STUDIA UNIVERSITATIS
BABEŞ-BOLYAI
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EUROPEAN SCHOOL ON MAGNETISM 2015

FROM BASIC MAGNETIC CONCEPTS TO SPIN CURRENTS

Aug 24 - Sep 4 [2015]
Cluj-Napoca, Romania

MAGNETISM.eu
A GATEWAY TO THE EUROPEAN MAGNETICS COMMUNITY

STUDIA UNIVERSITATIS
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PHYSICA

Volume 60 (2015), August, Special Issue

The EUROPEAN SCHOOL on
MAGNETISM

August 24^{th} - September 4^{th}, 2015 - Cluj-Napoca, Romania

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Like previous editions of ESM, the 2015 School aims at providing a thorough understanding of Magnetism based on a broad series of fundamental lectures, while offering the latest insights into up-to-date aspects of magnetism with lectures focusing on a special topic. The topic proposed in 2015 is spintronics with a special emphasis on Spin currents. This covers a wide range of fundamental phenomena in condensed matter physics, and opportunities for applications. The detailed topics to be covered are: basic concepts, magnetism in matter, thermal effects and magnetization processes, transport phenomena, spin-transfer effects, effects of electric field, spin currents, caloritronics etc.

The School is addressed at young scientists, mainly PhD students and post-docs, both experimentalists and theoreticians. It will gather circa 20 lecturers and a hundred participants coming mainly from Europe, with a few positions open to other countries. It will consist of a ten-day training of lectures and practicals provided by prominent scientists active in today's research, interactive question sessions, access to a library of magnetism-related books, and industrial contributions.

The EUROPEAN SCHOOL on MAGNETISM

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From basic magnetic concepts to spin currents

Welcome to Cluj! Welcome to the European School on Magnetism 2015!

About ESM and JEMS.
The European School on Magnetism (ESM) is an educational event organized every two years by the European Magnetism community. The practical organization is sustained by the Grenoble community of Magnetism and local organizers of the school site, while the scientific program is based on the input of an International Scientific Committee. ESM aims at providing a thorough understanding of the fundamentals of magnetism. The School is addressed at young scientists, mainly PhD students and post-docs, both experimentalists and theoreticians. It consists of a ten-day training course combining lectures, tutorials, computer and text-book based practicals, interactive question sessions, and an open-access on-site library dedicated to magnetism.

ESM is closely linked with its conference counterpart, the Joint European Magnetic Symposia (JEMS), the largest European conference on Magnetism. Since 2012, JEMS is scheduled every year but is postponed when either Intermag or ICM conferences are held in Europe. For instance JEMS2013 was held on the island of Rhodes, Greece, in August 2013 and the next JEMS event, JEMS2016, will be held in Glasgow, Scotland, UK, in August 2016. Indeed, it will follow the Intermag 2014 and ICM 2015 editions held in Europe on those years.

The JEMS and ESM actions aim at supporting European activity in magnetism, through the dissemination of knowledge and the education of young scientists. The organization of ESM is supported by a European advisory committee as well as the International Advisory Committee of JEMS, and benefits from financial support from various institutions.

About ESM 2015.
It is a great pleasure for us to host you in Cluj for this 7^{th} European School on Magnetism (ESM). ESM2015 will gather together 18 lecturers and around 110 participants (out of over 220 submitted applications) coming from 27 different countries, mainly from Europe, but also from South-America, Japan, Korea, China, Russia, Turkey and Israel. As with previous sessions of ESM, the 2015 School aims at providing a thorough insight into magnetism through a broad series of fundamental lectures, and to address a specific topic of current interest in more detail. While in 2013 the focus was on Energy, the European School on Magnetism 2015 is named: "From basic magnetic concepts to spin current" and is taking place from Aug. 24^{th} to Sep. 4^{th} 2015 in Cluj-Napoca, Romania. The school will benefit from the hosting of Cluj universities and its university campus, which we deeply acknowledge.

A first half of lectures will provide a general introduction to fundamentals of Magnetism. Then, more specialized lectures will deal with spin currents, thus focusing on *spintronics* and *spinorbitronics*. The giant and tunnel magnetoresistances in magnetic multilayers and the spin transfer torques rely on how the spins flow in magnetic nanostructures, which leads to the concepts of spin current. This reveals a shift of paradigm in the Information and Communication Technology toward the use of spin states instead of solely electrical charges to carry, store and manipulate information. Indeed, ferromagnetic materials and their magnetic state can be used to store information in a nonvolatile way, as used since years in hard disk drives. The electrical current, through spin dependent transport properties and the accompanying spin current is then used to either write or read this state in an efficient way. This is the basic working principle of Magnetic Random Access Memories, probably the next revolution, or at least evolution, that spintronics could bring to ICT.

Recently, this concept of spin current has been extended from the one of spin polarized current, when a charge current flows in ferromagnetic materials, to the concept of pure spin current, where spins up and spin down diffusive in opposite direction without net charge flux but with a full flow of spin angular momentum. These pure spin currents can be found in non-magnetic materials, shifting spintronics interest toward non-magnetic materials. Indeed, those pure spin currents could be generated or detected using spin-orbit coupling in non-magnetic materials instead of exchange interaction in ferromagnetic materials. It changes the way spintronics is being done; nowadays, non-magnetic materials can become active to produce or detect spin current! This could be achieved using either the Spin Hall effect or by Rashba coupling at interfaces, both using the spin-orbit interaction to couple charge and spins. For instance a non-magnetic material adjacent to a ferromagnetic one can be used to generate spin current and thus to control magnetic states. Moreover, the current will now flow along the interfaces instead of perpendicular to it. In a sense this bring us back to the origins of GMR, where currents were first flowing along magnetic layers before to being perpendicular to it.

Spin current and spin angular momentum can also be transferred by different ways, not solely by diffusing electrical spins current. For instance, collective magnetic excitations, called magnons, can be used to transfer angular momentum in an efficient way. Magnons can be generated and detected electrically, and magnonic materials, such as the magnetic oxide yttrium garnet $Y_2Fe_3O_4$, can be coupled to spin orbit materials. In that case, diffusive magnons are used instead of electrical spin currents, having much larger propagation length. Also, topological insulators, as well as Rashba effect, are of growing interest for spintronics, since there is an efficient coupling between charge and the spin state, what is called spin-momentum locking. A charge current induces a spin accumulation, and vice versa, which could be also used to tailor magnetic states of a nearby magnetic element. This could summarize the quest for such new materials and effects for spintronics: spin-orbit coupling can be more efficient than the exchange interaction to couple a charge and a spin as well as providing new geometry or working principles for spintronics devices.

Last but not least, spin orbit coupling, can be also responsible for interesting magnetic states, namely skyrmions, by the Dzyaloshinskii-Moriya interaction.

We hope that 2015 ESM edition, as well as a deep understanding of the fundamentals of magnetism, will provide you also key elements of these new horizons for spintronics and magnetism using spin currents and spin orbit coupling. It is worth mentioning that beside the physics classes, we will also have two industrial perspectives talks during the school as well as several practicals, question/discussion sessions, and relaxing events.

All previous editions, as well as the slides for all lectures can be found on ESM web site:

http://magnetism.eu/esm

As regards future events, note that the next ESM will be held from 9th to 20th October 2017 in Corsica, France. It aims at linking the communities of condensed matter physic magnetism, and nanomagnetism/spintronics.

We wish you a very nice School.
On behalf of the organizing committee and all the lecturers,
Laurent Vila.

PROGRAM

Introduction to the School (1h)
Opening and motivation for the school: Laurent Vila (Chair), *Grenoble, France*

I **Basic concepts (4h30)** p.11-12
- Basic magnetostatic and field properties, units: Michael Coey, *Dublin, Ireland*
- Magnetism of single atoms: Michael Coey, *Dublin, Ireland*

II **Magnetism in matter (4h30)** p.13
- Exchange and ordering, magnetostriction, localized and band magnetism: Steve Blundell, *Oxford, UK*
- Interaction with the lattice. Magnetic anisotropy and crystal electric field: Steve Blundell, *Oxford, UK*

III **Thermal effects and magnetization processes (4h30)** p.18, p.25
- Mean field, magnons, phase transitions: Claudine Lacroix, *Grenoble, France*
- Magnetization processes and dynamics: Ulrich Rößler, *Dresden, Germany*

IV **Transport (6h)** p.20, p.21
- Transport of heat, charge and spin: Gerrit Bauer, *Sendai, Japan*
- Common magnetoresistance measurements: AMR, AHE, GMR, TMR: Coriolan Tiusan, *Cluj-Napoca, Romania*

V **General tools (4h30)** p.14, p.16, p.28
- Ab initio calculations: Manuel Richter, *Dresden, Germany*
- Magnetic Imaging techniques: Laura Heyderman, *Zürich, Switzerland*
- Synthesis and nanofabrication: Laurent Vila, *Grenoble, France*

VI **Spin-orbit-related effects (3h)** p.27, p.24
- Spin-orbit effects in transport and magnetism: Tomas Jungwirth, *Nottinghman, UK; Praha, Czech Republic*
- Damping: Andrei Kirilyuk, *Nijmegen, The Netherlands*

VII **Spin currents (4h30)** p.38, p.30, p.31
- Theory of spin transport phenomena in magnetic tunnel junctions: Mair Chshiev, *Grenoble, France*
- Sources of spin currents: Sergio Valenzuela, *Barcelona, Spain*
- Spin caloritronics: Gerrit Bauer, *Sendai, Japan*

VIII **Interaction with various stimuli (4h30)** p.32, p.26, p.19
- Direct effects of electric field: Agnès Barthélémy, *Orsay, France*
- Control magnetism with light - Various time and length scales: Andrei Kirilyuk, *Nijmegen, The Netherlands*
- Magnonics: Dirk Gründler, *Lausanne, Switzerland*

IX **Industry perspectives (3h)** A few contributions are scheduled from industrials. They will cover science and technology, market and applications, and daily life in a company. p.29, p.33
- Magnetoresistive sensors: Johannes Paul, *Sensitec GmbH*
- Production of magnetic materials for spintronics: Lavinia Nistor, *Applied Materials*

Practicals (2-4h each)

Practicals are organized to practice the use of numerical or analytical techniques, related to topics covered by the lectures. Computers will be provided on-site and readily setup for the practicals. Each practical is typically 2-4h. Attendees will be asked on-site for their wishes to attend such or such practicals, however it is not possible to attend all tutorials. On the average, two to three practicals may be attended by each participant. Below is the latest list.

Units in Magnetism: **Olivier Fruchart**, *Grenoble, France.* p.39

Ab initio calculations: **Manuel Richter**, *Dresden, Germany.* p.41

Spin accumulation: **Laurent Vila**, *Grenoble, France.* p.44

Quantum basis of the spin manipulation by electric fields, **Coriolan Tiusan**, *Cluj-Napoca.* p.43

Spin and domain models, based on the free software Simulations for Solid State Physics (http://pages.physics.cornell.edu/sss/): **Dirk Gründler**, *Lausanne, Switzerland.*

Magnetic Force Microscopy: **Olivier Fruchart + expert students**, *Grenoble, France.* Attendees may bring their own samples.

Connecting experimental data with theory (a case study), **Gerrit Bauer**, *Sendai, Japan.*

Library

A library consisting of a large set of books dedicated to various aspects of Magnetism is on display during the entire School. Its purpose is first to get students aware of the existing books, get acquainted with their use, and also serve as a support for activities during the School.

Question-Answer sessions (5-10h)

The purpose of a research School is to provide young scientists with the basics in a working field. With this respect interactivity between students and lecturers should be promoted. Like in the previous editions, a key aspect of this interactivity is the possibility to raise questions at the end as well as during the course of the lectures. Besides, several sessions of questions take place, during which the lecturers or voluntary students present in more detail issues raised by the students during the lectures or anonymously through a question-box.

Posters

We encourage participants to bring posters to present their work. Students are asked to present their poster in a one-slide-two-minutes presentation as an exercise to summarize their work. The list of all poster presentations can be found on page 45.

BASIC MAGNETOSTATIC AND FIELD PROPERTIES, UNITS

Michael Coey [1]

Magnetostatics is the classical physics of the magnetic fields, forces and energies associated with distributions of magnetic material and steady electric currents. The concepts presented here underpin the magnetism of solids. The magnetic dipole moment $\mathbf{m}$ [Am^2] is the elementary magnetic quantity, and magnetization $\mathbf{M}(\mathbf{r})$ [Am^{-1}] is its mesoscopic volume average in condensed matter. The primary magnetic field is $\mathbf{B}$ [T], which appears in Maxwell's equation $\nabla \cdot \mathbf{B} = 0$ that follows from the absence of any magnetic monopoles in Nature to act as field sources. Sources of $\mathbf{B}$ are electric currents, and magnetic material, which may be assimilated to a distribution of atomic currents. Unlike conduction currents $\boldsymbol{j}_{\mathrm{c}}$ [Am^{-2}] the atomic currents responsible for atomic-scale magnetism $\boldsymbol{j}_{\mathrm{m}}$ cannot be measured directly. Hence an indispensable second magnetic field $\mathbf{H}$ [Am^{-1}], defined by $\mathbf{B}{=}\mu_0(\mathbf{H}+\mathbf{M})$, is introduced when dealing with magnetic or superconducting material. In static conditions where there is no time-varying electric field, $\nabla{\times}\mathbf{H} = \boldsymbol{j}_{\mathrm{c}}$. It is the local distribution $\mathbf{H}(\mathbf{r})$ that determines the equilibrium distribution $\mathbf{M}(\mathbf{r})$; the atomic currents cannot act on themselves. $\mathbf{B}$ and $\mathbf{H}$ have different units and dimensions, and in SI, μ_0 is *defined* as $4\pi \cdot 10^{-7}$ $\mathrm{T}/(\mathrm{Am}^{-1})$.

The field produced by a given distribution of magnetization can be calculated by integrating the dipole field due to each volume element $\mathbf{M}(\mathbf{r})\mathrm{d}V$, or using equivalent distributions of electric currents or magnetic charge. Magnetic charge $\mathrm{q_m}$ [Am] are fictional positive and negative monopoles, which offer the most convenient way of calculating $\mathbf{H}$. Magnetic scalar and vector potentials ϕ_{m} and $\mathbf{A}$ [Tm] are defined for $\mathbf{H}$ and $\mathbf{B}$, respectively, the former only when $\boldsymbol{j}_{\mathrm{c}} = 0$. Boundary conditions for the fields and potentials will be discussed.

Internal, external and demagnetizing fields are distinguished. The $\mathbf{H}$-field produced by a magnetized body is called the stray field outside the body, and the demagnetizing field inside. The internal field may be defined on a mesoscopic or a macroscopic scale, the former in terms of the tensor relation $H_{\mathrm{i}} = -\mathcal{N}_{\mathrm{ij}} M_{\mathrm{j}}$; the latter approximately in terms of a demagnetizing factor $1 \geq \mathcal{N} \geq 0$. The interaction of the magnetization with the demagnetizing field gives rise to shape anisotropy.

Magnetic forces, torques and energies are related to magnetization and external field; the thermodynamics of magnetic materials will be outlined. The apparent paradox that a magnetic field can do no work because the Lorentz force density $\mathbf{F}_{\mathrm{L}} = \mathbf{j} \times \mathbf{B}$ [Nm^{-3}] is always perpendicular to $\mathbf{j}$ and cannot therefore change its magnitude will be discussed. All these concepts will be developed with examples intended to reinforce an understanding of the numerical magnitudes of the quantities involved, and an ability to calculate them. There will be some reference to spin-polarized currents. The units and dimensions of all the quantities normally encountered in magnetism will be summarized, based on the units of mass, length, time and electric current (kg, m, s, A). Conversion to and from cgs will be mentioned, but the defects of the cgs system, which stem from the choice of μ_0 as a as a dimensional constant numerically equal to 1, and units of current, potential and resistance that do not feature on instruments in the Keithley catalogue, will be evident.

Background Reading:

J. M. D. Coey, *Magnetism and Magnetic Materials*, Cambridge University Press 2010, Chapter 2; Appendix B.

1. Trinity College Dublin, Ireland.

MAGNETISM OF ISOLATED ELECTRONS AND ATOMS

Michael Coey [1]

The magnetic moments in solids are essentially associated with the angular momentum of electrons, which has two distinct sources – orbital motion and spin. The reality of the connection between magnetism and angular momentum is demonstrated by the Einstein – de Haas experiment. The microscopic theory of magnetism is based on the quantum mechanics of electronic angular momentum, and the proportionality between angular momentum and magnetic moment is a factor two greater for spin than orbit, so that a unit $^1/_2\hbar$ [Js] of spin angular momentum or $\hbar$ orbital angular momentum both give rise to a magnetic moment of one Bohr magneton μ_B, $(e\hbar/2m_e)$ or $9.27 \cdot 10^{-24}$ Am^2. In quantum mechanics the spin angular momentum of the electron, with quantum number $s = {}^1/_2$ is conveniently represented by the 2×2 Pauli spin matrices, and the orbital angular momentum with quantum number $l = 0, 1, 2\ldots$ is represented by $(2l + 1)\times(2l + 1)$ matrices. The total magnetic moment $\mathbf{m}$ is therefore represented by the operator $(\mathbf{l}+2\mathbf{s})\mu_B$. The two types of angular momentum are coupled by the spin-orbit interaction $\propto \mathbf{l}.\mathbf{s}$.

The description of magnetism in solids is fundamentally different, depending on whether the electrons are regarded as localized on ion cores where they obey Boltzmann statistics, or delocalized in energy bands where they obey Fermi-Dirac statistics. Free electrons follow cyclotron orbits in a magnetic field, whereas bound electrons undergo Larmor precession, which gives rise to orbital diamagnetism. A starting point for discussion of magnetism in metals is the free-electron model that leads to temperature-independent Pauli paramagnetism and Landau diamagnetism. By contrast, localized noninteracting $s={}^1/_2$ exhibit Curie paramagnetism, varying as 1/T.

The localized picture is based on the magnetism of isolated multi-electron atoms or ions. Atomic physics is concerned with the energy levels of an isolated atom or ion. The starting point is the quantum mechanics of a single electron in a central potential, which leads to classification of the one-electron states in terms of four quantum numbers l, s, m_l and m_s. The first three; l, s and ml denote an orbital, which can be occupied by two electrons with opposite spin, $m_s = \pm\frac{1}{2}$. The individual electrons' spin and orbital angular momenta are coupled in an isolated many-electron ion to give total spin and orbital quantum numbers L and S, where only the electrons in partially-filled shells contribute. Spin-orbit coupling then operates to split the energy levels into a series of J-multiplets, the lowest of which is specified by Hund's rules. Normally it is only necessary to consider the Hund's-rule ground state to understand the magnetism. The Curie-law susceptibility, $\chi = C/T$ is calculated for a general value of J (Brillouin theory), and in the classical limit (Langevin theory).

When placed in a solid, the ion experiences a crystal field due to the charge environment, which disturbs the spin-orbit coupling, leaving either S or J as the appropriate quantum number. The crystal field creates new one-electron orbitals, which are linear combinations of the m_l states. It modifies the structure of the lowest M_S or M_J magnetic sublevels, which are split by the Zeeman interaction and it introduces single-ion anisotropy via spin-orbit interaction.

Background Reading:

J. M. D. Coey, *Magnetism and Magnetic Materials*, Cambridge University Press 2010, Chapter 3, 4.

1. Trinity College Dublin, Ireland.

EXCHANGE AND ORDERING, MAGNETOSTRICTION, LOCALIZED AND BAND MAGNETISM, INTERACTION WITH THE LATTICE, MAGNETIC ANISOTROPY AND CRYSTALLINE ELECTRIC FIELD

Stephen J. Blundell [1]

The exchange interaction between magnetic moments arises from the effects of the Coulomb interaction (which corresponds to a large energy) and the exchange symmetry of identical particles. We will consider particular incarnations of the exchange interactions: direct exchange, indirect exchange (superexchange and RKKY), and anisotropic exchange.

The exchange interaction leads to the presence of magnetic order, and we will consider this in both localized and itinerant systems. In the latter case, the magnetization of the electron gas will be treated, including a discussion of Pauli susceptibility and the Stoner criterion. We will also consider the model system of a triangle of spins and solve the problem exactly, revealing the key symmetries.

The Heisenberg model possesses rotational symmetry because the interaction $\mathbf{S}_i.\mathbf{S}_j$ has no preferred direction. However, magnetic moments in solids are sensitive the presence of the lattice. One consequence of this is magnetocrystalline anisotropy, which has an effect on the thickness of domain walls. Another consequence is magnetostriction.

The presence of the crystalline electric field splits the degeneracy of d-electron states and we will discuss how this leads to orbital quenching and the Jahn-Teller effect. The Goodenough-Kanamori-Anderson rules can be used to understand how superexchange operates in compounds with different geometries.

Further reading:

S. J. Blundell: Magnetism in condensed matter (OUP, 2001).
(my textbook, covers most of the material)

S. J. Blundell, Magnetism: A Very Short Introduction (OUP, 2012).
(popular introduction, for background only)

J.M.D. Coey: Magnetism and magnetic materials (CUP, 2009).
(Mike Coey's textbook, covers a lot of ground)

D.I. Khomskii: Basic aspects of the quantum theory of magnetism (CUP, 2010).
(harder book by a theoretician, but packed full of good insights)

1. University of Oxford, United Kingdom.

ELECTRONIC STRUCTURE CALCULATIONS FOR MAGNETIC SYSTEMS

Manuel Richter [1]

I will present basic ideas of density functional theory (DFT) in four units with a focus on magnetic systems. Some of the ideas presented before in the lectures on basic concepts (Coey: Magnetism of single atoms) and on magnetism in matter (Blundell) will be re-considered from the viewpoint of DFT and supplemented with several application examples. In a related tutorial, I will demonstrate that such calculations can be even performed by a fearless novice.

Unit 1: Hohenberg-Kohn-Sham theory and Local Density Approximation (LDA)

In this unit, I will introduce one of the most powerful models applied in recent condensed matter physics. As a starting point I will explain why we are not able to solve the Schrödinger many electron equation for systems larger than a few atoms and why it makes no sense to aim on this. As a consequence, we have to resort to **model theories** as opposed to quantum chemical *ab initio* calculations. One possible model, taking into account details of the system chemistry and geometry, is the Local Density Approximation (LDA). This is a **parameter free** but not a first-principles (a synonym for *ab initio*) approach. The LDA is based on the formally exact Hohenberg-Kohn theory and on the interacting electron gas model that can be solved numerically with an accuracy sufficient for all practical purposes. The related Kohn-Sham equations will be explained, their strength and limitations will be discussed.

Unit 2: Exchange, the root of condensed matter magnetism

Given the magnetic properties of electrons, quantum mechanical exchange is what provides their co-operation to form local atomic or molecular moments, or even long-range magnetic order in crystals. Elementary magnetic moments arrange themselves to lower the mutual Coulomb interaction of the electrons, being subject to symmetry restrictions of the fermionic wave function. I will discuss the particular cases of the two-electron wave function and of the homogeneous polarized electron gas. The Local Spin Density Approximation (LSDA) will be introduced and the LSDA Stoner parameter will be defined. Calculated spin polarization energies for atomic shells will be compared with related spectroscopic data. The spin splitting of the Kohn-Sham states will be evaluated.

Unit 3: Tight-binding approach, chemical binding in a nutshell

As a corollary of the virial theorem, the reduction of potential energy will be identified as the driving force behind chemical binding. I will use the hydrogen-molecule to explain the basic ideas of the linear combination of atomic orbitals (LCAO, or tight-binding) approach, as well as the notation of bonding and antibonding states. Bloch's theorem will be introduced, and the tightbinding formalism will be applied to a crystal. In this way, discrete levels of finite systems are replaced by the density of states (DOS) in extended systems. An important technical point is the appropriate choice of atomic- like orbitals in a multi-band tight-binding calculation.

Unit 4: Tight-binding meets exchange, real systems and applications

In order to summarize and to apply the knowledge gained in the previous units, the electronic structure and the magnetic ground state of appropriate model systems will be discussed. First, I will analyse the spin-polarized molecular levels of the iron dimer. Second, the band structure and spin-polarized DOS of bulk bcc iron will be presented and explained. A third system, $La(Fe,Si)_{13}$, will be used to extend the scope to systems of emerging practical relevance. The peculiar electronic structure of this compound yields an extraordinarily flat dependence of the total energy on the magnetic moment and a related strong susceptibility to external influence (magnetic field, temperature, pressure). As a consequence, $La(Fe,Si)_{13}$ is a favoured candidate for magneto-caloric applications. A final remark will be spent on topological insulators, recently disclosed non-magnetic systems with surface spin currents protected by the topology of the bulk band structure.

1. IFW Dresden e.V., P.O.B. 270116, D-01171 Dresden, Germany.

Suggested reading:

Helmut Eschrig, *The Fundamentals of Density Functional Theory*, Teubner-Texte zur Physik, Band 32, B.G. Teubner Verlagsgesellschaft, Stuttgart 1996, ISBN 3-8154-3030-5.
(Units 1, 2 and 3)

Manuel Richter, *Band structure theory of magnetism in 3d-4f compounds*, J. Phys. D: Applied Physics **31**, 1017-1048 (1998).
(Units 1, 2, and 4)

Manuel Richter, *Density Functional Theory applied to 4f and 5f Elements and Metallic Compounds*, Handbook of Magnetic Materials (Ed. K.H.J. Buschow), Vol. 13, Elsevier, Amsterdam 2001, pp. 87-228, ISBN 0-444-50666-7.
(Units 1, 2, and 4)

Claude Cohen-Tannoudji, Bernard Diu, and Franck Laloë, *Quantum Mechanics*, Vol. II, Hermann, Paris 1977, ISBN 0-471-16435-6.
(Units 2 and 3)

John Singleton, *Band Theory and Electronic Properties of Solids*, Oxford Master Series in Condensed Matter Physics, Oxford University Press, Oxford 2006, ISBN 0-19-850644-9.
(Unit 3)

Manuel Richter, Klaus Koepernik, and Helmut Eschrig, *Full-Potential Local-Orbital Approach to the Electronic Structure of Solids and Molecules*, in: Condensed Matter Physics in the Prime of the 21st Century, Ed. J. Jedrzejewski, World Scientific, Singapore 2008, pp. 271-291, ISBN 981-270-944-8.
(Unit 3)

Jürgen Kübler, *Theory of Itinerant Electron Magnetism*, International Series of Monographs on Physics, Vol. 106, Oxford Science Publications, Clarendon Press, Oxford 2000, ISBN 0-19-850028-9.
(Units 2, 3, and 4; general interest)

Stephen Blundell, *Magnetism in Condensed Matter*, Oxford Master Series in Condensed Matter Physics, Oxford University Press, Oxford 2006, ISBN 0-19-850591-4.
(Units 2 and 4; general interest)

Daniel C. Mattis, *The Theory of Magnetism Made Simple*, An Introduction to Physical Concepts and to Some Useful Mathematical Methods, World Scientific, Singapore 2006, ISBN 981-238-671-8.
(Unit 2; general interest)
Michael D. Kuz'min and Manuel Richter, *Mechanism of the strong magnetic refrigerant performance of* $LaFe_{13-x}Si_x$, Phys. Rev. B *76*, 092401 (2007).
(Unit 4)

C. Pauly et al., Nature Physics 2015.
(Unit 4)

MAGNETIC IMAGING TECHNIQUES

Laura Heyderman [1]

In order to fully understand the behaviour of magnetic materials, it is very important to know how the magnetic configurations look at the microscopic scale. There are several microscope techniques that have been developed to observe magnetic domains, which have evolved hand-in-hand with techniques developed to, for example, measure material microstructure or determine surface properties. These techniques can be based in the laboratory or at large scale facilities. Laboratory based techniques include magnetic force microscopy, Kerr microscopy and transmission electron microscopy. At synchrotron x-ray facilities, photoemission electron microscopy and transmission x-ray microscopy are available.

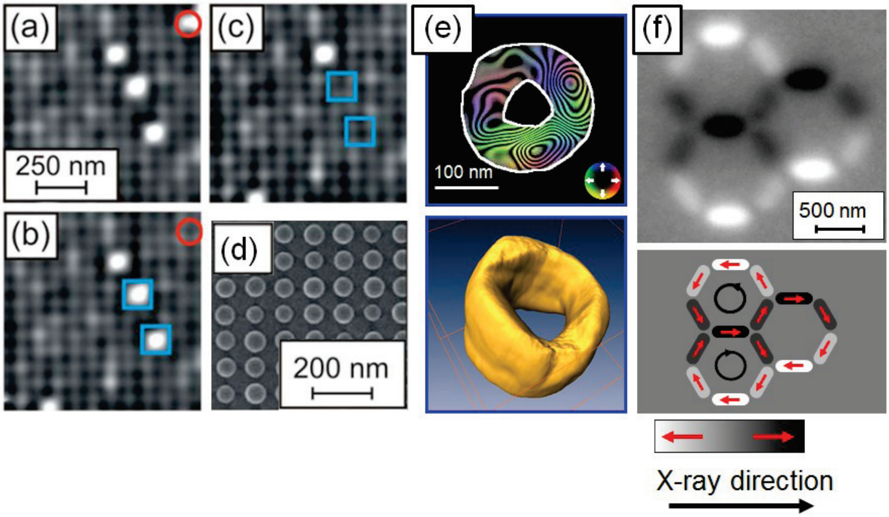

FIGURE 1 – Images demonstrating the usefulness of using different imaging techniques for the understanding of microscopic magnetic phenomena (a-c) MFM images of switching events in Co/Pt multilayer caps [1] coated on polystyrene nanospheres (d). (e) Electron holography image of the magnetic flux lines in a nanoscale magnetite ring depicted together with an electron tomography image of the same ring [2]. (f) Synchrotron x-ray photoemission electron microscopy image of the magnetic configuration in a so-called "artificial spin ice" made up of interacting single domain nanomagnets [3].

Magnetic imaging techniques come with their own advantages and disadvantages, and are often complementary. Depending on the scientific or technological question that needs to be answered, there are several factors that should be taken into account in order to decide which technique to use. For example, some magnetic imaging techniques give a measure of the magnetization (Fig. 1f), while others record the magnetic induction (Fig. 1e) or are sensitive to magnetic stray fields (Fig. 1a-c). Certain techniques are more suitable for measuring the magnetic configurations in materials with in-plane magnetic anisotropy, while others are better for the measurement of materials with strong out-of-plane magnetic components. Some techniques are more quantitative than others and some provide very high spatial resolution of a few nm's, which is particularly interesting when probing magnetism in systems confined to the nanoscale. One should also consider the depth sensitivity since some imaging techniques provide information from the full thickness of the film, whereas others are only sensitive to the surface.

In terms of the sample environment, certain imaging methods require ultra-high vacuum or other special requirements for the samples in terms of sample thickness, surface roughness, surface cleanliness, and material conductivity. For in-situ experiments, it is useful to know the maximum possible applied magnetic field or current, and whether the setup allows, for example, heating/cooling or application of

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strain to the samples. More advanced techniques provide not only magnetic information but also information about the crystallography, topography, chemical species, and/or electronic properties in parallel. Finally it is important to consider whether one would like to perform static or dynamic measurements and, if dynamic, what temporal resolution is required to capture the details of the evolving magnetic process.

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Some Useful Books

Magnetic Domains: The Analysis of Magnetic Microstructures
A. Hubert and R. Schäfer

Magnetic Microscopy of Nanostructures
H. Hopster and H. P. Oepen

Magnetism: From Fundamentals to Nanoscale Dynamics
J. Stöhr and H. C. Siegmann

Magnetic Nanostructures: Spin Dynamics and Spin Transport
Springer Tracts in Modern Physics 246 (2012), Editor(s): H. Zabel and M. Farle
http://link.springer.com/book/10.1007/978-3-642-32042-2/page/1

Magnetism and Synchrotron Radiation, Springer Proceedings in Physics, Vol. 133
Beaurepaire, E.; Bulou, H.; Scheurer, F.; Kappler, J.-P. (Eds.), Springer, Berlin Heidelberg, pp. 345 (2010)

MAGNETISM AT FINITE TEMPERATURE

Claudine Lacroix [1]

In these lectures I will present the basic concepts that determine the evolution of magnetic properties with temperature. The following aspects will be presented.

1-Mean field approximation

The concept of molecular field
Mean field approximation for different type of orderings (ferro-, antiferro-, ferri-, helimagnets. . .), and different crystal structures
Physical quantities in mean field approximation for localized spins (magnetization, susceptibility, specific heat). Curie-Weiss law
Mean field approximation for itinerant magnetic systems. Pauli susceptibility.
Landau expansion of free energy. 2nd and 1st order phase transitions. Ginzburg-Landau free energy

2-Phase transitions in magnetism

Phase transitions in Landau theory
Critical behaviour

3-Magnons

Magnons in ferromagnets in localized spin systems
Itinerant magnetic systems: spin waves vs Stoner excitations
Magnons in antiferromagnets
Contribution of magnons to the specific heat and magnetization

4-The role of dimensionality of the system: 1-, 2- and 3-dimensional systems

Mermin-Wagner theorem
Spin waves in 1- and 2D systems

Some general reference books

S. Blundell: Magnetism in condensed Matter (Oxford University Press, 2001)
J.M.D. Coey: Magnetism and Magnetic materials (Cambridge University Press 2009)
R. Skomski: Simple models of Magnetism (Oxford University Press, 2008)

More advanced books

D.I. Khomskii: Basic aspects of the quantum theory of magnetism (Cambridge University Press 2010)
N. Majilis: The quantum theory of magnetism (World scientific 2007)
P. Mohn: Magnetism in the solid state (Springer, 2006)

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FROM MAGNETIC RESONANCE TO MAGNONICS: REPROGRAMMABLE SPIN WAVE FLOW IN NANOSTRUCTURED MAGNETS

Dirk Gründler [1]

In this lecture we first outline the equation of motion of correlated spins, discuss the resonant behaviour of the magnetic susceptibility, and introduce the concept of an effective magnetic field. We then discuss the anisotropic dispersion relations for spin waves (magnons) in thin films in the long- wavelength limit and explain the reconfigurable artificial crystal, i.e., the paradigm of magnonics. This magnetic device allows one to tailor and reprogram spin-wave dispersion relations on demand.

For the first part we follow the book "Magnetic oscillations and waves" by A.G. Gurevich and G.A. Melkov, CRC Press, 1996.

The second part is contained in the review "Review and prospects of magnonic crystals and devices with reprogrammable band structure", M. Krawczyk and D. Gründler, J. Phys.: Cond. Matter 26, 123202 (2014).

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ELEMENTARY TRANSPORT THEORY FOR METAL SPINTRONICS

Gerrit Bauer [1]

Much of the “useful” spintronic devices are made from elementary metals and their alloys. Their functionality stems from the robustness of the magnetic order parameter of ferromagnetic metals with respect to elevated temperatures and nanostructuring into thin films and pillars. Typical energy scales in metals such as the Fermi energy and exchange interaction are of the order of 1-10 eV, while Fermi wave and exchange lengths are on an Ångstrom scale. In all but atom-sized structures or ultralow temperatures quantum effects due to confinement or disorder can then be safely disregarded, implying that a proper transport theory should be semiclassical and based on Boltzmann theory [1]. However, spintronic devices are often heterostructures made from different metals and insulators that are grown epitaxially. Semiclassical theory fails to describe atomically sharp interfaces that to date are grown routinely.

The topic of this lecture is a pragmatic approach to the theory of transport in metal-based spintronic devices, taking into account abrupt heterointerfaces into an otherwise semiclassical formalism (magnetoelectronic circuit theory), by integrating it with the scattering theory of transport as originally developed by Landauer and Büttiker [2]. Topics to be discussed are:

1. *Elementary transport theory*
   (a) Linear response theory of transport
   (b) Scattering theory of transport
   (c) Thermoelectricity and Onsager symmetry
   (d) Semiclassical transport
   (e) Giant magnetoresistance and spin valve effect
   (f) Spin-dependent thermoelectricity
2. *DC magnetoelectronic circuit theory* [3]
   (a) Transport in non-collinear magnetization textures, non-collinear spin valves
   (b) Spin transfer torque and spin mixing conductance
   (c) Spintronic Kirchhoff Laws
3. *AC magnetoelectronic circuit theory* [4]
   (a) Current-induced magnetization dynamics
   (b) Spin pumping and enhanced Gilbert damping
   (c) Noise in spin valves

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PHYSICS AND MEASUREMENTS OF COMMON MAGNETORESISTANCE PHENOMENA: AMR, AHE, GMR, TMR

Coriolan Tiusan [1, 2]

There are multiple ways in which magnetic materials can contribute to saving electric power and reducing CO2 emissions. For example, the conversion of electrical energy into mechanical work and vice versa is done using electric motors and generators, respectively, which imply the use of hard and soft magnetic materials. For electric vehicles, magnetic materials which retain their properties up to moderately high temperatures are needed. Advanced amorphous and nanocrystalline soft magnetic materials are also of interest for inductors/transformers in high frequency power electronics components and power conditioning systems. Thus, optimizing soft magnetic materials and extending the temperature span in which they are applicable can imply a notable enhancement in the energy efficiency of these devices. In this lecture we will overview the different families of soft magnetic materials with current technological interest, ranging from those which represent the largest volume in the global market (non-oriented and grain oriented electrical steels) to those with the lowest coercivity (amorphous and nanocrystalline alloys). We will focus on the mechanisms by which low coercivity values can be achieved, as well as on the different properties which should be optimized for a material to be suitable for its application as a soft magnet in the quasistatic frequency range or up to radiofrequencies.

Even the most complex spintronics devices embedded in the last generation technologies have at origin some basic spin and charge dependent transport phenomena. The aim of this lesson is to illustrate some major phenomena such as: *Anisotropic Magnetoresistance (AMR)*, the *Anomalous Hall Effect (AHE)*, the *Giant Magnetoresistance (GMR)* and the *Tunneling Magnetoresistance (TMR)*. When appropriate, we are distinguishing on different transport geometries: current-in-plane (CIP) and current-perpendicular-to-plane (CPP). After a brief explanation of the physical basis for each of these phenomena, we are going to illustrate it with major historical examples from the literature up to the state-of-the art in the field, followed by common and next generation device applications.

Anisotropic magnetoresistance

The resistivity of a ferromagnetic film submitted to an in-plane magnetic field varies with the angle θ between the flowing current I and the film magnetization M [Tsy] as: $\rho(\theta) = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp}) \cos^2(\theta)$. The and define the extreme resistivities when the current is either parallel or perpendicular to the magnetization. Phenomenologically, the AMR arises from the scattering asymmetry of electrons induced by the spin-orbit interaction, typically stronger when they flow along a direction parallel to the magnetization [RefAMR]. Historically, the AMR in $Ni_{80}Fe_{20}$ has been used as main magnetoresistance (MR) effect in early generations of read heads, before using the GMR. In practice, as we will illustrate, in magnetic multilayered systems where the CIP-GMR signal is small, the measured magnetoresistance effect has to be always corrected with respect to AMR, using specific compensated transport geometries.

Anomalous Hall effect

When a conductor is placed in a magnetic field, the Lorenz force pushes the electrons against one side of a conductor, defining the so-called Hall Effect. However, in ferromagnetic metals, this effect can be order of magnitude higher than in non-magnetic systems. This defines the anomalous Hall Effect (AHE). The origin of AHE is complex, often controversial, and involves intrinsic and extrinsic mechanisms [NagRMP2010]. The intrinsic mechanisms are mainly correlated to the material band structure. Within external electric field, electrons acquire an anomalous velocity perpendicular to the electric field, related to their Berry's phase curvature. The extrinsic mechanisms, *side-jump* and *skew-scattering*, implicate scattering. As a result, electrons with opposite spin are deflected along opposite directions. In *side-jump*, the electron velocity is deflected in opposite directions by opposite electric fields experienced when approaching and leaving an impurity. The *skew-scattering* represents a symmetric scattering due to the

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effective spin-orbit coupling of the electron or the impurity. Each mechanism has a specific scaling low. In this lesson we will illustrate how AHE analysis, within proper scaling law framework [TiaPRL2009], can be used to extract mechanisms responsible for AHE. Furthermore, we will illustrate the use of AHE measurements as a versatile magnetic analysis tool. From anomalous Hall effect measurements in variable temperature on lithographically patterned stripe lines with transverse Hall contacts, we can extract the variation of the anisotropy.

Giant Magnetoresistance

The GMR effect represents the variation of the resistance of a magnetic multilayer system, constituted by alternating ferromagnetic and nonmagnetic metallic layers, with respect to the relative orientation of the magnetization directions in the ferromagnetic films. Historically, the GMR was discovered in multilayers coupled antiferromagnetically [BaiPRL1988,BinPRB1989]. There, at remanence, an antiferromagnetic antiparallel (AP) configuration has been naturally stabilized, in contrast to the parallel (P) configuration attained at saturation for large in plane applied magnetic fields. For applications, the GMR effect has been successfully implemented developing the ***hard-soft architecture of spin valves***. In this architecture two magnetic layers with different magnetic rigidity are involved, one magnetically soft, called free layer, and the other magnetically hard, which is the reference fixed layer. Within a field window where the hard layer is magnetically locked, the free layer can be manipulated, providing a magnetoresistive signal defined as: $GMR = (R_{AP} - R_P)/R_P$ and a dependence of the multilayer resistance in $\cos\theta$ with respect to the relative angle between the magnetizations of the soft and the hard magnetic layers, respectively. Several solutions for achieving the hard magnetic subsystem are briefly illustrated, from Synthetic Antiferromagnets to Exchange Bias. We will explicitly discuss GMR measuring and applications for both CIP and CPP geometries.

Tunnel magnetoresistance

Tunnel magnetoresistance When two ferromagnetic films are separated by an extremely thin insulating barrier, the electron could flow across by quantum tunneling. The system is called Magnetic Tunnel junction (MTJ). The tunneling current is spin-dependent and, likewise a spin valve, the tunnel resistance depends on the relative configuration of the MTJ's magnetic electrode's magnetizations. The TMR effect is defined as: $TMR = (R_{AP} - R_P)/R_P$ with respect to the MTJ resistances in AP and P configurations. A special attention will be devoted to the TMR effects in MTJ, as elementary bricks of read-head sensors in high density hard disks and magnetic random access memories. After the historical analysis of TMR in polycrystalline MTJs, where the electronic transport is well described within the free-electron models, we will underline the correlation between the electronic structure and the magneto-transport properties in single crystalline MTJs [YuaJPD2007,TiuJPCM2007]. In these systems, the TMR effects are triggered by band structure features and symmetry dependent transport effects. The conduction channels are determined by electrons with given symmetry of their Bloch functions, as selected within the ferromagnetic electrodes. They will be selectively attenuated within the single crystal tunnel barrier, as a function of corresponding symmetry. Furthermore, we will illustrate by original experimental results how innovative magnetotransport characteristics and spin-torque properties can be tailored by either interfacial engineering or by involving magnetic electrodes constituted from complex alloys, from simple transition metal to full Heusler systems. Beyond standard TMR phenomena, we will briefly discuss the effect of the spin-orbit coupling in magnetic tunnel junctions by distinguishing Anisotropic Tunneling Magnetoresistance (ATMR) and Tunneling Anisotropic Magnetoresistance (TAMR) effects [MatPRB2008].

Beyond the specific analysis of each magnetoresistive phenomena, this lesson will indirectly sequentially illustrate the complexity of the experimental techniques involved in the elaboration of the experimental systems where they are measured: from single magnetic films, to complex magnetic multilayers (GMR, MTJ) lithographically patterned for current-in-plane or current-perpendicular-to-plane transport geometries. Therefore, we will rapidly shot on aspects related to ultra-high vacuum deposition techniques (sputtering, molecular beam epitaxy), in-situ characterization tools (RHEED), lithography techniques for patterning of CPP devices (optical, e-beam), tunneling spectroscopy experiments, atomic/magnetic force microscopy, XRD, TEM and HR-TEM, surface analysis techniques (AES, XPS, XMCD, spin polarized photoemission), different other static and dynamic (HF) magnetic and magnetotransport characterization tools.

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MAGNETIC DAMPING

Andrei Kirilyuk [1]

Damping of the motion of the magnetization vector, particularly the damping of the large amplitude motion, plays a significant role both in performance of magnetic devices, and in the fundamental processes such as for example ultrafast laser induced dynamics.

In ferromagnetic media, spin motions are described commonly through use of the Landau-Lifshitz equation that contains a phenomenological parameter α, the Gilbert damping constant. This controls the dissipation rate associated with either the small amplitude motions probed in ferromagnetic resonance (FMR) or Brillouin light scattering (BLS) studies of long wavelength spin excitations in ferromagnetic media and also that of large amplitude spin motions associated with magnetization reversals. The damping constant α is generally extracted from data on a particular system of interest; in most analyses, it is assumed either explicitly or implicitly that the damping rate is intrinsic to the material from which the sample is fabricated.

The aim of this lecture is to discuss the effects of basic dissipative mechanisms involved in the dynamics of the magnetization. The mechanisms may be roughly divided into direct relaxation to the lattice, and indirect relaxation via excitation of many magnetic modes. The first ones strongly depend on the nature of magnetic materials: we speak of "breathing Fermi surface" in itinerant magnets, and consider magnetostriction and magnon-phonon coupling in the localized ones.

The second type of mechanisms involves extrinsic contributions to the spin damping rate and other parameters that may control the dynamic response of magnetization. Such contributions are of great interest because they are subject to control through sample preparation, for example, to produce very narrow FMR lines. Conversely, in selected instances, one may wish to see spin motions more heavily damped. As an example of the latter case, it is desirable to suppress "ringing" of magnetization after reversal in certain devices.

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MAGNETIZATION PROCESSES AND DYNAMICS

Ulrich K. Rößler [1]

In these lectures magnetization processes are covered within phenomenological continuum theory. The basic ingredients will be introduced in terms of Ginzburg-Landau functionals and dynamical equations. Along our itinerary, some microscopic models for the phenomenological formulations can explain the microscopic underpinning and quantify the various phenomenological parameters arising in these theories.

Basic notion of magnetization dynamics will be introduced for ferromagnetic systems. Within the micromagnetic approximation the Landau-Lifshitz-Gilbert (LLG) equation can be used to describe diverse phenomena from extended oscillatory waves to eigenmodes at and transport of micromagnetic objects as domain walls, vortices, or skyrmions. Extending the dynamics to include longitudinal processes motivates the formulation of the Landau-Lifshitz-Bloch (LLB) equation. Including thermal noise in these deterministic dynamical equations can be achieved in the form of Langevin equations for either formulation. Some pitfalls in the interpretation of these stochastic equations will be highlighted.

In the second half of the lecture, coupled magnetic systems will be introduced where the dynamics and processes of the primary magnetic order (ferromagnetic magnetization but also antiferromagnetic order parameters) are influenced by other degrees of freedom in a material.

Such systems like multiferroics, display a rich phenomenology of processes with a wide perspective to explore new effects. The crucial symmetry considerations in formulating possible couplings between magnetic order parameters and other degrees of freedom provide a secure guideline to construct appropriate phenomenological theories. Some selected examples will be used to illustrate useful approaches towards such complex systems: the dynamics of weak-ferromagnets, i.e. antiferromagnets with canted spin-structure; coupled magnetic and dielectric excitations, called ferroelectromagnons in magnetic dielectrics or ferroelectrics; excitations and waves in magnetoelastically coupled systems. Within such theories, some exotic effects like localized and incommensurate quasi-static states, corresponding non-linear excitations, but also linear non-reciprocal wave propagation can be predicted and analysed.

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LIGHT CONTROL OF MAGNETISM: VARIOUS TIME- AND LENGTH SCALES

Andrei Kirilyuk [1]

While the basic possibilities for direct laser manipulation of magnetization have been indicated a long time ago, only recently was it possible to apply such control in magnetically ordered materials [1,2].

The question was immediately triggered whether one could use the same mechanism for practical switching of the magnetization in e.g. recording media. A seemingly straightforward answer came very soon afterwards, with a direct demonstration of all-optical light helicity-dependent magnetic recording in thin films of metallic GdFeCo alloys [3]. In spite of the fact that the switching was clearly reproducible and robust, the exact process and mechanism of it remained elusive for a long time. The most obvious explanation via the inverse Faraday effect could only very qualitatively account for the observed features. Taking into account several factors, all-optical switching of the magnetization in rare-earth - transition metal alloys was assigned to a completely different effect: a combination of ultrafast laser-induced demagnetization with the angular momentum conservation in the exchanged-coupled sublattices of a ferrimagnet, on a subpicosecond time scale [4].

In spite of the recent extensive work on all-optical switching of magnetization in a variety of samples [5,6], confusion persists as to its mechanism. Here we demonstrate, using various time resolved imaging techniques, that this confusion may be largely due to the fact that this phenomenon involves behaviour on multiple scales, both in space and time. At 100's fs, independent demagnetization of sublattices is observed accompanied by spin diffusive processes at <10 nm distances, as shown by time-resolved X-ray scattering [7]. This is followed by the exchange spring driven behaviour [4] with reversal and formation of skyrmion-like domains [8] at a few ps times.

In order to tune the exchange interaction between the sublattices, the alloyed samples were replaced with multilayers. Intriguingly, very large scale coherent precession could be observed that accompany the growth of large domains [9]. The presence of the compensation point added an extra spatial feature to the reversal dynamics in the multilayer samples.

To be technologically meaningful, the all-optical switching must be able to compete with the bit densities of conventional storage devices, restricting optically-switched magnetic areas to sizes well below the diffraction limit. We have recently demonstrated reproducible all-optical switching of magnetic domains of few tens of nm size [10], in a ferrimagnetic TbFeCo alloy using gold plasmonic antenna structures. It has also been found that the focusing of light to a nm sized area is helped by the light interference effects occurring within the magnetic structures themselves [11].

To summarize, such ultrafast exchange-driven ultrafast magnetization dynamics is not only potentially useful, but also provides us with invaluable information about the behaviour of magnets away from their thermodynamic equilibrium. For recent review the reader is referred to [4]. Considering the progress in the development of compact ultrafast lasers, optical control of magnetic order may also potentially revolutionize data storage and information processing technologies.

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SPINT-ORBIT EFFECTS IN TRANSPORT AND MAGNETISM

Tomas Jungwirth [1]

Since the relativistic spin-orbit interaction couples electron's momentum and spin it can lead to a range of effects when the system is brought out of equilibrium by, e.g., applied electric fields. Anisotropic magnetoresistance is a classical example of a relativistic magneto-transport effect, discovered in transition metal ferromagnets more than 150 years ago, that led to the development of the first generation of spintronic magnetic sensors and random access memory chips [1,2]. Remarkably, non-equilibrium spin-phenomena may occur even in non-magnetic spin-orbit coupled conductors. Prime examples are the spin Hall effect and the inverse spin galvanic effect which were experimentally discovered a decade ago as companion effects in normal semiconductors [3]. In the spin Hall effect, an electrical current passing through a material with relativistic spin-orbit coupling can generate a transverse pure spin current. In the inverse spin galvanic effect, a non-equilibrium spin-density of carriers is generated in spin-orbit coupled systems which lack inversion symmetry. Recently discovered relativistic spin torques in ferromagnets, originating from the spin Hall and inverse spin galvanic effects, are a subject of an intense research and are a candidate spintronic technology for a new generation of electrically-controlled magnetic memory and logic devices. Apart from paramagnets and ferromagnets we will show in the lecture that the relativistic magneto-transport phenomena provide means for realizing spintronic functionalities also in antiferromagnets.

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MATERIAL ELABORATION AND NANOFABRICATION TECHNIQUES FOR SPINTRONICS

Laurent Vila [1]

In this lecture, some basic principle of material elaboration and nanofabrication process by lithography techniques will be presented. These are key elements in our research field, in parallel to modeling and measurement techniques. One example could be MRAMs, where one needs to master the elaboration of very complex heterostructures, having some key layers thinner than 1 nm, and to shape them into nanopillars with top and bottom contacts, at challenging technological nodes, before playing with spin transfer torque or magnetic oscillations. Basic research projects will also drastically depend on the material elaboration abilities as well as their shaping into nanodevices or the building of the measurement environment at the nanoscale.

In this view, the lecture shall offer some key elements of the material elaboration and nanofabrication techniques. The general idea is to present their working principle and to provide some process guidelines. We will follow a progressive route, from the material elaboration, mask fabrication, by lithography, followed by transfer techniques and process control trough metrology steps.

For the material elaboration, the main technique to be discussed is sputtering deposition, some emphasis on molecular beam epitaxy and other deposition techniques will be also provided. For nanofabrication, electron beam lithography is the method of choice for nanopatterning at the lab scale. Several mask strategies will be presented. In contrast to semi-conductor technology, the transfer techniques using reactive ion etching are much less mature and require usually physical routes for spintronics devices. This will be object of the third part of the lecture. Finally, we will emphasize the importance of controlling the process using several metrology tools.

The lecture outline will be as follows:

1. Material elaboration
2. Lithography
3. Transfer techniques
4. Metrology

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MAGNETORESISTIVE SENSORS

Johannes Paul [1]

All magnetic sensors convert a magnetic signal into an electrical signal. For example the sensor can detect the angle of an applied magnetic field and delivers an analog or digital output which corresponds to the field angle. This general property is used to detect and control linear or rotational movements of magnets. Typically the magnet is mounted on a body which moves, e.g. a shaft or a valve or a bearing. Measuring the magnetic field immediately tells the movement of the body which holds the magnet. Based on this straight forward principle, the wheelspeed sensor [1] in vehicles is realized or many other linear or rotational sensors.

The two main magnetic sensor technologies are magnetoresistive sensors and Hall sensors [2,3]. The volume production of magnetic sensors is dominated by Hall sensors, because they offer the sensing element and the conditioning circuit in a monolithically integrated chip. Hall sensors are mainly used in consumer electronics such as compass application and for diverse automotive applications. Magnetoresistive sensors dominate the field of high precision measurements. They are also more temperature stable and can be used at higher temperatures, too. In this paper, only magnetoresistive sensors are discussed.

All magnetoresistive sensors are based on materials which change their electrical resistance depending on the strength and/or the angle of an external magnetic field. Because the resistance changes strongly with temperature, too, Wheatstone bridge designs are required with four magnetoresistive elements. Here each of the four elements follow the same temperature dependence such the temperature dependence of the bridge voltage is zeroed. By proper design the bridge voltage only reflects the response to the external magnetic field.

Today, three different technologies are used in MR-based sensors. This is the anisotropic magnetoresistive effect or AMR effect, the giant magnetoresistive effect of GMR effect, and the tunneling magnetoresistive effect or TMR effect [4]. In the talk these basic MR effects are introduced and discussed. For deeper understanding angle sensors and linear motion sensors are discussed for AMR and TMR. The relevance of key parameters like bridge offset, amplitude and phase will be explained. Special focus will be given on robustness and stress tests of sensors. Also quality control in mass production of spintronic devices will be discussed. Finally some highly fascinating applications can be shown.

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[4] http://en.wikipedia.org/wiki/Magnetoresistance

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FROM PHYSICS TO PRODUCT FROM MRAM TO MAGNETIC LOGIC UNIT (MLU)

Sergio O. Valenzuela [1, 2]

Sources of spin currents

A flow of electron charge is a charge current. The physics of the charge current has been studied for more than a century and is at the heart of modern electronics. However, because an electron also carriers a spin, the existence of electron flow naturally implies the possibility of flowing spins and of spin currents. With the advent of novel nanofabrication techniques in the last decades, the interest in spin currents has grown, giving birth to many novel phenomena in modern Magnetism. In this lecture, we will introduce the concept of spin current and discuss the different sources that are available to generate it. From the theoretical point of view, the formulation is not simple and still challenging, but its concept is extremely useful and versatile. We will show that spin currents can be generated using ferromagnetic sources, Zeeman-split density of states, magnetization dynamics (spin-pumping) and relativistic effects involving spin-orbit coupling (spin Hall effect). We will also see that a spin current can be carried by a spin wave a collective excitation of magnetization in magnets, or driven by the topological band structure in certain types of solids.

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SPIN ELECTRONICS AND CALORITRONICS OF MAGNETIC INSULATORS

Gerrit Bauer [1]

Spin caloritronics is the science and technology striving to understand and control not only spin and charge, but also heat currents in small structures and devices [1]. Spin caloritronic effects can be roughly classified into two groups. In ferromagnetic metals and its heterostructures the two-current series resistor mode works well to describe the giant magnetoresistance and related phenomena. Thermoelectrics can be formulated in a two current model as well [2], leading to phenomena such as the spin-dependent Seebeck and Peltier effects. The elementary excitations of the order parameter of a ferromagnet are spin waves or magnons that may carry spin and heat currents as well. The thermal actuation of spin waves by metallic contacts and the thermal pumping of spin current into the contacts lead to the phenomena of the spin Seebeck and spin Peltier effects that are relatively easy to observe and analyze in magnetic insulators [3] such as the ferrimagnet yttrium iron garnets (YIG). These materials have been studied intensively for half a century and can be grown with exceptional magnetic quality.

This lecture addresses the electric and thermal properties of magnetic insulators with and without metal contacts. We will discuss the theory of electric and thermal actuation of the magnetic order parameter in these structures at the interfaces and the bulk of the magnet. Topics to be discussed are:

1. *Magnetic insulators*
   (a) YIG crystal structure and properties
   (b) Spin waves in YIG
2. *Bilayers of magnetic insulators and normal metals*
   (a) Spin torque and spin pumping
   (b) Spin Seebeck effect
   (c) Spintronic Kirchhoff Laws
   (d) Spin Hall magnetoresistance
3. *Onsager analysis*
4. *Spin Seebeck effect in rare-earth doped YIG*

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ELECTRIC CONTROL OF MAGNETISM

Agnès Barthélémy [1]

Electric control of magnetism is currently drawing much attention due to its overwhelming advantage in energy consumption compared to magnetization manipulation by magnetic fields or spin polarized currents.

Different strategies have been proposed to exploit electric fields to affect the magnetization, magnetic anisotropy, exchange bias, Curie temperature, spin transport, etc., of magnetic systems. First observed in diluted magnetic semiconductors [1], such demonstrations were more recently extended to ferromagnetic transition metals [2] generally used in spintronics devices such as magnetic tunnel junctions due to their higher Curie temperature. This goal also boosted the field of multiferroic materials or architectures in which magnetic and ferroelectric orders can coexist and be coupled [3].

In this lecture we will review the progress in this field as well as the different mechanisms that allow such electric field control of magnetism including spin-dependent screening, interfacial bonding, surface/interface Rashba effect.

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FROM LAB TO THE FAB: PRODUCTION OF MAGNETIC MATERIALS FOR SPINTRONICS APPLICATIONS

Lavinia E. Nistor [1]

Materials, more or less sophisticated, are present in our life since several thousand years. Man's intelligence, in the need to improve his life condition, contributed to the evolution of the materials used in our daily life (from the simplest ones like the wood and stone to more complex ones like bronze and iron). The impact of materials in Man's evolution was so strong than we can assert it helped to model civilizations. For instance, in the case of Hittites (18th century before Christ), the improvement of the technique to fabricate very good quality iron made them one of the most advanced and powerful civilizations of the antiquity and helped them to dominate the Mediterranean region [Hum_04]. Another example from history: the bronze discovery was due to the insertion of 10% tin (Sn) in copper (Cu) in order to decrease its melting temperature, making easier the elaboration of different objects.

The appreciation of the materials impact in Man's history and evolution was illustrated in the History by naming each era after the material used:
– stone age - 4500 BC
– bronze age - 1700 to 0 BC
– iron age – 1500 AC to 1950 AC
The last era, the Iron age, is closer to our days. Iron is a material with a lot of applications in our days in different forms. Iron in pure state is a magnetic material very ductile and can be used as compass or as the core of a coil but is susceptible of corrosion. Adding some impurities such as C, P (1%) and Cr (10%), changes the mechanical properties of Fe and becomes stronger and it transforms in stainless steel.

One particular amazing demonstration of iron workmanship is the famous iron pillar from Delhi in India. The pillar made of forged iron is seven meters tall and has a purity of about 99.2% (quality obtained only in XIXth century in Occident), containing only small amounts of sulphur (0.08% S), phosphorus (0.11% P), silicon (0.46% Si), and carbon (0.08% C). This was fabricated by Indians in the middle of IIIrd century C.E. by using a one-step technique for steel fabrication by doing a mixture of Fe with glass then slowly heated in fire based on wood charcoal and then cooled. This metallurgic curiosity was solved only in 2002 when has been found that the Fe is protected by surface layer of iron hydrogen phosphate [2]. It is speculated that a combination of climatic factors, high P and S contents and a large heat capacity helped the inclusion of S and P at the surface. At that time the process of fabrication was not understood and was explained as a purification by fire. But later the process was scientifically explained: during heating the glass was purifying the iron by the impurities and the C and P was incorporated at the surface. The steel that we use today was discovered by a French metallurgist and geologist Pierre Berthier in 1821 studying the alloys of Fe with Cr. This examples show that the process of fabrication of materials as annealing or incorporating impurities can make a big difference in the materials physical properties opening the way for new applications.

In our days a lot of research work is conducted to improve the materials properties or discover new materials and understand their properties in order to feed our needs in terms of technological applications or to discover interesting phenomena to be understood and valorized. Today, the new techniques of thin film fabrication (nm thickness) like Molecular Beam Epitaxy or Physical Vapour Deposition (PVD, or sputtering) allowed growing very thin films of magnetic materials, metals or insulators in complicated stacks and made possible to evidence new physical phenomenon like:
– Interfacial perpendicular magnetic anisotropy (PMA) [Gra_68]
– Giant MagnetoResistance (GMR) [Bai_88, Bin_89]
– Tunnel MagnetoResistance (TMR) [Moo_95]
– Oscillatory character of RKKY exchange coupling [Par_91]

All these fascinating phenomena consider the spin of the electron in addition to its charge, associating magnetism and electronic transport in a new research area: the *spin electronics or Spintronics*.

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2. https://en.wikipedia.org/wiki/Iron_pillar_of_Delhi

As shown in the paragraph before the fabrications techniques can change and model material. So today as well research laboratories and Industrials R&D and Engineering divisions are focused a lot on new techniques of materials fabrication. Once the process is well developed and understood in the laboratory and meets industry requirements, as cost of manufacturing, it is transferred to mass production and for that the industry need to be prepared with very stable and precise tools. One of the biggest tools manufacturer industrials for electronic materials for semiconductor industry and "*one of the most important U.S. companies you've probably ever heard of, is Applied Materials*" [Thomas Friedman, The New York Time].

Applied Materials is the number one equipment manufacturer of PVD tools, having the leadership of the metallization over 20 years. This success was possible by dedication of the Applied Engineers and Scientists, to provide a solution for advanced metallization applications by replacing the chemical vapor deposition (CVD) technique with physical vapour deposition (PVD). Applied was already innovating for the CVD tools for example the Precision 5000 CVD tool was the first cluster tool and one of the industry's first single-wafer multi chamber platform. Since the impact that this released platform had on industry, a P5000 is available to be seen in Smithsonian Museum in United States of America. This platform served to the development of the first Applied PVD tool and the CVD reactor was transformed in PVD one, without a success at the beginning because the vacuum was not good enough and affected film growth. But this first attempt to make a PVD tool challenged Applied Scientists and Engineers to improve the vacuum by changing the platform from one load lock chamber to dual load-lock chambers, and the Endura platform was born in 1990 as the first ultra-high vacuum (UHV) production system (10^-9 Torr). Based on these innovations, the Endura system has played an instrumental role in enabling major industry milestones and inflections, including [AMAT]:

- Scaling aluminum interconnects to sub-1 micron designs
- Revolutionary transition to copper dual damascene interconnect
- Groundbreaking materials and architectural change in transistors: metal gate and 3D FinFET

Today the memories industry is searching for a new candidate for non-volatile memories applications. A high density/stable/fast MRAM memory using a tunnel magneto resistance phenomenon discovered in thin magnetic/metal/insulator films, is one of the nonvolatile memory candidates which could be used in different applications and replace the different memories of present times. Applied Materials is closely following the needs in tools for new technologies by constantly investing in R&D and Engineering of around 1.2 M$. Since this technology requires very thin films of 2Å to 200Å thick and more than 6 materials the actual single wafer multichamber cluster Endura is no more enough. A multicathode chamber can be a solution to increase the number of materials possible to an industrial tool and not increase the size of the tool. But the difficulty with a multicathode chamber is mostly related to the chamber design in order to have:

- Good film uniformity on 300mm wafers using smaller targets than the wafer size
- Manage the cross contamination between the targets in an industrial elegant way
- Manage the particles that can be created by sputtering of different materials in the same chamber, for examples metals have bad adhesion on oxides

The GMR discovery offered a new concept for magnetic sensor device: the *spin valve* [Die_91] *which had a huge impact on the HDD industry.* Giving a much improved sensitivity at nanoscale than inductive or even anisotropic magnetoresistance sensors, the spin valves were rapidly integrated in the read/write heads of the hard disk drive (HDD) industry. This allowed a fast increase of the HDD areal density, and inspired a new device for industrial applications, the *Magnetic Tunnel Junction.* The evolution from GMR heads to TMR in HDD heads is an example showing that even the film stack is complex can be industrialized giving a hope for the Magnetic Tunnel Junctions integration in MRAM chips.

The magnetic tunnel junctions (MTJ) are spintronic devices having two magnetic thin layers separated by a very thin insulator (oxide) layer so that electrons can pass from one ferromagnetic layer to the other by tunnelling. In this case the *spin filtering* effect is dominant compared to spin diffusion and the result is a very high relative resistance variation as a function of the magnetization alignment in the magnetic layers, called Tunnel MagnetoResistance (TMR). This is why MTJ devices have a higher output signal than spin valves, making them very attractive for industrial applications. The difference in the resistance values between the P and AP configuration of the magnetic layers can be used for binary coding so that new recording media applications or logic circuits can be imagined.

In the future, consumer needs for recording media will demand to combine high access speed, reduced noise, reliability, portability, non-volatility and low power consumption in the smallest possible chip with high density. For the last one the requirements of the memory industry regarding the memory point size are more aggressive than the read/write heads of the hard disk drive (HDD) industry, asking for memory points of the size of a transistor today (30nm). Even though this requirement on the size makes the integration of the MTJ in a MRAM chip more difficult, the advantages of MRAM make it worth it trying.

MRAM is attractive for industrial applications because it could, in principle, replace other kinds of memories and reduce consumption and operation time compared to FLASH (non-volatility) with a unlimited read/write endurance (10^15 read-write cycles), in addition to those of conventional RAM memories (speed of SRAM). For instance using a MRAM in a computer, data could be loaded directly into the working memory and wouldn't have to juggle between main memory (SRAM) and hard disk. This could make possible instant-on systems and innovate in the computer architecture. Already in 2013 Toshiba showed 80% reduction of energy consumption in the cache memory of an ARM-core based CPU when using an MRAM cach memory compared with an SRAM.

But, even if MRAM writing technique seems the simplest one using an applied field to switch the free layer magnetization, the architecture required is complicated and requires a lot of space for the electrodes that create the magnetic field, making impossible to reach high densities. In addition, Field Induced Magnetic Switching MRAM architectures reach their limits when the cell size is reduced below 100 nm. Decreasing the cell size will increase the current density necessary to produce the switching field and also the write power, the selection errors for writing the memory cells will also increase, as the impact of the thermal fluctuations on the data stability. A 4Mb-MRAM was commercialized by Freescale Motorola (now EverSpin) in 2006 [Eve_06] and finds applications in satellite, aerospace, automotive/telecommunications industries or memory embedded in controllers or printers.

A new physical phenomenon for magnetization switching, the spin transfer torque switching (STT) predicted by Slonczewski in 1996 [Slo_96, Ber_96] and first measured in spin valves [Kat_00, Sun_02, Puf_03] gives the possibility to create a STT-MRAM architecture showing considerable advantages:

- No more addressing errors because only the pillars traversed by the pulse current will be written.
- Increasing the memory density, by suppressing write line, enables 1 Transistor-1 MTJ per cell similar to DRAM and makes possible the MTJ cell size reduction.

In the case of nano-magnetic elements with in-plane magnetization, the thermal stability limit is not related to the current induced switching parameters, but to their shape. In materials without preferred in-plane axis for the magnetization (without crystalline anisotropy), a specific elliptical shape is required to stabilize the magnetization along the long in-plane axis in order to minimize the magnetostatic energy. Reducing cell size makes impossible to keep the elliptical shape and to prevent from magnetization curling due to thermal fluctuations. One solution is to define the magnetization direction of the free layer by coupling it to an antiferromagnetic layer (AF). The switching of the free layer is realized by heating the MTJ cell above the blocking temperature of the antiferromagnet. Based on this phenomenon Spintec proposed a new write concept based on thermally-assisted spin transfer torque switching (STTTAS-MTJ) [Pre_04, Oun_02, Noz_06, Her_10].

Using materials with out-of-plane anisotropy seems to be the only solution to increase the density of the memory chip and enhance the robustness against thermal fluctuations by keep the magnetization along one well-defined axis in MTJ (perpendicular to the film plane) [Mor_06, Car_08, Yoo_05]. Furthermore studies [Man_06, Nak_08] have shown that STT perpendicular structures may present lower critical switching currents and higher STT efficiency.

PMA can have different origins, either bulk (in hcp CoCrPt, heavy rare earth/transition metal alloys, or FePt $L1_0$ ordered alloys, or interfacial (in Pt/Co, Pd/Co, or Co/Ni multilayers). It has also been observed that a quite large PMA can be induced at the interfaces between the ferromagnetic electrodes and an oxide [Mon_02, Rod_03]. One can take advantage of this PMA from the oxide-magnetic electrode interface to fabricate out-of-plane MTJ.

The new out-of-plane MTJ elements are promising for industrial applications of memories and interesting for fundamental physics. The difficulty here is to find the right materials that can give at the same time the good structural match with the MgO barrier for high TMR and also an important perpendicular anisotropy to keep the magnetization out of plane in 0 field. The most interesting candidates for pMTJ electrodes are FePt $L1_0$ materials and the Magnetic Metal/Oxide bilayers. But this material requires fine tuning of the depositing tool. For Magnetic Metal/Oxides as CoFeB/MgO we need a PVD tool with a good precision for thickness deposition ($\sim$ 20 Å for CoFeB and 10Å for MgO) but also for interface roughness since in this films the anisotropy is an interface effect related mostly on the hybridization of the FeCo d orbitals and O p orbitals. For $L1_0$ ordered alloys as FePt in addition of the deposition precision of films as thin as 1-2Å we need a good vacuum and low deposition rates (<0.5 Å/s). On both materials we can play with the annealing in order to help the FeCo-O bond formation in MM/Ox materials and the Fe diffusion for the $L1_0$ ordered alloys of FePt. Also the Fe content can change the anisotropy properties for FeCo-O bonds and the ordering parameter on the FePt $L1_0$ ordered alloys. Results on this materials development and improvement in perpendicular MTJ structures will be presented during the talk.

But even if the stability problem seems to be solved by improving PVD tools for film process and choosing the right materials for the perpendicular MTJ stack other questions can arise in order to have an industrial device and are related to the scalability. The scalability can be limited by materials but also by nanofabrication techniques. In order to have a competing product we need to have memory pillars of 30nm or less in the size of a transistor in our days. So Applied Materials is investing a lot in development of the tools for etching in order to pattern nanometric devices. Some results will be shared during my presentation on electrical properties of patterned MTJ using the new developed etch tools by Applied Materials.

STT-pMRAM will be able to compete with FLASH memories and SRAM if these technical aspects are solved at similar production cost. Otherwise MRAM will be used in special markets like Battery-Backed SRAM replacement and would be attractive in applications where speed and permanent data storage are needed, eliminating the use of combined memories. Some examples of applications are the replacement of components of server systems, networking and data-storage devices, home-security systems and computer printers. The consequences are enormous considering the circuit size reduction, low system energy resulting in increased battery life, enhanced performance by improving efficiency of data transfer (the computer start speed). Even more, with MTJ it will be possible to take advantage of processional dynamics for low power operation or to obtain tunable radiofrequency oscillators leading to new RF devices for the mobile phone industry.

The engineering of pMTJ for MRAM applications is a real challenge and a difficult task because good TMR and PMA properties will impose constraints and limit the working window of the device. As observed the key for improvement of device properties are the materials combination and fabrication by good mastering of the thin film growth with very precise and stable tools but also the understanding the materials properties and physical phenomenon.

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THEORY OF SPIN TRANSPORT PHENOMENA IN MAGNETIC TUNNEL JUNCTIONS

Mairbek Chshiev [1]

The lecture will be devoted to quantum theory of spintronic phenomena in magnetic tunnel junctions (MTJ) with non collinear orientation of magnetizations. The concepts of spin current tensor and corresponding spin transfer torques (STT) will be introduced and discussed in the framework of different approaches including free electron and tight-binding models. The properties of in-plane (parallel) and out-of-plane (field-like) components of spin transfer torques as a function of applied bias, barrier thickness and distance from the interface in the free layer will be established. The relation between the equilibrium field-like component of the spin transfer torque and interlayer exchange coupling (IEC) between magnetizations of ferromagnetic layers across an insulating spacer comprising the magnetic tunnel junction will be demonstrated. The properties of STT and IEC as a function of MTJ structural and material composition asymmetry will be discussed.

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The European School on Magnetism 2015 - Practical on units

Olivier FRUCHART

[March 28, 2015]

In this tutorial we derive the dimensions for physical quantities of use in magnetism, and their conversions between cgs-Gauss and SI.

1 Notations

We use the following notations:

- X is a physical quantity, such as force in $F = mg$. It may be written $\mathbf{X}$ for vectors.
- $\dim X$ is the dimension of X expressed in terms of powers of fundamental dimensions, here length (L), mass (M), time (T) and electrical current (I). For example, dimensions of speed and electrical charges read: $\dim v = \mathsf{L}\cdot\mathsf{T}^{-1}$ and $\dim q = \mathsf{I}\cdot\mathsf{T}$. As a shortcut we will use here a vector matrix to summarize the dimension of quantities, with components the powers of fundamental dimensions; it will be written $[X]$ for the dimension of X. The above examples now read $[v] = [\mathsf{L}] - [\mathsf{T}] = [1\ 0\ {-1}\ 0]$ and $[q] = [\mathsf{I}] + [\mathsf{T}] = [0\ 0\ 1\ 1]$. We use shortcuts $[\mathsf{L}]$, $[\mathsf{M}]$, $[\mathsf{T}]$ and $[\mathsf{I}]$ for the four fundamental dimensions.
- In a system of units α (*e.g.* SI or cgs-Gauss) a physical quantity is evaluated numerically based on the unit physical quantities: $X = X_\alpha \langle X\rangle_\alpha$. X_α is a number, while $\langle X\rangle_\alpha$ is the standard (*i.e.*, used as unit) for the physical quantity in the system considered. For example $\langle L\rangle_{\mathrm{SI}}$ is a length of one meter, while $\langle L\rangle_{\mathrm{cgs}}$ is a length of one centimeter: $\langle L\rangle_{\mathrm{SI}} = 100\langle L\rangle_{\mathrm{cgs}}$. For derived dimensions we use the matrix notation. For example the unit quantity for speed in system α would be written $[1\ 0\ -1\ 0]_\alpha$.

2 Expressing dimensions

- Based on laws for mechanics, find dimensions for force F, energy $\mathcal{E}$ and power $\mathcal{P}$, and their volume density E and P.
- Based on the above, find dimensions for electric field $\mathbf{E}$, voltage U, resistance R, resistivity ρ, permittivity ϵ_0.
- Find dimensions for magnetic field and magnetization $\mathbf{H}$ and $\mathbf{M}$, induction $\mathbf{B}$ and permeability μ_0.

3 Conversions

Physics does not depend on the choice for a system of units, so doesn't any physical quantity X. The conversions between its numerical values X_α and X_β in two such systems is readily obtained from the relationship between $\langle X\rangle_\alpha$ and $\langle X\rangle_\beta$, writing: $X = X_\alpha\langle X\rangle_\alpha = X_\beta\langle X\rangle_\beta$. Let us consider length l as a example. $l = l_{\mathrm{SI}}\langle L\rangle_{\mathrm{SI}} = l_{\mathrm{cgs}}\langle L\rangle_{\mathrm{cgs}}$. As $\langle L\rangle_{\mathrm{SI}} = 100\langle L\rangle_{\mathrm{cgs}}$ we readily have: $l_{\mathrm{SI}} = (1/100)l_{\mathrm{cgs}}$. Thus the numerical value for the length of an olympic swimming pool is 5000 in cgs, and 50 in SI. For derived units (combination of elementary units), $\langle X\rangle_\alpha$ is decomposed in elementary units in both systems, whose relationship is known. For example for speed: $\langle v\rangle_\alpha = \langle L\rangle_\alpha\langle T\rangle_\alpha^{-1}$. Notice that in the cgs-Gauss system, the unit for electric charge current may be considered as existing and named Biot or abampère, equivalent to 10 A.

Exhibit the conversion factor for these various quantities, of use for magnetism:

- Energy $\mathcal{E}$, energy per unit area E_{s}, energy per unit volume E. The unit for energy in the cgs-Gauss system is called erg.

- Express the conversion for magnetic induction B and magnetization M, whose units in cgs-Gauss are called Gauss and emu, respectively. Express related quantities such as magnetic flux ϕ and magnetic moment μ.
- Let us recall that magnetic field is defined in SI with $B = \mu_0(H + M)$, whereas in cgs-Gauss with $B = H + 4\pi M$, with the unit called Oersted. Express the conversion for μ_0 and comment. Then express the conversion for magnetic field H.
- Discuss the cases of magnetic susceptibility $\chi = \mathrm{d}M/\mathrm{d}H$ and demagnetizing coefficients defined by $H_\mathrm{d} = -NM$.

Electronic structure calculations for magnetic systems

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I will present basic ideas of density functional theory (DFT) in four units with a focus on magnetic systems. Some of the ideas presented before in the lectures on basic concepts (Coey: Magnetism of single atoms) and on magnetism in matter (Blundell) will be re-considered from the viewpoint of DFT and supplemented with several application examples. In a related tutorial, I will demonstrate that such calculations can be even performed by a fearless novice .

Unit 1: Hohenberg-Kohn-Sham theory and Local Density Approximation (LDA)

In this unit, I will introduce one of the most powerful models applied in recent condensed matter physics. As a starting point I will explain why we are not able to solve the Schrödinger many-electron equation for systems larger than a few atoms and why it makes no sense to aim on this. As a consequence, we have to resort to **model theories** as opposed to quantum chemical *ab initio* calculations. One possible model, taking into account details of the system chemistry and geometry, is the Local Density Approximation (LDA). This is a **parameter free** but not a first-principles (a synonym for *ab initio*) approach. The LDA is based on the formally exact Hohenberg-Kohn theory and on the interacting electron gas model that can be solved numerically with an accuracy sufficient for all practical purposes. The related Kohn-Sham equations will be explained, their strength and limitations will be discussed.

Unit 2: Exchange, the root of condensed matter magnetism

Given the magnetic properties of electrons, quantum mechanical exchange is what provides their cooperation to form local atomic or molecular moments, or even long-range magnetic order in crystals. Elementary magnetic moments arrange themselves to lower the mutual Coulomb interaction of the electrons, being subject to symmetry restrictions of the fermionic wave function. I will dicuss the particular cases of the two-electron wave function and of the homogeneous polarized electron gas. The Local Spin Density Approximation (LSDA) will be introduced and the LSDA Stoner parameter will be defined. Calculated spin polarization energies for atomic shells will be compared with related spectroscopic data. The spin splitting of the Kohn-Sham states will be evaluated.

Unit 3: Tight-binding approach, chemical binding in a nutshell

As a corollary of the virial theorem, the reduction of potential energy will be identified as the driving force behind chemical binding. I will use the hydrogen-molecule to explain the basic ideas of the linear combination of atomic orbitals (LCAO, or tight-binding) approach, as well as the notation of bonding and antibonding states. Bloch's theorem will be introduced, and the tight-binding formalism will be applied to a crystal. In this way, discrete levels of finite systems are replaced by the density of states (DOS) in extended systems. An important technical point is the appropriate choice of atomic-like orbitals in a multi-band tight-binding calculation.

Unit 4: Tight-binding meets exchange, real systems and applications

In order to summarize and to apply the knowledge gained in the previous units, the electronic structure and the magnetic ground state of appropriate model systems will be discussed. First, I will analyze the spin-polarized molecular levels of the iron dimer. Second, the band structure and spin-polarized DOS of bulk bcc iron will be presented and explained. A third system, $La(Fe,Si)_{13}$, will be used to extend the scope to systems of emerging practical relevance. The peculiar electronic structure of this compound yields an extraordinarily flat dependence of the total energy on the magnetic moment and a related strong susceptibility to external influence (magnetic field, temperature, pressure). As a consequence, $La(Fe,Si)_{13}$ is a favored candidate for magneto-caloric applications. A final remark will be spent on topological insulators, recently disclosed non-magnetic systems with surface spin currents protected by the topology of the bulk band structure.

Suggested reading:

Helmut Eschrig, *The Fundamentals of Density Functional Theory*, Teubner-Texte zur Physik, Band 32, B.G. Teubner Verlagsgesellschaft, Stuttgart 1996, ISBN 3-8154-3030-5.
(Units 1, 2 and 3)

Manuel Richter, *Band structure theory of magnetism in 3d-4f compounds*, J. Phys. D: Applied Physics **31**, 1017-1048 (1998).
(Units 1, 2, and 4)

Manuel Richter, *Density Functional Theory applied to 4f and 5f Elements and Metallic Compounds*, Handbook of Magnetic Materials (Ed. K.H.J. Buschow), Vol. 13, Elsevier, Amsterdam 2001, pp. 87-228, ISBN 0-444-50666-7.
(Units 1, 2, and 4)

Claude Cohen-Tannoudji, Bernard Diu, and Franck Laloë, *Quantum Mechanics*, Vol. II, Hermann, Paris 1977, ISBN 0-471-16435-6.
(Units 2 and 3)

John Singleton, *Band Theory and Electronic Properties of Solids*, Oxford Master Series in Condensed Matter Physics, Oxford University Press, Oxford 2006, ISBN 0-19-850644-9.
(Unit 3)

Manuel Richter, Klaus Koepernik, and Helmut Eschrig, *Full-Potential Local-Orbital Approach to the Electronic Structure of Solids and Molecules*, in: Condensed Matter Physics in the Prime of the 21st Century, Ed. J. Jedrzejewski, World Scientific, Singapore 2008, pp. 271-291, ISBN 981-270-944-8.
(Unit 3)

Jürgen Kübler, *Theory of Itinerant Electron Magnetism*, International Series of Monographs on Physics, Vol. 106, Oxford Science Publications, Clarendon Press, Oxford 2000, ISBN 0-19-850028-9.
(Units 2, 3, and 4; general interest)

Stephen Blundell, *Magnetism in Condensed Matter*, Oxford Master Series in Condensed Matter Physics, Oxford University Press, Oxford 2006, ISBN 0-19-850591-4.
(Units 2 and 4; general interest)

Daniel C. Mattis, *The Theory of Magnetism Made Simple*, An Introduction to Physical Concepts and to Some Useful Mathematical Methods, World Scientific, Singapore 2006, ISBN 981-238-671-8.
(Unit 2; general interest)

Michael D. Kuz'min and Manuel Richter, *Mechanism of the strong magnetic refrigerant performance of* $LaFe_{13-x}Si_x$, Phys. Rev. B **76**, 092401 (2007).
(Unit 4)

C. Pauly *et al.*, Nature Physics 2015.
(Unit 4)

PRACTICAL
Quantum basis of the spin manipulation by electric fields

Coriolan TIUSAN[1,2]

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[2]National center of Scientific Research (CNRS), France

1/ Starting from the non-relativistic Dirac Hamiltonian, written for the case of a 2D free-electron gas with a confinement direction perpendicular to the propagation direction, we deduce the Rashba Hamiltonian. This strategy allows the direct identification of the Rasba interaction term and interaction constant alpha, as a measure of the spin-orbit interaction. One can thus understand how alpha can be controlled via the external electric field (in Datta-Das spin transistor geometry).

2/ as in a standard QM problem within the Heisenberg-Dirac formalism, we solve the stationary Schrodinger equation by diagonalising the spin-orbit Hamiltonian and find the eigenvalues and the stationary eigenfunctions.

3/ Furthermore, we study the time evolution, solving the time dependent Schrodinger equation. Then, by calculating average values of the spin operators Sx, Sy, Sz we can demonstrate and discuss the spin precession

4/ We analyse the spin-orbit influence on the calculated parabolic e(k) band structure and discuss how the spin-orbit constant alpha can be extracted from ARPES experiments. We can illustrate with some examples of ARPES for materials with important potential in spin-orbitronics (when materials with significant SO are used for generation of spin currents by spin-Hall effects).

The European School on Magnetism 2015
Calculation of spin accumulations and spin signals in nanostructures using spin resistors elements

L. Vila, Institut Nanosciences et Cryogénie, CEA Grenoble, France

The development of spintronics devices depends crucially on the understanding and calculation of spin transport in various nanostructures. In this practical we will use a simple method to calculate analytically the spin accumulations, spin currents and magnetoresistances in complex systems [1]. This can be used both for CPP experiments in multilayers and for multi-terminal nanostructures made of semiconductors, oxides, metals and carbon allotropes. This method primarily addresses the spin transport in multi-terminal spintronics structures, typically composed of several nanowires connected through transparent or non-transparent interfaces. Such a system can be described by a network of spin resistors connected by nodes, where each node is transparent. The concept of spin resistor is inspired from electric resistor concept, but here focus on spin current transport solely. Each wire and each non-transparent interface of the nanostructure (or each layer in the case of CPP transport) will be assigned to a corresponding spin resistor. We will then build the total systems of equation in the form of a Matrix, whose elements are the spin resistors that connect each node pairs, that link vector of current, at each node, to that of voltage at each node. This matricial product can be solved formally, in some simple case, or numerically, in more complex cases. The spin signal calculation, even of complex systems, becomes then a geometrical game, to construct the matrix and vectors, which then can be solved in a few minutes.

[1] W. Savero Torres, A. Marty, L. Vila, P. Laczkowski, M. Jamet and J-P. Attané, tbp

List of Posters

1. Abdallah Iman 'Magnetic and Structual Properties of Co_2MnSi Heusler alloys'
2. Adanakova Olga 'Temperature stability of exchange bias field and magnetoresistance of permalloy layer in $Fe_{20}Ni_{80}$/Tb-Co films'
3. Adhikari Rajdeep 'Dynamical generation of spin currents in GaN'
4. Aghavnian Thomas 'Structural and magnetic properties interaction in $CoFe_2O_4/BaTiO_3$ multiferroic heterostructures'
5. Ajejas Bazán Fernando 'Magnetization reversal mechanisms and magnetoresistance changes in thin film systems with tailored magnetic anisotropy'
6. Akosa Collins 'Phenomenology of chiral damping in noncentrosymmetric magnets'
7. Andersson Mikael 'A model superspin glass system'
8. Andriushchenko Petr 'The combinatorial approach for calculating the partition function for the Ising 1D spin chain'
9. Aza Eleni 'Two-dimensional frustrated manganites with coupled degrees of freedom'
10. Azimi Maryam 'Quantum information processing in multiferroic spiral spin chain'
11. Badiane Khalifa 'Electronic properties of single Cr atoms on GaAs(110) surface probed by Scanning Tunneling Spectroscopy'
12. Banasik Monika 'Magnetic properties and magnetization dynamics of magnetic tunnel junctions bottom electrode with different buffer layers'
13. Bochmann Sebastian 'Magnetic nanomaterials for three dimensional storage devices'
14. Boeije Maurits 'Magnetic and structural properties of hexagonal $(Mn,Fe)_3(Si,Ga)$ alloys'
15. Bouard Chloé 'B_{20} FeGe thin films elaboration for skyrmions observation'
16. Butler Katherine 'Spin torque oscillators and nanomagnetic logic for beyond-CMOS computing'
17. Carvalho de Melo Rodrigues Débora 'Magnon softening on magnetic surfaces'
18. Cerqueira Sá José António 'Micromagnetic simulations of the magnetization reversal processes in nanostructured arrays'
19. Chen Jinjie 'Kondo Effect and Inelastic Excitation on Metal Beta-diketonate Complexes'
20. Chinni Federico 'Magnetic properties of thin films and dot arrays based on the exchange-coupled IrMn/NiFe system'
21. Chitanu Elena 'Synthesis by co-precipitation method of exchange-spring hard ferrite nanocomposites'
22. Cimatti Irene 'Magnetic bistability of a sublimable Fe_4 Single Molecule Magnet'
23. Ciubotariu Oana-Tereza 'Investigation of Polycrystalline $La_{0.67}Sr_{0.33}MnO_3$ Layers on Silicon (111)'
24. Coelho Paulo 'Double Barrier Magnetic Tunnel Junctions'
25. Collet Martin 'Magnetic auto-oscillators made from nanometer-thick yttrium iron garnet (YIG)'
26. Corte-LeÓn Héctor 'Magnetic scanning gate microscopy of a domain wall nanosensor'
27. Dao Trong Phuong 'Spin-orbit torques in Au_xW_{1-x}/CoFe bilayer systems'
28. de Milly Xavier 'Dipolar coupling of spin transfer nano oscillator'
29. Deger Caner 'Magnetostatic spin wave resonance in patterned mumetal thin films'
30. Diaz Bachs Albert 'Stern-Gerlach measurements on Co doped with Rh'
31. Dirba Imants 'Increased magnetic moment and anisotropy induced by lattice expansion from α-Fe to α'-Fe_8N'
32. Edström Alexander 'Electronic structure calculations of d-electron materials with large magnetocrystalline anisotropy'
33. Elovaara Tomi 'Magnetophotoresistance in $Pr_{1-x}Ca_xMnO_3$'
34. Fabre Mathieu-Bhayu 'Three terminal spintronic oscillators'

35. Ferraro Elena 'Nonequilibrium fluctuations in nanomagnets'
36. Garandel Thomas 'First principles calculation of the Co(0001)/MoS_2 interface and spin injection from Co to MoS_2'
37. Gladii Olga 'Spin wave propagation and spin polarized electron transport in single crystal iron films'
38. Gomez-Arista Ivan 'Thermal induce transparency for short spin wave pulses in YIG'
39. Gort Rafael 'Ultrafast demagnetization, a transport property?'
40. Greving David
41. Grzybowski Michal 'Effect of magnetic field on intraionic photoluminescence of (Zn,Co)Se'
42. Hänni Nora 'Phase Transitions and Magnetic Properties in Series of Kagome-Compounds $Na_2M_3Cl_8$ (M=Ti, Mn, Mg)'
43. Hepburn Carolyna 'Surface acoustic wave propagation in magnetoelastic $Fe_{1-x}Ga_x$ thin films'
44. Hirian Razvan 'Effect of milling energy on the interphase exchange coupling of $Nd_2Fe_{14}B/\alpha$-Fe Nanocomposites'
45. Huisman Thomas 'Femtosecond control of spin-polarized photocurrents at the interfaces of metallic ferromagnetic heterostructures using circular polarized light'
46. Insinga Andrea 'Optimized Magnetic System for MagnetoCaloric Heat Pump'
47. Jaiswal Samridh 'Correlating Spin Orbit Effects and Structural Inversion Asymmettry in Multilayer Stacks'
48. Jiménez-Cavero Pilar 'Tunnel transport through $SrMnO_3$ / $La_{\frac{2}{3}}Sr_{\frac{1}{3}}MnO_3$ epitaxial bilayers investigated by CAFM'
49. Kalvig Roger 'Carbon induced modification of magnetic properties of Mn_5Ge_3 thin films studied by FMR and ^{55}Mn NMR'
50. Kaur Daljit 'Synthesis & Studies of structurally tailored cobalt nanowires'
51. Khan Mahmood 'Experimental analysis of magnetic materials for energy applications under non conventional supply conditions'
52. Kipgen Lalminthang 'XAS Study of Spin-Crossover Molecules $Fe(bpz)_2$bipy and $Fe(bpz)_2$phen on Surfaces'
53. Korniienko Ievgeniia 'Antiferromagnet NiO as a promissing material for spin pumping'
54. Lauer Viktor 'Control of the spin-wave relaxation in a magnetic insulator of macroscopic dimensions via spin-orbit torque'
55. Le Goff Adrien 'Dynamic and static characterizations of nanoscale Spin Transfer Torque Magnetic Random Access Memories'
56. Lopez Sanchez Jesus 'Raman study of ϵ-Fe_2O_3 nanoparticles embedded in SiO_2 Sol-gel films'
57. Makridis Antonios 'Promising green synthesis leads to cancer treatment through different magnetic hyperthermia strategies'
58. Marynowska Agata 'Ion beam modification of magnetic and structural properties of Fe/Pt multilayers'
59. Moreau-Luchaire Constance 'Skyrmions at room temperature: From magnetic thin films to magnetic multilayers'
60. Moreno-Ramírez Luis M. 'Characterization of mechanically alloyed magnetocaloric materials'
61. Moretti Simone 'Influence of Joule heating on current-induced domain wall depinning'
62. Mouillon Alexandre 'Spin-Orbit torques characterization by Anomalous Hall Effect quasi-static measurments in materials with perpendicular magnetic anisotropy'
63. Neves Bez Henrique 'First order magnetocaloric materials applied for heat pumps'
64. Omori Yasutomo 'Spin Hall Effect in Ferromagnetic metals'
65. Ortiz Pauyac Christian 'Spin swapping in ferromagnetic films'
66. Pancaldi Matteo 'Spin-wave modes and magnetization reversal in ferromagnetic nanostructures subjected to asymmetric magnetostatic interactions'

67. Pascotto Gastaldo Vinicius 'Investigation on Magnetoelectricity and Multiferroicity in Quadruple Perovskites'
68. Pauselli Maurizio 'Spin wave eigenmodes excited by spin transfer torque in circular nanopillars: influence of lateral size and Oersted field studied by micromagnetic simulations'
69. Pavlosiuk Oest 'Shubnikov-de Haas oscillations in the antiferromagnetic superconductor HoPdBi'
70. Perrin Yann 'Artificial square spin ice'
71. Piazzi Marco 'Magnetocaloric effect at the exchange-inversion with magnetoelastic coupling'
72. Porter Stephen 'Multiferroic Tunnel Junctions: A Spin Filtering Approach'
73. Raoux Arnaud 'Geometrical aspects of orbital magnetism'
74. Robert Anthony 'Easy axes alignment of Co nanoclusters'
75. Safonova Nataliia 'Tuning of magnetic properties of $L1_0$ FePt based thin films by ion irradiation'
76. Sauther Schorsch 'Magnetic properties of conduction electrons in ZnO-based heterostructures: de Haas-van Alphen oscillations and other effects'
77. Scheerder Jeroen 'Electrical detection of spin transport in metallic and graphene based lateral spin valves'
78. Schleicher Benjamin 'Structural and magnetic phase transition in epitaxial Ni-Mn-Ga-Co films on ferroelectric substrates'
79. Schott Marine 'Electric-field-effects on magnetic properties of ferromagnetic/oxide stacks'
80. Schroeter David 'Epitaxy and magnetism of FeGe thin films'
81. Škrátek Martin 'Measurement of magnetic nanoparticles in bio-structures'
82. Šmejkal Libor 'Manipulation of magnetic moments in antiferromagnets'
83. Song Kyung Mee 'Electric field induced interfacial magnetic anisotropy in CoFeB/MgO'
84. Staňo Michal 'Fabrication and imaging of magnetic nanotubes'
85. Steenbock Torben 'Quantum chemical evaluation of a Green's-function approach to exchange spin coupling'
86. Streib Simon 'Hard-core boson approach to spin-1/2 triangular-lattice antiferromagnets near the quantum critical point'
87. Talantsev Artem 'Effect of carrier concentration on remnant magnetization of MnSb clusters in granullar GaSb-MnSb films'
88. Trepte Kai 'Magnetic and electronic properties of DUT-8(Ni)'
89. Ummelen Fanny 'Asymmetric domain-wall depinning induced by Dzyaloshinskii Moriya interaction'
90. van der Tol Johan 'Magnetic deflection on atomic clusters'
91. Vautrin Christopher 'Recovering perpendicular anisotropy thanks to ultrathin Ta layer insertion'
92. Wagner Kai 'Spin-wave propagation within domain walls'
93. Wartelle Alexis 'Magnetic field-induced domain wall motion in cylindrical nanowires'
94. Witas Piotr 'Thermoelectric Properties of Heavy Fermion Compound $Ce_3Co_4Sn_{13}$'
95. Wrześniewski Kacper 'Andreev transport through triangular quantum dots'
96. Xiao Shunhao 'Spin-dependent relaxation dynamics at molecule-ferromagnet interfaces'
97. Yaari Maayan 'The possibility of quantum deflagration in the Fe_8 molecular magnet'
98. Ye Jingfan 'In-situ Neutron Reflectometry on Thin Magnetic Layers and Heterostructures '
99. Zahnd Gilles 'Spin current in Lateral Spin Valves'

2015 European School on Magnetism: « From basic magnetic concepts to spin currents »

24 August – 4 September 2015 – Cluj-Napoca, Romania

Email, research topic and arrival / departure dates are indicated for each person to help you get in touch with them.

Chair

Laurent VILA
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Spintronics - spin currents

24/08 → 04/09

Organizers

Viorel POP
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3d-4f intermetallic compounds, interphase exchange coupling in hard/soft magnetic nanocomposite

24/08 → 04/09

Olivier FRUCHART
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Domain walls and magnetization processes

24/08 → 04/09

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Magnetism of intermetallic and magnetocaloric materials

24/08 → 04/09

Claudine LACROIX
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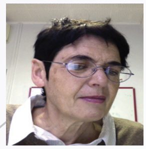

Magnetism and superconductivity of strongly correlated systems

25/08 → 31/08

Lecturers

Michael COEY
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Magnetic materials and phenomena

23/08 → 28/08

Steve BLUNDELL
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Magnetism in condensed matter

25/08 → 28/08

Ulrich ROSSLER
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Magnetization dynamics

24/08 → 02/09

Laura HEYDERMAN
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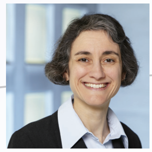

Magnetic thin films and hybrid nanostructures

25/08 → 28/08

Gerrit BAUER
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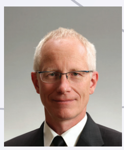

Spintronics - Spin caloritronicss

26/08 → 03/09

Coriolan TIUSAN
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(Tunneling) Magnetoresistance

24/08 → 04/09

Manuel RICHTER
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Electronic structure of magnetic materials

24/08 → 27/08

Tomas JUNGWIRTH
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Spintronics with antiferromagnet

01/09 → 02/09

Mair CHSHIEV
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Theory of spintronic phenomena in magnetic nanostructures

01/09 → 04/09

Agnes BARTHELEMY
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Multiferroics in thin films

01/09 → 03/09

Andrei KIRILYUK
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Magnetism at femtosecond and nanometer scale

28/08 → 30/08

Sergio VALENZUELA
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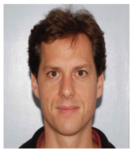

Spintronics and spincaloritronics

01/09 → 03/09

Johannes PAUL
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Magnetic materials for sensors

30/08 → 02/09

Lavinia NISTOR
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Magnetic thin films, fabrication techniques memory devicess

02/09 → 07/09

Dirk GRUNDLER
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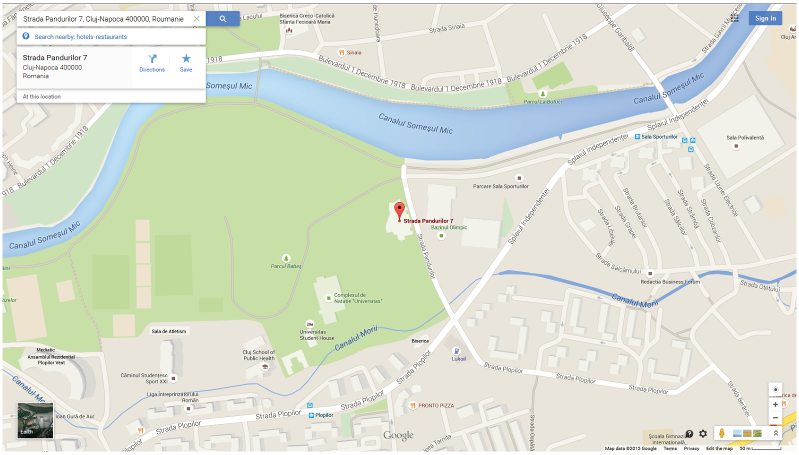
Nanoscale magnetic materials fab and charac, Magnetometry on low-dimensional electron systems, GHz spectroscopy, magnonics

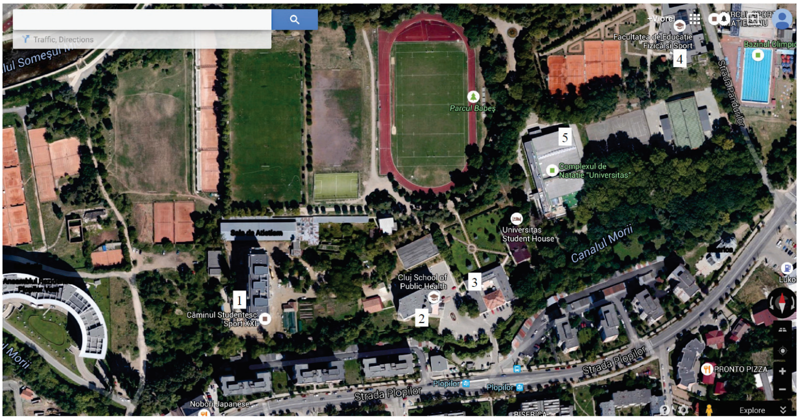
24/08 → 29/08

THE EUROPEAN SCHOOL ON MAGNETISM

Local information

The lectures, board and accommodation during ESM 2015 will be at the Faculty of Physical Education and Sport of Babes-Bolyai University, Pandurilor Street, No.7, RO- 400174 Cluj-Napoca; see on-line map, or static map (below) highlighting all ESM places: accommodation, lectures and so on.





1. Student accommodation
2. Lecturer accommodation (Hôtel Universitas)
3. Lunch and dinning place
4. Lectures (Faculty of Sport)
5. Swimming pool

Welcoming and registration for participants will take place at Hotel UNIVERSITAS-Babes Bolyai University Hotel, Pandurilor Street, No.7 (entrance from Plopilor Street, near the tram station), Cluj-Napoca, Phone: +40 264 429 788.
Participants will be met at the airport. Transport to the school site will be proposed. In case of trouble, you may reach the local chair, Viorel Pop: +40746 201 051.

Some advice about the Romanian (and more)...

Pronunciation

Romanian is a latin-based language, and above all a phonetic language, therefore each letter within a word is pronounced. There are a few special ones, as well as special phonetic groups:

ă The sound which French and Romanian people make when they are at a loss: "ăăăă..." It sounds just like the "u" in the English word "but", and somewhat close to the English indefinite article "a".

â/î This might be the trickiest one; it is used when people are faced with a dilemma: "âîîî...". Its pronunciation lies somewhere between the german "y"/"ü" (or French "u") and the English "ee".

ț The letter ț is pronounced "tz" like in the Italian "grazie" or "forza".

ș The letter ș is pronounced "ch" like in the French "choux", or like in the English "shaman".

ce This group is pronounced "tché" like the first syllable of the English words "cello" and "chestnut".

A few useful words and phrases

Good day	Bună ziua / Bună seara (the latter being used rather in the evening)
Good bye	La revedere
Please	Vă rog / te rog
Thank you	1. Very polite - Vă mulțumesc 2. Polite - Mulțumesc 3. Friendly - Mersi (pronounced just like in French)
Excuse me/Sorry	1. Very polite - Vă rog să mă scuzați 2. Polite - Mă scuzați 3. Friendly - Scuze / Pardon

I don't speak Romanian	Nu vorbesc română
Do you speak English/French?	1. Vorbiți engleză / franceză? (polite) 2. Vorbești engleză / franceză? (friendly)
I am looking for the address: (...)	Caut adresa: (...)
I would like to order...	Aș dori...[2]
This tastes (very) good - This is delicious	Este (foarte) bun - Este delicios
Excuse me? (I missheard)	Poftim? / Pardon?

Furthermore: do no hesitate to try and speak in English with the inhabitants of Cluj (or even French).

Local specialties

Mămăligă cu brânză și smântână Polenta with cheese and sour cream. A nice one best tried in a traditional restaurant.

Sarmale A Romanian specialty for meat fans, where the meat (which is similar to ground beef) is rolled up in cabbage leaves and boiled.

The cuisine has similarities with the French one, however the meat is always cooked through! Red meat lovers should remember to specifically ask for it. Furthermore, there is quite a tradition with soup.

In terms of alcohol, there should be a better selection of wines (*vin*) than beers. The wine labels go from dry (*sec*) through half-dry (*demi-sec*) to half-sweet/half-fruity (*demi-dulce*) and fruity (*dulce*). Here are a few suggestions from local wines: Fetească Neagră, Frâncușă de Cotnari (white and dry), and Lacrima lui Ovidiu (red, sweet). As far as beers (*bere*) are concerned, they are Pilsner most of the time; there isn't such a great variety. However, beer fans may ask for a blond beer (*bere blondă*) or a dark beer (*bere brună*) with: "O bere (...), vă rog", or try one of the following suggested brands: Ursus, Timișoreana and Bergenbier.

The organizers of the ESM 2015 gratefully acknowledge the help and advice provided by Ioan Augustin Chioar (Institut Néel, Grenoble, France) regarding the Romanian language and cuisine.

2. Practical and polite way of saying "I would like to have..."

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This booklet has been edited by Alexis Wartelle (Institut Néel, Grenoble).

Timetable of the European School on Magnetism ESM2015 - Updated 28 June 2015

	Mo 24/08	Tue 25/08	We 26/08	Th 27/08	Fr 28/08	Sa 29/08	Su 30/08	Mo 31/08	Tu 01/09	We 02/09	Th 03/09	Fr 04/09	
9h-9h30		Opening / Intro.	Coey (2/3)	Coey (3/3)	Lacroix	Tiusan (1/2)	Tiusan (2/2)	Excursion	Jungwirth	Valenzuela	Nistor	Transfer to Cluj airport	9h-9h30
9h30-10h													9h30-10h
10h-10h30													10h-10h30
10h30-11h		Coffee	Coffee	Coffee	Coffee	Coffee	Coffee + Posters		Coffee + Posters	Coffee + Posters	Coffee		10h30-11h
11h-11h30		Coey (1/3)	Blundell (2/3)	Blundell (3/3)	Grundler	Kiriyuk I					Practicals / Library		11h-11h30
11h30-12h							Questions		Vila	Questions			11h30-12h
12h-12h30	Transfer from Cluj airport and registration												12h-12h30
12h30-13h		Tutorials intro	Clips poster	Clips poster	Clips poster	Clips poster				Fill-in evaluation			12h30-13h
13h-13h30		Lunch	Lunch	Lunch	Lunch	Lunch	Lunch		Lunch	Lunch	Lunch		13h-13h30
13h30-14h													13h30-14h
14h-14h30													14h-14h30
14h30-15h		Blundell (1/3)	Richter	Heyderman	Bauer I (1/2)	Bauer I (2/2)	Kirilyuk II		Paul	Bauer II	Chshiev		14h30-15h
15h-15h30													15h-15h30
15h30-16h													15h30-16h
16h-16-30		Coffee	Coffee	Coffee	Coffee	Coffee	Coffee		Coffee	Coffee	Coffee		16h-16-30
16h30-17h		City tour	Questions	Practicals / Library	Sport	Rossler (1/2)	Rossler (2/2)		Practicals / Library	Barthelemy	Questions, evaluation and closing		16h30-17h
17h-17h30													17h-17h30
17h30-18h													17h30-18h
18h-18h30													18h-18h30
18h30-19h													18h30-19h
19h-19h30	Buffet / Transfer from Airport		Dinner	Dinner		Dinner	Dinner	Dinner	Dinner	Banquet	Dinner		19h-19h30
19h30-20h		Dinner & Drinks			Dinner								19h30-20h
20h-20h30													20h-20h30
20h30-21h			Practicals / Library	Computer Practical	Questions and beers		Practicals / Library						20h30-21h
21h-21h30													21h-21h30
21h30-22h													21h30-22h
22h-22h30													22h-22h30

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