ , for  $4 \times [\text{Co/Ni}]$ ), a uniaxial anisotropy constant  $K_u = 3.5 \times 10^5 \text{ J/m}^3$ , and a magnetic polarization  $\mu_0 M_s = 0.7 \text{ T}$  of each FM layer, and no coupling between SAF and FL. The measured coercivity,  $\mu_0 H_c$ , of the SAF and the FL in the continuous films is 0.23 T and 0.018 T, respectively.

The dc-resistance of a circular nanopillar of diameter 200 nm as a function of the applied field perpendicular to the surface of substrate is shown in Fig. 3. In the measurements the applied current is kept constant and equal to 0.5 mA. The direction of the magnetic moment in FM1, FM2 and FL varies with the applied field and is represented by arrows; the bottom arrow represents FM1, middle FM2 and top FL. At positive saturation field, the direction of magnetic moments of all the FM layers in the structure are parallel to the direction of the applied field, corresponding to a state with low resistance. As the field is reduced, the magnetic moment of FM1 reverses due to the antiferromagnetic exchange coupling between FM1 and FM2. Since FM1 and FM2 have the same film structure (Co/Ni multilayers) their magnetic anisotropy is similar. However, the Zeeman energy of FM1 is smaller than that of FM2 because the

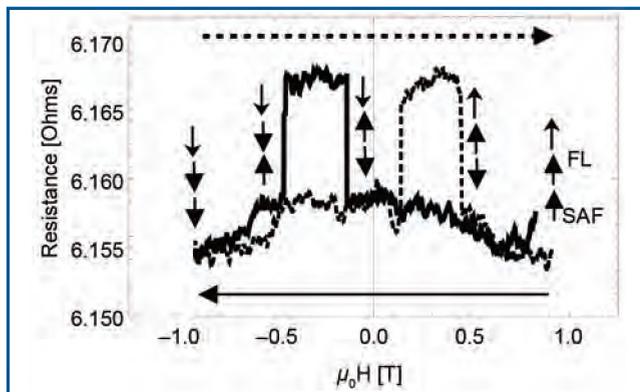


Fig. 3  $R_{dc}$  measurement of the nanopillars as a function of the applied magnetic field. The vertical arrows represent the directions of the magnetic moments of FM1 (bottom arrow), FM2 (middle arrow) and FL (top arrow). The solid line represents the resistance measurements when the field sweeps from 0.9 T to  $-0.9 \text{ T}$  and the dotted line represents the change in resistance when the field sweeps from  $-0.9 \text{ T}$  to 0.9 T.

magnetization of FM1 is smaller than that of FM2. For this reason, the magnetic moment of FM1 in the SAF reverses first. The change from the parallel to antiparallel alignment between the magnetic moments of FM1 and FM2 in the SAF results in a slight increase in resistance.

Further reduction of the applied magnetic field causes the reversal of the magnetic moment in FL at  $\mu_0 H = -0.13 \text{ T}$ . At this field, alignment between the magnetic moments of the adjacent magnetic layers are antiparallel (both FM1 and FM2 are in the AP state, and FM2 and the FL are in the AP state) and hence resistance of the nanopillar increases to its highest value. The orientation of magnetic moments in the FM layers is unchanged from  $\mu_0 H = -0.13$  to  $-0.49 \text{ T}$ . At  $\mu_0 H = -0.49 \text{ T}$  both magnetic layers in SAF (FM1 and FM2) simultaneously rotate. This sets the magnetic moment of the FL parallel to that of FM2 resulting in a decrease of the nanopillar resistance. Even at this field the antiferromagnetic coupling across Ru is strong enough to ensure that mutual alignment between magnetic moments of FM1 and FM2 stays antiparallel. At negative saturation field, the magnetic moments of all the FM layers are aligned with the applied field, corresponding again to a state with the lowest resistance. The same trend is observed when the applied field sweeps from the negative saturation ( $\mu_0 H = -0.8 \text{ T}$ ) to the positive ( $\mu_0 H = 0.8 \text{ T}$ ).

The change in resistance due to the transition from the parallel to antiparallel alignment between the magnetic moments of FM1 and FM2 (Co/Ru/Co at  $\pm 0.62 \text{ T}$ ) is about two and a half times smaller than the change in resistance due to the transition from the parallel to antiparallel alignment between the magnetic moments of FM2 and FL (Co/Cu/Co at  $\pm 0.13 \text{ T}$  and  $\pm 0.49 \text{ T}$ ). This is due to the possible inter-diffusion of Co and Ru interfaces<sup>[26]</sup> and also due to a small difference between the spin-polarized density of states at the Fermi level<sup>[27]</sup>. The  $R_{dc}$  measurements are repeated for different values of applied current and it is observed that the coercive field of both the SAF and FL in the patterned nanopillars increases as compared to the continuous films, with the coercivity field of the SAF reaching  $\mu_0 H_c = 0.49 \text{ T}$  and that of the FL  $\mu_0 H_c = 0.098 \text{ T}$ . The increase of the coercivity field in both SAF and FL in nanopillars is due to size effects. In large magnetic structures, a defect or non-uniformity can act as a centre for a magnetic domain nucleation that causes the magnetization reversal at magnetic fields several orders of magnitude smaller than  $2K_u/M_s$  (where  $K_u$  is the magnetic anisotropy energy and  $M_s$  is the saturation magnetization of the magnetic structure). In *nm*-size magnetic structures much larger magnetic fields are required to nucleate a magnetic domain and cause the magnetization reversal<sup>[28,29]</sup> since the energy term due to the direct exchange interaction is dominant in *nm*-size structures.

The resistance as a function of d.c. current, measured at zero applied field, is shown in Fig. 4. The critical current,  $I_c$ , required to reverse the magnetization of FL from parallel to

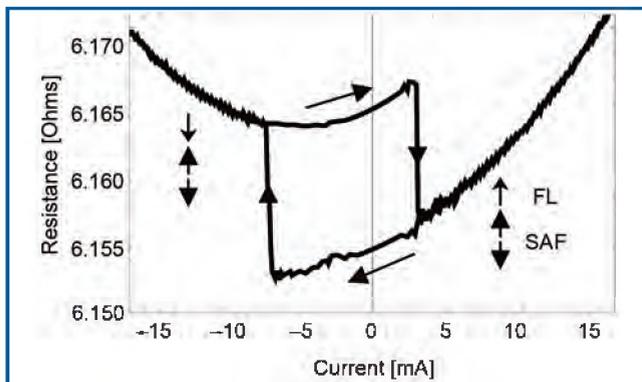


Fig. 4 Resistance measurement of the nanopillar as function of the applied dc current at a zero applied magnetic field. The arrows represent the directions of the magnetizations of FM1 (bottom arrow), FM2 (middle arrow) and FL (top arrow). The offset in resistance at 0 mA is due to the infinite resistance at zero current.

antiparallel alignment is  $I_c = 6.6$  mA and from antiparallel to parallel is  $I_c = 3$  mA.

The efficiency of current induced magnetization reversal of the FL can be determined from the expression  $I_c/(V_{FL}H_c)$ , where  $V_{FL}$  and  $H_c$  are the volume and coercivity of the FL, respectively. In our nanopillars  $V_{FL} = 1.01 \times 10^{-22}$  m<sup>3</sup> and  $H_c = 0.098$  T resulting in  $I_c/(V_{FL}H_c)$  is  $6.7 \times 10^{20}$  A/T m<sup>3</sup>. This is almost twice

as efficient a current-induced magnetization reversal of FL than previous report for the devices with a SAF reference layer<sup>[20]</sup>. To decrease  $I_c$ , damping of the FL has to be minimized as shown in Equation 1. In previous study<sup>[20]</sup> FL was designed using both Co/Ni and Co/Pd multilayers. Co/Pd multilayers have higher damping than Co/Ni multilayers<sup>[30–32]</sup>. We further reduced damping in our Co/Ni multilayers by increasing the Co to Ni thickness ratio as suggested by Shaw *et al.*<sup>[33]</sup> and Mizukami *et al.*<sup>[34]</sup>. This can explain the higher efficiency of the spin transfer torque in our nanopillars.

## CONCLUSION

We investigate current-induced magnetization reversal in perpendicularly-magnetized 200 nm diameter circular nanopillars with a unique magnetic layer design: a Co/Ni multilayer free layer (FL) and a synthetic antiferromagnet (SAF) reference layer. In our design, the dipolar field acting on FL is only 0.038 T, more than two times smaller than reported in devices with a single ferromagnetic reference layer<sup>[24]</sup>. In our devices the current-induced magnetization reversal of FL is almost twice as efficient as reported for the devices with a SAF reference layer<sup>[20]</sup>. This is attributed to a low damping design of our FL.

## ACKNOWLEDGEMENTS

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# THE FIRST REGIONAL CONFERENCE ON WOMEN IN PHYSICS, ISLAMABAD, PAKISTAN

BY ADRIANA PREDOI-CROSS

There are many documented efforts worldwide to increase the representation of women in physics at all academic levels. Regardless, some would argue that women are still under represented, in particular at the senior academic levels and in industry. One way we can facilitate an increase in the participation of women in physics, is by sharing our understanding of challenges faced by women, knowledge about good practices, successful policies and lessons learned in attracting and retaining those who have the interest and choose to pursue a career in physics and contribute to innovation and the advancement of scientific knowledge, at community, national and international levels. “Talent knows no gender” says an author.

Many countries try to ensure that the solution to increasing the number of women in science needs to bring to the table representatives of stakeholders at all levels: community, educational, industry, policy makers, and government. In this setting the *First Regional Conference on Women in Physics* was organized in late April, 2016 in Islamabad, Pakistan by the University of Peshawar and the National Center for Physics with support from several national and international organizations: the Centre for Physics Education Karachi, The Abdus Salam International Centre for Theoretical Physics, Italy, the Higher Education Commission, Islamabad, and the Organisation of Islamic Cooperation Standing Committee on Scientific and Technological Cooperation.

The approaches in fixing the problem of the low representations of women in physics have cultural and ethnic aspects, but there are common elements to them such as increasing the participation of young girls in scientific activities by changing the way we teach, thus enhancing the existing curricula with hands-on demonstrations, physics related animations and PhysClips, and by enrolling young girls in science fairs, physics tournaments and olympiads. The importance of mentoring and networking at all academic levels cannot be ignored as well as the importance of outreach activities. In addition, having positive female physicists as role models portrayed in publications and in the media, plays an important role and breaks the stereotype of female geeks in lab coats, and also informs the younger generation of the multitude of career paths, many of them considered non-traditional career paths, or even unpredictable career paths.

Balancing a career in physics and having a family sometimes requires customized solutions, making personal sacrifices and a staggered approach to academic achievement. We also have to emphasize that the interest in physics should be nurtured in females of all ages, even if their interest aroused later in life. Professional societies, student clubs can play an important role in making sure that more and more individuals understand the way things work, the importance of education. Paraphrasing, we could say that it takes a community to bring up a budding scientist and help him or her become a science wiz.

One hundred participants (mostly Pakistani and a few South Asians) attended the conference and presented their thoughts and research results through plenary and invited talks, oral contributions and poster presentations. Several of the invited speakers were from the U.S.A., Iran and Canada (myself). There were many thought provoking discussions and informal or candid discussions, sharing of ideas and suggestions. The participants of the conference discussed many of the challenges faced by women in physics of different ages in Pakistan and made plans for informal mentoring and networking activities. A special issue of the Canadian Journal of Physics planned for November 2016 will feature papers based on the conference presentations and discussions. The organizers are already making plans for the next conference in this series that will take place in 2020.



Organizers, plenary and invited speakers at the *First Regional Conference on Women in Physics-2016*.

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## CAP MEMBER CHARLES GALE AWARDED 2016 KILLAM RESEARCH FELLOWSHIP

### *CHARLES GALE, MEMBRE DE L'ACP, REMPORTE UNE BOURSE KILLAM*

Charles Gale, James McGill Professor in the Department of Physics at McGill University, is one of six outstanding scholars who have just been awarded a Killam Research Fellowship. Dr. Gale will work on "Nuclear Matter under Extreme conditions: Elucidating the Properties of the Quark-Gluon Plasma". Dr. Gale was awarded the CAP/CRM Prize in Theoretical and Mathematical Physics in 2015. Information about the Killam Research Fellowships, Dr. Gale's award, and the other 2016 recipients can be found at <http://killamprogram.canadacouncil.ca/en/fellowship-winners-2016/charles-gale>.



Charles Gale, James McGill Professor au département de physique à l'Université McGill, est l'un des six chercheurs reconnus qui viennent de recevoir une bourse de recherche Killam en 2016. Le Dr Gale va travailler sur la matière dans des conditions extrêmes : élucider les propriétés du plasma quark-gluon. Il a reçu le prix ACP-CRM de physique théorique et mathématique en 2015. On trouvera plus d'information sur les bourses de recherche Killam, la bourse accordée à Dr. Gale, et les autres boursiers de 2016 <http://programmekillam.conseildesarts.ca/gagnants-boursiers-2016/charles-gale>.

## CONGRATULATIONS TO ORDER OF CANADA RECIPIENTS ART McDONALD (CAP MEMBER) AND PETER CALAMAI (CAPF BOARD MEMBER)

### *FÉLICITATIONS À ART McDONALD (MEMBRE DE L'ACP) ET PETER CALAMAI (MEMBRE DU CA DE LA FONDATION DE L'ACP) RÉCIPENDAIRES DE L'ORDRE DU CANADA*

The CAP congratulates CAP member Art McDonald from Queen's University/SNOLAB who was promoted to Companion of the Order of Canada, and CAPF Board member Peter Calamai, retired science writer most notably with *Southam News*, *The Ottawa Citizen*, and *The Toronto Star*, who was invested as an Order of Canada member on Friday, May 13 (see the announcement on the Governor General's website at <http://www.gg.ca/document.aspx?id=16410&lan=eng> for full details).

The Order of Canada was created in 1967, during Canada's centennial year, to recognize outstanding achievement, dedication to the community and service to the nation. Since its creation, more than 6 000 people from all sectors of society have been invested into the Order.



Art McDonald

L'ACP félicite Art McDonald de l'Université Queen's/SNOLAB, membre de l'ACP, qui sera promu Compagnon de l'Ordre du Canada et Peter Calamai, journaliste scientifique à la retraite (notamment à *The Ottawa Citizen* et *The Toronto Star* de *Southam News*) et membre du c.a. de la Fondation de l'ACP, qui sera investi membre de l'Ordre du Canada le vendredi 13 mai (voir l'annonce sur le site web du Gouverneur général à <http://www.gg.ca/document.aspx?id=16410&lan=fra> pour tous les détails).



Peter Calamai

L'Ordre du Canada a été créé en 1967, année du centenaire du Canada, pour reconnaître des réalisations exceptionnelles, le dévouement remarquable d'une personne envers la communauté ou une contribution extraordinaire à la nation. Depuis sa création, plus de 6 000 personnes de tous les milieux ont été investies de l'Ordre.

# PHD PHYSICS DEGREES AWARDED IN CANADIAN UNIVERSITIES\*

## DOCTORATS EN PHYSIQUE DÉCERNÉS PAR LES UNIVERSITÉS CANADIENNES\*

DECEMBER 2014 TO DECEMBER 2015 / DÉCEMBRE 2014 À DÉCEMBRE 2015

### BROCK UNIVERSITY

- CASLIN, K., "Investigation of Frustrated Quasi-One-Dimensional Quantum Spin-Chain Materials", (F. Razavi), October 2015.
- MARQUARDT, D., "A-Tocopherol's Antioxidant Role: A Biophysical Perspective", (T. Harroun), June 2015. Currently following a Post Doctoral fellowship at the Institute for Molecular Biosciences, University of Graz, Graz, Austria.

### CARLETON UNIVERSITY

- CHAMBERLAND, M., "Application of Three-Dimensional Motion Tracking of Low-Activity Fiducial Positron-Emitting Markers in Radiation Therapy and Positron Emission Tomography", (T. Xu), May 2015.
- GRANVILLE, D., "Development of a Technique to Simultaneously Verify Linear Energy Transfer and Absorbed Dose in Therapeutic Proton Beams", (G. Sawakuchi), October 2015.
- HARTLING, K., "Theoretical and Experimental Constraints on Large Electroweak Scalar Multiplets", (H. Logan), October 2015.
- MCCARTHY, T., "Measurement of the Top Quark Mass in the All-Hadronic Top-Antitop Decay Channel Using Proton-Proton Collision Data from the ATLAS Experiment at a Centre-of-Mass Energy of 8 TeV", (G. Oakham), October 2015.
- ORTON, E., "Extra-Cardiac Interference in Myocardial Perfusion Imaging with Rubidium-82 and Positron Emission Tomography", (G. Wells), October 2015.
- RODRIGUES, M., "Automation of the Cytokinesis-Block Micronucleus Assay Using Imaging Flow Cytometry for High Throughput Radiation Biodosimetry", (R. Wilkins), May 2015.
- UENO, R., "Search for Electroweak SUSY Signatures with Two Leptons and Missing Energy with the ATLAS Detector", (M. Vincter), February 2015.
- WHALEN, K., "From Discovery to Precision Measurements: Electron Identification, Electron-Like Backgrounds, and Measurement of the Differential Fiducial Cross-Sections of the Higgs Boson in the Four-Lepton Decay Channel with the ATLAS Detector", (M. Vincter), February 2015.

\*Supplement to the list published in Vol. 72, No. 1 (2016).

\*Supplément à la liste publiée dans le Vol. 72, no 1 (2016).

### MCGILL UNIVERSITY

- BELIN, A., "The phase structure of entanglement measures and their role in holography and quantum gravity", (A. Maloney), June 2015.
- DE HAAN, T., "Cosmological constraints from the South Pole telescope galaxy cluster survey", (M. Dobbs), February 2015.
- FERRARI, A., "Flexible polyelectrolytes: like-charged attraction, linear stability, and long-term structure", (M. Grant), February 2015.
- KENNEDY, J., "Instrumentation and Analysis for Observations of the Sunyaev-Zel'dovich Effect from Galaxy Clusters with the APEX-SZ Experiment", (M. Dobbs), February 2015.
- LHERMITTE, J., "Using coherent X-rays to measure velocity profiles", (M. Sutton), June 2015.
- LÓPEZ AYÓN, G., "Local mechanical stimulation based approaches for the study of cells", (P. Grutter), February 2015.
- LU, EGANG, "Thermalization of a QCD system via kinetic approach", (G. Moore), February 2015.
- PARK, N., "Essays in late time cosmology", (R. Brandenberger), June 2015.
- SAVARD, R., "Mass transport in single nanopores", (G. Gervais), June 2015.
- WANG, K., "Search for physics beyond the standard model in multi-jet events recorded with the ATLAS detector in p-p collisions at square root of  $s = 8$  TeV using the large Hadron collider", (A. Warburton), October 2015.
- ZAMFIR, M., "Probing neutron star interiors with type I x-ray bursts", (A. Cumming), February 2015.

### QUEEN'S UNIVERSITY

- ALAM-SAMIMI, A., "Magnetic Barkhausen Noise Testing: Steel Grades and Stress Response", (L. Clapham and T. Krause), November 2015, now a Postdoctoral Researcher at Queen's University, Kingston, ON, Canada.
- ALAYASHI, W., "Branched Nanostructured Anodes for Dye-Sensitized Solar Cells", (K. Robbie), May 2015, now currently unemployed.
- CAMPBELL, J., "Feedback controlled electromigration for the fabrication of point contacts and noise measurement applications", (R.G. Knobel), November 2015, now a Process Specialist at a start up company in St. John's, Newfoundland, Canada.
- DESJARDINS, D., "Analytical Modelling for Transient Probe Response in Eddy Current Testing", (L. Clapham and T. Krause), November 2015, now a Flight Commander with RCAF, CFB Trenton, ON, Canada.
- JOYCE, A., "Crossed-Array Transducer for Real-Time Three-Dimensional Ultrasound Imaging",

(G.R. Lockwood), May 2015, now a staff Engineer at uBeam, Santa Monica, California, USA.

- KAMAHA, A., "Improved Limits on the Existence of Dark Matter. The Final Results from the PICASSO Experiment", (A.J. Noble), May 2015, now a Postdoctoral Researcher at Queen's University, Kingston, ON, Canada.
- KAMANDAR DEZFOULI, M., "Quantum Non-linear Optics in Lossy Coupled-Cavities in Photonic Crystal Slabs", (M.M. Dignam), November 2015, now a Postdoctoral Researcher at Queen's University, Kingston, ON, Canada.
- LEE-WADDELL, K., "A Multi-wavelength Investigation of the Gas-rich Dwarf Galaxy Populations of Three Interacting Groups: NGC3166/9, NGC 871/6/7 and NGC 4725/47", (K. Spekkens), November 2015, now a Research Scientist at CSIRO, Sydney, Australia.
- NADEAU, P., "Cryogenic Scintillators for Rare-Event Searches", (P. Di Stefano), November 2015, now a Postdoctoral Researcher at SNO-LAB, Sudbury, ON, Canada.

### SIMON FRASER UNIVERSITY

- AKHTARI ZAVAREH, A., "Off-Axis electron holography of isolated ferromagnetic nanowires", (K. Kavanagh), December 2014, now a Post Doctoral Fellow at SFU, Burnaby, BC, Canada and searching for employment.
- DAWE, E.N., "Evidence for standard model Higgs boson decays to tau lepton pairs in the ATLAS detector supported by a search in the fully hadronic final state", (D. O'Neil), December 2014, now a Research Fellow in Experimental Particle Physics at the University of Melbourne, Melbourne, Australia.
- HOHERTZ, D., "Optimizing the refractive index sensitivity of extraordinary optical transmission based sensors", (K. Kavanagh), December 2014, now an Applied Photonics Engineer at Novadaq, Burnaby, BC, Canada.
- LEUNG, S.S.W., "Can localized impurities exert global effects on lipid model membranes?", (J. Thewalt), April 2015, now a Post Doctoral Fellow at the Simon Fraser University, Burnaby, BC, Canada.
- LOTFI MAHYARI, Z., "Universal inhomogeneous magnetic-field response in the normal state of cuprate high-Tc superconductors", (J. Sonier), April 2015, now searching for employment.
- SHAGHAGHI, M., "2H-NMR study of model membranes: Investigating the effect of sterol structure on the chain ordering and phase behaviour of lipid mixtures", (J. Thewalt), December 2014.

## UNIVERSITY OF ALBERTA

- AVENDANO NANDEZ, J.L., "Common Envelope: The Dynamical Aspects", (N. Ivanova), November 2015.
- AYESHESHIM, A., "High-Power Terahertz Pulse Generation and Nonlinear Terahertz Carrier Dynamics in Semiconductors", (F. Hegmann), June 2015.
- COMEAU, M., "Electrical Resistivity Structure of the Altiplano-Puna Magma Body and Volcan Uturuncu from Magnetotelluric Data", (M. Unsworth), November 2015.
- DE LOS REYES, G., "Ultrafast Photoluminescence Spectroscopy of Silicon Nanocrystals", (F. Hegmann), November 2015.
- FOSTER, D., "Force Spectroscopy of Nucleic Acid Folding in the Single-Molecule Limit", (M. Woodside), November 2015.
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## UNIVERSITY OF VICTORIA

CAMPBELL, W., "Readout of polymer gel dosimeters using a prototype fan-beam optical computed tomography scanner", (A. Jirasek and D. Wells), May 2015, now a Postdoctoral Fellow at the University of Colorado School of Medicine, Boulder, Colorado, USA.

KING, G., "Search for Lepton Universality Violation Using  $Y(3S)$  Decays", (J. M. Roney), May 2015, now a Postdoctoral Scholar at Stanford University School of Medicine, Stanford, California, USA.

SHAW, C., "Investigating the use of protein-targeted pegylated gold nanoparticle probes in the surface-enhanced Raman spectroscopy of cells", (A. Jirasek), May 2015, now a Radiation Oncology Medical Physics Resident at Nova Scotia Health Authority, Halifax, Nova Scotia, Canada.

TOWNSON, R., "Enhancing the speed of radiotherapy dose calculation with applications in dose verification", (A. Jirasek and S. Zavgorodni), May 2015, now searching for employment.

WANG, X., "Force-free magnetospheres, Kerr-AdS black holes and holography", (A. Ritz), May 2015, now a Postdoctoral Fellow at Huazhong University of Science and Technology, Wuhan Hubei, China.

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### GENERAL INTEREST

**DOING GLOBAL SCIENCE: A GUIDE TO RESPONSIBLE CONDUCT IN THE GLOBAL RESEARCH ENTERPRISE**, InterAcademy Partnership, Princeton University Press, 2016; pp. 192; ISBN: 9780691170756; Price: 20.95.

**GROUP THEORY IN A NUTSHELL FOR PHYSICISTS**, A. Zee, Princeton University Press, 2016; pp. 632; ISBN: 978-0-691-16269-0; Price: 125.95.

**THE COSMIC WEB: MYSTERIOUS ARCHITECTURE OF THE UNIVERSE**, J. Richard Gott, Princeton University Press, 2016; pp. 272; ISBN: 9780691157269; Price: 33.77.

**THE NEW COSMOS (V)**, David J. Eicher, Cambridge University Press, 2016; pp. 295; ISBN: 9781107068858; Price: 33.95.

**THE SINGULAR UNIVERSE AND THE REALITY OF TIME**, Roberto Mangabeira Unger, Cambridge University Press, 2014; pp. 566; ISBN: 9781107074064; Price: 33.95.

### UNDERGRADUATE TEXTS

**A STUDENT'S GUIDE TO PYTHON FOR PHYSICAL MODELING**, Jesse M. Kinder & Philip Nelson, Princeton University Press, 2015; pp. 160; ISBN: 9780691170503; Price: 31.95.

**ASTRO**, Shohini Ghose, Vesna Milosevic-Zdjelar, Arthur Read, Nelson Education, 2015; pp. 225; ISBN: 978-0176650186; Price: 96.85.

**ASTROPHYSICS IN A NUTSHELL SECOND EDITION**, Dan Maoz, Princeton University Press, 2016; pp. 312; ISBN: 9781400881178; Price: 118.95.

**PHYSICS: AN ALGEBRA-BASED APPROACH**, Ernie McFarland, Alan Hirsch, Joanne O'Meara, Nelson Education, 2015; pp. 928; ISBN: 978-0176531867; Price: 155.95.

**WHAT DOES A BLACK HOLE LOOK LIKE?** Charles D. Bailyn, Princeton University Press, 2014; pp. 224; ISBN: 9781400850563; Price: 48.95.

## GRADUATE TEXTS AND PROCEEDINGS

**A GUIDE TO MONTE CARLO SIMULATIONS IN STATISTICAL PHYSICS**, David P. Landau, Kurt Binder, Cambridge University Press, 2014; pp. 530; ISBN: 9781107074026; Price: 97.95.

**DYNAMICS OF QUANTISED VORTICES IN SUPERFLUIDS**, Edouard B. Sonin, Cambridge University Press, 2016; pp. 400; ISBN: 978-1107006683; Price: 177.95.

**EXPERIMENTAL STUDIES OF NEUTRINO OSCILLATIONS**, Takaaki Kajita, World Scientific Publishing, 2016; pp. 120; ISBN: 9789814759267; Price: 19.29.

**INTRODUCTION TO MANY-BODY PHYSICS**, Piers Coleman, Cambridge University Press, 2016; pp. 810; ISBN: Cambridge University Press; Price: 91.48.

**LEARNING THE ART OF ELECTRONICS: A HANDS-ON LAB COURSE**, Thomas C. Hayes, Paul Horowitz, Cambridge University Press, 2016; pp. 1150; ISBN: 978-0521177238; Price: 82.76.

**PEREGRINATIONS FROM PHYSICS TO PHYLOGENY: ESSAYS ON THE OCCASION OF HAO BAILIN'S 80TH BIRTHDAY**, Kok Khoo Phua & Mo-Lin GE (Editors), World Scientific Publishing, 2016; pp. 388; ISBN: 978-9814759083; Price: 107.95.

**PWA90: A LIFETIME OF EMERGENCE**, Edited by Piers Coleman, Premi Chandra, Gabi Kotliar, World Scientific Publishing, 2015; pp. 252; ISBN: 9789814733625; Price: 47.50.

**STATISTICAL MECHANICS AND APPLICATIONS IN CONDENSED MATTER**, Carlo Di Castro and Roberto Raimondi, Cambridge University Press, 2015; pp. 544; ISBN: 978-1107039407; Price: 91.95.

BOOK REVIEWS / *CRITIQUES DE LIVRES*

Book reviews for the following books have been received and posted to the *Physics in Canada* section of the CAP's website: <http://www.cap.ca>. When available, the url to longer versions are listed with the book details.

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**A GUIDE TO MONTE-CARLO SIMULATIONS IN STATISTICAL PHYSICS** (3rd Edition) by David P. Landau and Kurt Binder, Cambridge University Press, 2015, ISBN: 978-1107074026, price 97.95.

The preface and the introduction gives a good introduction to the importance of simulation research and the many possibilities that it has opened in different research areas. They emphasize not only the importance of simulations, but also their interpretation as they explain the features of Monte Carlo methods. As the title suggests, the book mostly focuses on simulations in statistical physics, however it also includes a brief introduction to Monte Carlo methods used in fields other than physics in the later chapters.

The book is composed of 15 chapters where chapters 1 to 4 provide the introduction to Monte Carlo methods and some necessary background in statistical physics. It introduces the random number generation. The authors explain what kind of simulations can be made in different situations, and discuss their limitations. They emphasize that the "aim of simulation is not to provide a better 'curve fitting' to experimental data than does analytic theory". The importance of simulation is to understand the physics; by creating an idealised computer experiment.

Chapters 5 to 11 are the main contents of the book, the authors guides the reader through many different case studies in Statistical Physics as they introduce algorithms and give advices on how to deal with each case. Chapters 12 to 14 cover topics that are related to Monte Carlo methods or statistical physics that are important to discuss,

but not necessarily related to Monte-Carlo simulations in statistical physics. Then authors conclude with an outlook to future developments and applications.

This book is a great source for Monte Carlo simulations for senior undergraduate students with knowledge of statistical mechanics and interest in the field. Every chapter contains some introduction to the specific phenomenon being investigated that undergraduate students without much in-depth background could follow through with some individual work. However, this book is mostly intended for graduate students and researchers who want to learn about the use of Monte Carlo methods in statistical physics. The examples provided in this book are written in FORTRAN and it is included in the Appendix.

Fuluny Jang  
University of British Columbia

**TRANSMISSION LINES** by Richard Collier, Cambridge University Press, 2013, pp: 318, ISBN: 978 1 107 02600 1, price 107.70

In his book, *Transmission Lines*, Collier discusses the fundamentals of two-conductor transmission lines, metallic and dielectric waveguides, and fibre optic cables. Collier divides his book into three sections.

First, two-conductor transmission lines are discussed. An equivalent circuit analysis is used to describe the transient response of transmission lines to step and pulse inputs. Next, sinusoidal inputs are considered which leads to a discussion of reflection coefficients and the equivalent impe-

dance of a length of transmission line. The first section concludes with an analysis of coupled transmission lines and their use in the design of directional couplers, filters, and mixers. Collier includes many examples throughout the entire text. The presentation of the complex waveforms that can arise when a pulse propagates along a transmission line terminated by reactive loads was illuminating and Collier's discussion of the various "tee" designs was a treat.

The second section of the text uses electromagnetic theory to derive the wave equations for electric and magnetic fields. The various solutions to the wave equation (TE, TM, and TEM) are considered for fields in metallic waveguides, coaxial cables, dielectric slabs, stripline, and fibre optic cables. In order to avoid complex mathematics, Collier at times makes use of results and techniques not developed within the text. For example, conformal mapping was used to transform a coaxial geometry into a parallel plate geometry. Readers not familiar with conformal mapping may have a difficult time with this part of the text. Also, the solutions for the electromagnetic fields within circular waveguides and coaxial cables makes use of Bessel functions which are not thoroughly discussed. Collier's discussion of attenuation in two-conductor transmission lines and waveguides, however, was very engaging. In particular, his calculation of the resonances and quality factors of a length of shorted transmission line was intriguing.

Finally, the third section introduces the reader to a unique "photonic theory" of transmission lines. Collier convincingly shows how a superposition of plane waves can be used to reproduce many of the

results obtained using electromagnetic theory. As Collier himself puts it, parts of the final chapter are “somewhat sketchy”. In particular, this reviewer found the discussion of the mass of a photon more than a little suspect.

It is clear that, over his career, Collier has developed a deep theoretical and practical understanding of transmission lines. His book provides a stimulating overview of the fundamentals of two-conductor transmission lines, waveguides, and fibre optic cables and he emphasizes important applications. Collier tends to introduce concepts through worked examples. In this reviewer’s opinion, in some places the examples walk the reader through algebraic manipulations in too much detail which can distract from the important physics. In the second half of the book Collier frequently refers to other works cited at the end of each chapter. Readers looking for a first introduction to transmission line theory may be best served by using Collier’s book as a supplement to one of the many more traditional texts on the subject.

Jake Bobowski  
University of British Columbia Okanagan

**BAYESIAN PROBABILITY THEORY: APPLICATIONS IN THE PHYSICAL SCIENCES** by Wolfgang von der Linden, Volker Dose, Udo von Toussaint, Cambridge Univ. Press, 2014, pp: 541, ISBN: 9781107035904, price 120.95.

Probability theory and its cousin, statistics, are unique areas of mathematics in that their interpretation is still under debate. Two schools of thought contend: For many years, the frequentist interpretation, where probability is defined in terms of limiting frequencies (e.g., the number of heads divided by the number of coin flips, or “trials”), has dominated. More recently, the Bayesian interpretation, where probability is defined as the “degree of rational belief” in a proposition, has

gained many converts. The frequentist interpretation has been more familiar and, in the eyes of its adherents, is more “objective.” The Bayesian view, which can be applied to non-repeatable events, has a wider applicability, allows for a more systematic and more intuitive presentation of basic concepts. Also, its explicit incorporation of prior information can sometimes lead to much stronger inferences.

The book *Bayesian Probability Theory: Applications in the Physical Sciences*, by Wolfgang von der Linden, Volker Dose, and Udo von Toussaint, wears its colours on its cover: It is the most thorough exposition to appear of the Bayesian view of probability and data analysis that is written by and for physicists. The authors, senior theorists from Germany and Austria, have been active in applying Bayesian ideas in a wide range of areas, ranging from condensed-matter physics to astronomy to climate research. The book includes a rich variety of case studies based on their work, including, as a random sampling, estimation of the quantum Hall constant, detection of outlier experiments among the measurements of the gravitational interaction constant, and the problem of inferring absorbance for a complex response function given noisy measurements of its real part over a limited frequency range.

Although the book has many advanced applications, it assumes no prior knowledge of either probability or statistics. Indeed, the early chapters can serve as a text for advanced undergraduate or graduate courses on the topic, depending on the subset used. Later chapters will interest those caring about specific applications and theorists interested in the foundations of the field or in Monte Carlo methods to handle the high-dimensional integrals that are a part of Bayesian analyses. A particular strength of the book is its dual presentation of Bayesian and frequentist methods. Since the latter are so embedded in scientific papers and elementary discussions of

data analysis, it is vital to understand both points of view. The authors here take the logical tack of presenting short chapters on frequentist perspectives *after* their Bayesian version has been presented. They keep the clarity of the Bayesian view while adding a broader perspective.

The combination of an elementary level start and state-of-the-art completeness makes for a big book — 637 pages. Some of the heft results from repetition, as the same topic is often revisited as different points of view or techniques are developed. My main complaint, though, is that the presentation, notation, and language are often rather stiff and formal. A random example: “It has been proved that Bayesian probability theory is the only theory which handles partial truths consistently. It is the content of the next chapter.” (p. 31). The statements are accurate, but a native speaker would not put it quite that way. Further, the notation can be pedantic. For example, the authors make the important point that every probability depends on background information. True, but is it necessary to write  $P(A | I)$  rather than  $P(A)$  everywhere in the book? Perhaps stating the point and reminding the reader from time to time would be enough. Finally, the authors have a tendency to state a general result first and give comments and examples afterwards. Some readers will like that style, which can be clear, precise, and rigorous; others will prefer that the intuition come first.

As a first introduction, this book competes with slimmer ones that are lighter in their prose. A personal favourite is D. S. Sivia’s *Data Analysis: A Bayesian Tutorial* (2nd ed., Oxford Univ. Press, 2006). But the present work by von der Linden, Dose, and von Toussaint is an impressive book, and all those interested in serious problems in data analysis in physics would do well to read and study it.

John Bechhoefer  
Simon Fraser University

The Editorial Board welcomes articles from readers suitable for, and understandable to, any practising or student physicist. Review papers and contributions of general interest of up to four journal pages in length are particularly welcome. Suggestions for theme topics and guest editors are also welcome and should be sent to [bjoos@uottawa.ca](mailto:bjoos@uottawa.ca).

Le comité de rédaction invite les lecteurs à soumettre des articles qui intéresseraient et seraient compris par tout physicien, ou physicienne, et étudiant ou étudiante en physique. Les articles de synthèse d'une longueur d'au plus quatre pages de revue sont en particulier bienvenus. Des suggestions de sujets pour des revues à thème sont aussi bienvenues et pourront être envoyées à [bjoos@uottawa.ca](mailto:bjoos@uottawa.ca).



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