NWO GRADUATE PROGRAM IN ADVANCED MATERIALS

PHD PROPOSAL

Novel Materials and Transport Phenomena with Classical and Quantum Skyrmions

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Top Master Programme in Nanoscience
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Theory of Condensed Matter
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Abstract

Magnetic skyrmions are non-coplanar nanosized spin structures, similar to tiny knots. First observed in 2009, they were found to have highly unusual physical properties, which make them suitable for spintronics applications. Being very small and highly mobile, skyrmions can be used as building blocks of a new generation of low-dissipation data processing and memory devices. The unusual dynamics of skyrmions driven by electrical and thermal currents is directly related to their non-trivial topology and its understanding is of fundamental importance. The proposed theoretical research will investigate new topological effects in the transport of charge and heat resulting from the coupled dynamics of skyrmions, electrons and magnons. The novelty of our approach lies in the study of skyrmions with new low-energy collective modes and in considering quantum effects, which will become important for nanometre-sized skyrmions in ultra-high density devices. One of the main goals of the proposed research is to identify and predict new skyrmion materials.

Research proposal

1 Introduction and background

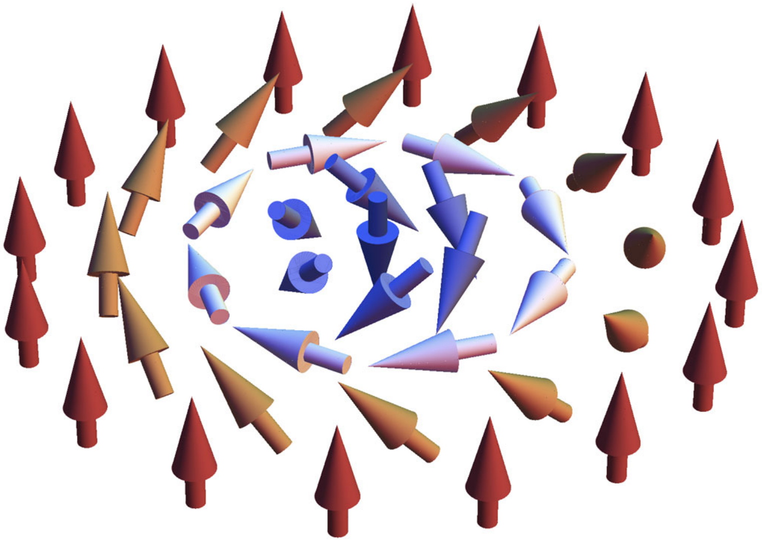
Skyrmions take their name from the British nuclear physicist T.H.R. Skyrme [1], who introduced them in the early 60's as a soliton solution of the nonlinear sigma model to describe mesons and baryons in a unified theory. With the advent of Quantum chromodynamics, skyrmions went out of the focus of the scientific community for about twenty years. It is in the seemingly unrelated field of Solid State Physics that they made their reappearance in the late 80's, when Bogdanov and Yablonskiy theoretically predicted the existence of spin structures similar to skyrmions in non-centrosymmetric magnetic materials [2]. Following these pioneering theoretical works, several experimental groups have recently found skyrmions in magnetic materials (ferromagnets, multiferroics and ferrimagnets) using a variety of techniques such as neutron scattering [3], Lorentz Transmission Electron Microscopy (LTEM) [4] and spin-resolved Scanning Tunneling Microscopy (srSTM) [5].

1.1 General properties of Skyrmions

In the context of condensed matter physics, magnetic skyrmions, or simply skyrmions, are particle-like nanometre-sized spin textures with a nontrivial topology that guarantees their stability against perturbations. A single skyrmion is shown in figure 1, where arrows represent spins. Skyrmions are stable in the sense that they are topologically protected: they are characterized by a topological integer number that cannot be changed by a continuous deformation of the spin configuration. The topological skyrmion number (or topological charge), $N_{sk} = {}^{1}/_{4\pi} \iint d^2r\, \mathbf{n} \cdot (\partial_x \mathbf{n} \times \partial_y \mathbf{n})$, counts how many times the unit vector vector $\mathbf{n}\,(\mathbf{r})$ in the direction of magnetization wraps around a unit sphere [6, 7]. For a single skyrmion $N_{sk} = \pm 1$. In addition to the topological charge, skyrmions are characterized by chirality and helicity (see figure 2). So far, only the skyrmions with the chirality $m = \pm 1$ and helicity $\gamma = \pm {}^{\pi}/_{2}$ have been observed.

Skyrmions appear in the ground state of several magnetic materials in some interval of temperatures and magnetic fields. How extended the region of skyrmion phase is depends on the interactions stabilizing these spin textures and on the dimensionality of the magnetic material. Most skyrmion phases in bulk materials only exist in a tiny pocket of the phase diagram near the transition temperature. The phase diagram of bulk MnSi with the

Figure 1: An isolated skyrmion. The spin orientation is indicated by arrows.



region where skyrmion crystals are formed is shown in figure 3. Thin films, nanoribbons and similar confined-geometry nano-structures, on the other hand, show phase diagrams with wider skyrmion phases extending to low temperatures and low applied magnetic fields (see for example the phase diagram of thin film $\mathrm{Fe_{0.5}Co_{0.5}Si}$ shown in figure 4).

Four mechanisms leading to the skyrmion state have been identified so far:

1. Long range magnetic dipolar interactions;
2. Dzyaloshinskii–Moriya (DM) interactions;
3. Four-spin exchange interactions (and in general more exotic exchange interactions);
4. Frustated exchange interactions.

Long range magnetic dipolar interactions are crucial for the formation of magnetic bubbles, some of which have the topology of skyrmions, in magnetic thin films with a perpendicular easy-axis anisotropy. The dipolar interactions favour an in-plane magnetization thus competing with the uniaxial anisotropy and resulting in a periodic stripe domain spin structure where the regions of up and down magnetization are separated by Bloch walls. An

Figure 2: Different skyrmion structures with varying vorticity m and helicity γ. The arrows and colours represent in-plane spin directions, while the brightness indicates the component normal to the plane (white = up, black = down).

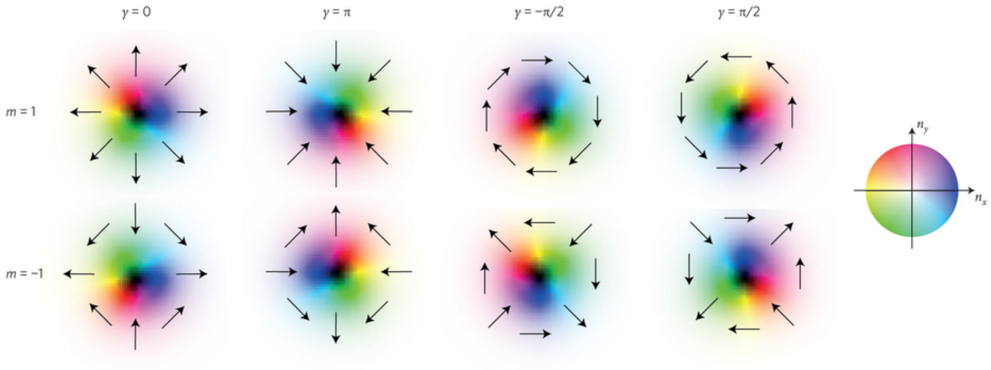


Figure 3: **a**: Phase diagram of MnSi at ambient pressure as a function of T and B [3]. Experimental points show boundaries between the different phases. The A-phase, shown schematically in the panel **b**, is characterized by a crystal of skyrmions.

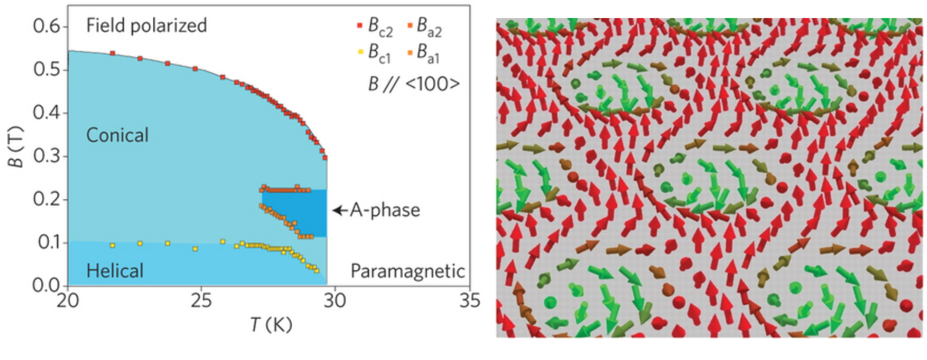
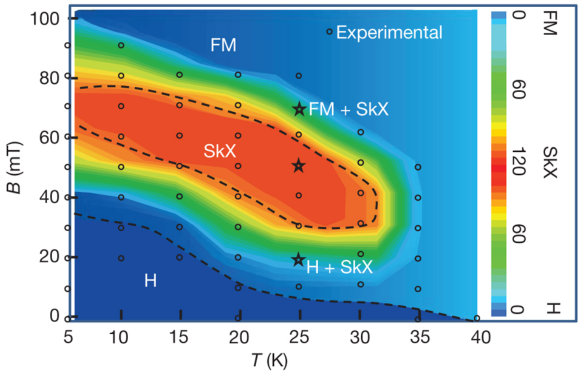

a **b**

Figure 4: Observed phase diagram of $Fe_{0.5}Co_{0.5}Si$ thin film in the B–T plane [4]. The colour bars indicate the skyrmion density per $10^{-12}\,m^2$. Dashed lines show the phase boundaries between the skyrmion crystal (SkX), spiral (H) and ferromagnetic (FM) phases.



applied magnetic field results in the formation of cylindrical domains (or magnetic bubbles) with the topology of skyrmions [8]. Since the magnetodipolar interactions are relatively weak, the skyrmions in thin magnetic films have typical dimensions of 100–1000 nm.

Another mechanism for the formation of skyrmions is the antisymmetric Dzyaloshinskii–Moriya interaction, $\mathbf{D}_{12} \cdot \mathbf{S}_1 \times \mathbf{S}_2$. It originates from the relativistic spin-orbit coupling and is present in many magnetic systems, often resulting in a small canting of spins (e.g., weak ferromagnetism of antiferromagnets). The DM interaction becomes particularly important in magnets whose crystal lattice lacks inversion symmetry. In this case, terms linear in gradient of magnetization, e.g. $D\,(\mathbf{n} \cdot \nabla \times \mathbf{n})$ (Lifshitz invariant), are allowed by symmetry in the phenomenological expression of the free energy, resulting in a coherent rotation of the spins. Thus the DM interaction in non-centrosymmetric magnets transforms a uniform magnetic state into a helical spiral. An applied magnetic field favours a state with three coexisting spirals, which is the skyrmion crystal (SkX) state. SkX phases in non-centrosymmetric magnets have been experimentally observed in MnSi [3], $Fe_{1-x}Co_xSi$ [9], FeGe [10] and $Mn_{1-x}Fe_xGe$ [11]. The size of skyrmions stabilized by DM interactions is in the range of $5 - 100\,\mathrm{nm}$. As this size is inversely proportional to the coupling constant D, materials with a higher value of D host smaller skyrmions. For example, skyrmions formed in MnGe have a radius of $\sim 3\,\mathrm{nm}$.

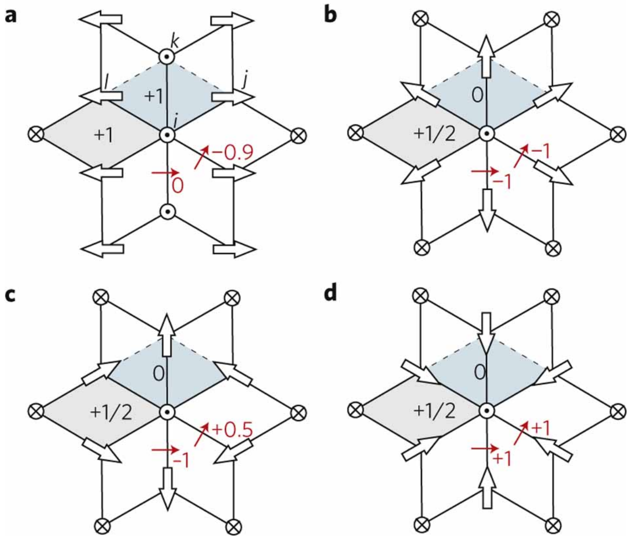
The four-spin exchange interaction occurs due to electron hopping between four adjacent sites (ring exchange). Its coupling constant is usually smaller than the Heisenberg exchange constant J and its contribution to the energy is often ignored. Nevertheless, there are systems where the four-spin exchange interaction plays an important role in the formation of complex magnetic structures. For example, *Heinze et al* [5] investigated the formation of skyrmions in hexagonal Fe films of one-atomic-layer thickness on the Ir(111) surface. Here the four-spin exchange interaction can compete with the exchange energy, as the nearest-neighbour ferromagnetic exchange coupling is unusually small for Fe/Ir(111) due to the strong $\mathrm{Fe}-\mathrm{Ir}$ hybridization. The four-spin interaction plays a crucial role in coupling different spin spirals (1D) into two-dimensional magnetic structures, but also DM interactions are important in such materials, as they lower the energy of the skyrmion ($N_{sk}=+1$) and antiskyrmion ($N_{sk}=-1$) lattices with respect to the multi-spiral state (see figure 5). Skyrmions resulting from such interactions are very small. Their size is comparable to the period of the underlying lattice.

Skyrmions have been theoretically predicted to form also in systems with competing Heisenberg exchange interactions, e.g. in triangular ferromagnets with next-nearest-neighbour antiferromagnetic interactions. The absence of inversion symmetry of the crystal lattice is not required for this mechanism [12, 13]. Skyrmions in such frustrated magnetic materials would be very small in size (∼lattice constant) and present many degeneracies: in contrast to the case of DM-stabilized skyrmions, where the chirality and helicity are fixed by the sign of D, here the formation of skyrmions of any of the types shown in figure 2 is possible. Unfortunately, to date, no frustrated materials satisfying the right properties have been experimentally synthesized, leaving the research opportunities to find new skyrmion materials wide open.

1.2 Possible applications of skyrmions

The interest of the scientific community in skyrmions is mostly driven by the fact that skyrmions are very promising information bits for novel types of spintronic storage and logic devices [21]. Magnetic bubble memories have been a topic of intense study in the 70's and are now used for niche applications. The research on manipulation of skyrmions is becoming very active, and a number of encouraging results is increasing the confidence of scientists that one day skyrmions will be implemented in devices useful to everyone. Today's hard-disk drives already achieve high densities of storage, but the increasing complexity and fragility of their mechanical parts motivate the need for solid state devices with comparable or even higher bit

Figure 5: **a**–**d**: Illustration of a spin spiral and skyrmions of different rotational senses and topological charge N_{sk}. **a:** 90° spin spiral ($N_{sk} = 0$); **b**: clockwise skyrmion ($N_{sk} = +1$); **c**: antiskyrmion ($N_{sk} = -1$); **d**: anticlockwise skyrmion ($N_{sk} = +1$). The size and sign of the four-spin interaction term is indicated by black numbers for different diamonds (shaded areas) consisting of four adjacent lattice sites (ijkl). The in-plane projection of the DM vector $\mathbf{D}$, which couples spins on adjacent sites, is also given by red arrows for pairs of nearest neighbours. The value of the DM term is indicated by red numbers. Adopted from ref. [5].



densities. The prime example of such devices [22] is based on ferromagnetic domains (spin up or spin down), separated by domain walls and located on a magnetic nano-ribbon in a train fashion. The train of domain walls can be moved electrically through the spin torque, thus making it possible to read and write magnetic bits. However, there are some problems with this technology. Namely, the critical current densities necessary to depin domain walls are too high, resulting in too much energy consumption and dissipation. Furthermore, the dimension of the magnetic domains cannot be made smaller than about 50 nm, rendering this approach still too far from the transition to a competitive technology.

Skyrmions might help to solve most of these issues. *Joniets et al* have demonstrated that the critical currents needed to move skyrmions are about six orders of magnitude smaller than the ones needed to move domain walls [19], suggesting that the skyrmion-based devices would have much lower power consumption. Moreover, skyrmions that can be as small as a few nanometres (and in principle, even comparable to interatomic spacing) can potentially provide an ultra-high information-storage density.

Significant challenges still have to be met before skyrmionic devices can become a reality. All the studied skyrmion systems, for example, show a crystal of skyrmions at low temperatures (up to 250 K). For memory applications though, we would need to be able to manipulate single skyrmions at room temperature. To tackle this issue, Fert, Cros and Sampaio have recently shown through micro-magnetic simulations that layered structures of high-T_c materials and surface-induced DM interactions can stabilize skyrmions at room temperature [20]. A significant step forward for the realization of skyrmion writing/deleting processes was made at the University of Hamburg, where PhD student Romming and co-workers were able to write and delete single skyrmions with a spin-polarized STM tip on an ultra-thin magnetic film [23].

Even lower energy consumptions could be achieved following a parallel and modern all-spin approach, named *magnonics*. The scope of this new research field (initialized in 2009 in Dresden[1]) is still under debate, but the main concept is the one to manipulate information bits with magnons instead of electrical currents. Energies involved in the dynamics of all-spin systems are much lower with respect to the conventional ones where electrical currents are used, therefore, moving the skyrmions with magnons will be

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[1] The first magnonics conference, entitled 'Magnonics: From Fundamentals to Applications' was held in Dresden in August 2009, sponsored by the visitor programme of the Max Planck Institute for the Physics of Complex Systems (MPIPKS).

much more energetically efficient. Recently, a collaboration between the University of Groningen and *RIKEN (Japan)* found that magnon currents can force skyrmions to rotate in a Feynman's ratchet-like fashion, suggesting that magnons can indeed be used to control the motion of these spin textures [25].

1.3 Skyrmion dynamics and new topological effects

The non-coplanar skyrmion spin configuration brings about some novel and intriguing physics, in particular, when we consider the propagation of spin-polarized electrons through skyrmions. Understanding electron-skyrmion interactions is very important for the control of skyrmions with electrical currents.

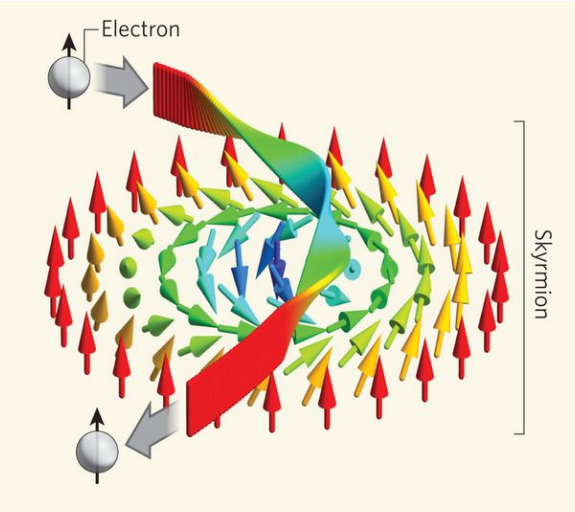
When a spin polarized electron propagates through the spin texture of a skyrmion, its wave function gains a Berry phase deriving from the non-trivial skyrmion topology. This phase happens to coincide with the phase gained by the wave function of a charged particle propagating in a magnetic field. Therefore, effectively the skyrmion acts on electrons as a flux ϕ of magnetic field. Moreover, this magnetic flux is quantized: $\phi = N_{sk}\phi_0$, where $\phi_0 = \frac{hc}{e}$ is the elementary magnetic flux.

The resulting effective gauge potential for electrons is $a_\mu = \frac{1}{2}\left(1 - cos\theta\right)\partial_\mu\phi$, where θ and ϕ are the spherical angles describing the direction of the local magnetization [14] and μ is the space-time index. The 4-vector potential $a = (a_0, \mathbf{a})$ gives rise to internal electric and magnetic fields, $\mathbf{e}$ and $\mathbf{b}$: just like in the case of the electromagnetic vector potential $\mathbf{A}$, $\mathbf{b} = \nabla \times \mathbf{a}$ and $\mathbf{e} = -\nabla a_0 - \partial_0\mathbf{a}$. It is important to notice that these effective fields are often very strong. An estimate of the magnitude of $\mathbf{b}$ is $\langle \mathrm{b} \rangle \sim \frac{\phi_0}{\pi R_0^2}$, where R_0 is the radius of the skyrmion. Thus the smaller the skyrmions, the larger the fields. For MnSi with $R_0 \sim 18\,\mathrm{nm}$ the effective magnetic field is about $20\,\mathrm{T}$, while for MnGe with $R_0 \sim 3\,\mathrm{nm}$ it is about $400\,\mathrm{T}$.

When electrons pass through a static skyrmion (see figure 6), their motion is affected by the magnetic field $\mathbf{b}$. When the current is higher than some critical pinning value, the skyrmions gain a momentum from the electrons and generate an electric field $\mathbf{e}$, which in turn also affects the motion of electrons. A deep understanding of this coupled electron-skyrmion dynamics is of fundamental importance for the field, both from the applied and the theoretical points of view, and most of the ongoing research today focuses on this issue.

Depending on the sign of the skyrmion topological charge, electrons passing through a skyrmion are scattered to the left or to the right, giving rise

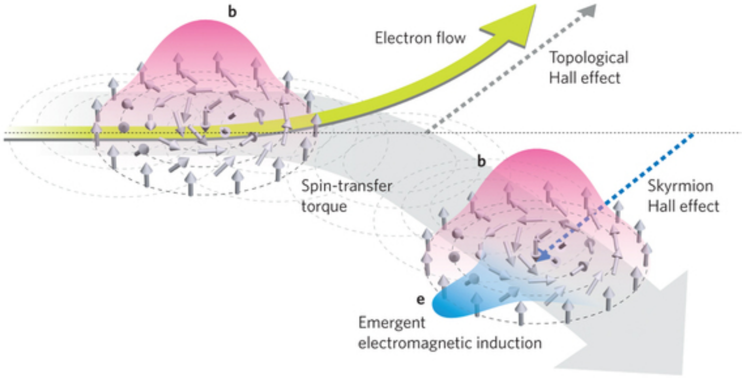
Figure 6: Artist-impression of a single electron moving through a skyrmion in the adiabatic approximation, in which the electron spin aligns perfectly with the local magnetic moment. This interaction gives rise to the Berry phase gauge potential a_μ.



to a novel type of Hall effect, the Topological Hall Effect (see figure 7). It was shown that the Hall resistivity ρ_{xy} decreases with increasing velocity of the skyrmions [16, 15]. Indeed the velocity of moving skyrmions can be measured exploiting such a dependence. Another Hall effect resulting from the Gilbert damping of skyrmions, is the Skyrmion Hall Effect (SHE), i.e. the motion of skyrmions in the direction normal to the applied electrical current [17]. The topological magnon Hall effect (TmHE) has also been measured and theoretically modelled recently [25].

While the emerging electromagnetic fields from the electron-skyrmion interactions resemble the usual electromagnetic fields, the dynamics of skyrmions is highly unusual. In particular, the Y coordinate of the skyrmion plays the role of momentum for the X coordinate, and *vice versa*, i.e. there is a canonical conjugate relation between the X and Y coordinates of the skyrmion. Another unusual consequence of the non-trivial skyrmion topology, is the fact that the skyrmion velocity is perpendicular to the force applied to it. This results in the gyroscopic motion of skyrmions.

Figure 7: Artist impression of topological phenomena related to skyrmions. Adopted from [26].



2 Research goals

Like many of the interesting phenomena that occur in nature, the dynamics of skyrmions is very complex and difficult to model. Although a number of important steps have been made towards a deeper understanding of the dynamics of skyrmions and all involved processes, the current theoretical description is based on many simplifying assumptions and approximations. For example, the dynamics of skyrmions is considered independently of the dynamics of electrons. This latter is assumed to be given, to be uniform and time-independent. In reality, this is far from true, since the emerging electromagnetic fields that affect the motion of electrons are highly non-uniform.

2.1 Coupled electron-skyrmion dynamics

Many problems and questions still remain partially or totally unsolved. One of them is the intrinsically coupled dynamics describing the motion of skyrmions under electrical currents, which is fundamental for future applications. One has to solve simultaneously the Boltzmann equation for the electron distribution $f(\mathbf{r}, \mathbf{k}, t)$:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_r f - e\left[(\mathbf{E} + \mathbf{e}) + \mathbf{v} \times (\mathbf{B} + \mathbf{b})\right] \cdot \nabla_k f = -\frac{1}{\tau}(f - f_0) \tag{1}$$

and the Landau-Lifshitz-Gilbert equation for the spins:

$$\frac{\partial \mathbf{n}}{\partial t} + (\mathbf{j} \cdot \nabla)\,\mathbf{n} = -\mathbf{n} \times \frac{\delta H_s}{\delta \mathbf{n}} + \mathbf{n} \times \left[\alpha_G \frac{\partial \mathbf{n}}{\partial t} + \beta\,(\mathbf{j} \cdot \nabla)\,\mathbf{n}\right] \tag{2}$$

where, in equation (1), $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields, $\mathbf{e}$ and $\mathbf{b}$ are the emergent electric and magnetic fields, $\mathbf{k}$ is the electron wave vector, $\mathbf{v}$, τ, $-e$ and f_0 are the velocity, mean free time, charge and equilibrium distribution function of electrons, respectively; and in equation (2), H_s is the spin Hamiltonian, $\mathbf{j}$ is the electron current density, α_G is the Gilbert damping constant and β represents non-adiabatic effects.

This system has been approached so far in simplified ways. For example, fixing the value of the current $\mathbf{j}$ and finding the resulting skyrmion motion, or fixing the position of the skyrmions and finding the effects on the motion of electrons. The proposed research focuses on finding a general solution to this system of equations, taking into account the feedback from the emerging electromagnetic fields. The solution of this system of equations will enable us to predict new charge transport phenomena in skyrmion crystals.

2.2 Coupled magnon-skyrmion dynamics

The interest in the field of magnonics is visibly increasing in today's research as it leads to an energy saving alternative of the current-based motion of skyrmions, replacing the charge currents by magnon currents. Very intriguing is also the possibility to make devices based on insulating magnets, like the insulating helimagnet Cu_2OSeO_3 [18].

It has been shown that a skyrmion also acts on magnons as an effective (quantized) flux of magnetic field [24, 25]. Qualitatively, it is very similar to the case of electrons, but the flux for magnons is two times larger, since magnons are spin-1 particles. The effects observed for charge currents, like the topological Hall effect, have also been suggested to occur for magnon currents (topological magnon Hall effect). All of this suggests a similarity between the effects of electron-skyrmion and magnon-skyrmion interactions.

This area of study is new and unexplored, which is why this research proposal focuses on studies of magnon-skyrmion dynamics and the control of skyrmions with magnons

In addition to the similarities, there are of course differences when dealing with magnon currents. In the first place, magnons do not carry charge, but orbital momentum and heat. Thus the study of magnonics could help understand and find novel thermo-electric effects, new dissipation mechanisms, spin relaxation processes and transport effects never found before.

Moreover, unlike charge, the number of magnons is `not` conserved: this brings some, otherwise forbidden, interesting phenomena into the game. Problems to tackle can be the radiation of magnons from a moving skyrmion: what is the flux of magnons emitted by a moving skyrmion? And what is its relation with the velocity of the skyrmion? Further, these new processes could mean a radiative friction applied to skyrmions. How important it is and what is its physical origin, are the questions which will be addressed in the proposed research.

2.3 Quantum effects

Skyrmions can have rather varying dimensions, and consequently, the models used to describe them also change quite a lot. Most of the skyrmions we have seen so far have been approached with a macroscopic, phenomenological, Landau-style description. This was possible because the size of the skyrmions was much larger than the lattice constant of the hosting materials. When skyrmions become too small though, their stability is no longer guaranteed by topology, because angles between neighbouring spins become large. Such skyrmions can decay into magnons, especially when driven by external currents or fields. The study of the stability of small skyrmions is very important for their applications as information bits. In addition, small skyrmions have to be treated quantum mechanically. In particular, their orbital angular momentum has to be quantized. Such quantum treatment and the resulting effects have never been considered before. Interesting quantum effects to investigate are, for example, the rotational motion of quantum skyrmions at 0 K and the spontaneous decay of skyrmions into multi-magnons. The collective dynamics of skyrmions in the quantum regime needs a special treatment and has not been considered yet.

2.4 Innovative materials

A topic of big scientific interest is the stabilization of skyrmions in frustrated magnets. We have seen that such skyrmions can be very small in size and possess more degrees of freedom (e.g. helicity) compared to the skyrmions in MnSi. This could mean a lower effort to move or rotate them, for example. To date no materials are known that host such skyrmions.

We will study models of frustrated magnets to understand the necessary requirements that lead to the stabilization of skyrmions. This study will help the quest for new skyrmion materials, and is aimed at proposing real materials that can be synthesized at the Zernike Institute for Advanced

Materials.

3 Methods

Several approaches will be necessary to pursue this research. As mentioned above, dynamics of skyrmions can be understood by solving the phenomenological Landau-Lifshitz-Gilbert equation. The distribution of electrons and magnons in non-equilibrium systems will be found from the solution of the microscopic Boltzmann equation. We shall use both analytical and numerical methods to solve this coupled system of equations.

Monte Carlo simulations will be used to study frustrated magnets. Numerical simulations will also be used to study the skyrmion dynamics driven by magnon currents. For example, the magnon modes in the presence of a skyrmion have to be numerically computed by solving a Schrödinger-like equation.

4 Potential collaborations

There are several research groups at the Zernike Institute for Advanced Materials directly or indirectly related to the topic of this research proposal. This calls for collaboration with the following groups:

Physics of nanodevices Prof. Dr. Bart J. van Wees working on spin caloritronics (spin and heat transport) in nanodevices. Prof. Dr. Tamalika Banerjee working on the propagation of spin currents in magnetic insulators.

Optical condensed matter physics Collective skyrmion modes can be excited by the magnetic field of a light wave in the THz region. The transition from a spiral state to a skyrmion crystal can be seen in optical absorption. We can use the expertise of Dr. Raan I. Tobey in the optical study of excitations in skyrmion crystals.

Solid state materials for electronics It will be very desirable to collaborate with Dr. Graeme R. Blake and Prof. Dr. Beatriz Noheda Pinuaga in the synthesis of novel skyrmion materials and their characterization. Their expertise in neutron and X-ray scattering techniques will be very valuable.

5 Planning and timing of intermediate steps

The four years of research will be approximately organized as follows:

1st/2nd year Learning the theoretical methods and the state of the art of the research on skyrmions. Focus on the study of the coupled dynamics of electron-skyrmion and magnon-skyrmion systems.

3rd year Study of the quantum effects. Design of new materials potentially good for skyrmionics.

4th year Summarize the work done. Thesis writing.

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Starting date and project duration

The intended starting date for the project is 1st September 2014, for a total duration of four years.

Further financial support, infrastructure, research material

Funding is requested for the salary of one PhD position (4 years) to be filled by the applicant + 5k€/year (4 years) of running budget (schools, conferences, travels). There is no need of further financial support for research material and infrastructure.

Curriculum Vitae

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Occupational field and competences

Theoretical Condensed Matter Physics. Computational and theoretical physics. Experimental methods in physics, especially with regard to nanoscience-related techniques.

Professional experience

September 2013 – present	Research work (Master thesis) at the Center For Theoretical Physics (CTN) - group of Theoretical Condensed Matter Physics. Zernike Institute for Advanced Materials, University of Groningen - Groningen (The Netherlands) Research topic: dynamics of Skyrmions. Supervisor: Prof. M. Mostovoy
Spring & Summer 2013	Speaker and organizing committee member, 10th edition of the Top Master in Nanoscience advanced research symposium, titled “Exploring the greatness of the small”.
Feb–June 2013	Research project on the mechanism of intramolecular photostabilization in self-healing cyanine fluorophores. Molecular Microscopy group, subgroup of the Single Molecul Biophysics group – Zernike Institue for Advanced Materials, RUG.
2008 – 2011	Private lectures on Physics and Math subjects to high school and university students.
August 22–31 2011	Attendance to the summer school on semiconductor devices and CMOS “Campus@Micron” at the italian site of Micron Technology, in Avezzano (AQ), with positive result in the final test–out (**32**/**35**). Info about the project at http://www.micron.com/italy/univrel/workshop/campusatmicron.html
January 2011 – July 2011	Research work at STN laboratories (Surfaces Thin films and Nanostructures) in the Physics department of the university of L’Aquila with a view to the elaboration of my final thesis. Research topic: Graphene and Graphene Oxide. Supervisor and research team leader: Dr. Luca Ottaviano (http://www.aquila.infn.it/~lottavia/main/LOTPAGE.htm).
May 15–18, 2011	Participation and organization support to “ GraphITA” (http://graphita.bo.imm.cnr.it/), important and successful workshop on Graphene with attendance of scientists and researchers from 34 different countries, including the 2010 Nobel Prize for Physics Prof. Konstantin Novoselov.
June and July 2010	Researcher (scholarship winner) in the project “Microswimmer olympics” in the Physics department of UCD – University College Dublin (Ireland). Research topic: motion (swimming) at low Reynolds numbers – computational. Project leader: Dr. Vladimir Lobaskin (http://www.ucd.ie/research/people/physics/drvladimirlobaskin/).

Selected works

“Magneto Optic Plasmonics”. Review paper – University project (RUG), July 2013.

“Assembling stable fuorophores for single-molecule spectroscopy”. Presented at the Nanoscience Symposium “Exploring the greatness of the small”. University of Groningen, June 2013. Part of this work (article where I am aknowledged): *ChemPhysChem*, **14**, 4084–4093 (2013)

“Study of chemical composition at the edges of Graphene Oxide by X-ray photoemission spectroscopy and optical microscopy”. Bachelor exp. thesis – Università dell’Aquila, July 2010.

“Swimming at low Reynolds numbers”. Presented at the Summer School Symposium. Physics department of UCD – University College Dublin (Ireland), August 2009.

“The solar neutrino problem”. Review paper – University project (UCD), October 2009.

Education and training

Sep 2012 – Aug 2014

International Master degree (M.Sc.): “Top Master Programme in Nanoscience” at the Zernike Institute for Advanced Materials, University of Groningen (RUG) (The Netherlands).
www.rug.nl/research/zernike/education/topmasternanoscience
Thesis topic: dynamics of Skyrmions.

Sep–Dec 2011

M.Sc. student in Physics of Matter at “La Sapienza” university of Rome (RM)–Italy. Quitted earlier due to new carrier opportunities.

Sep 2007 – Jul 2011

Bachelor’s degree (B.Sc.): Physics at “Università degli studi” university of L’Aquila (AQ), with final grade **110/110 magna cum laude**.
Thesis title: “Studio della composizione chimica ai bordi di Ossido di Grafene mediante spettroscopia di fotoemissione a raggi X e microscopia ottica” *Study of chemical composition at the edges of Graphene Oxide by X-ray photoemission spectroscopy and optical microscopy*.

Sep 2009 – Jun 2010

Erasmus EMPS third year student at University College Dublin (Ireland), A.Y. 2009-2010, School of Physics. Degree: Physics.

July 2007

Diploma of Higher Secondary School: *Maturità Scientifica* – Liceo Scientifico at “Liceo Scientifico Galileo Galilei” Pescara (PE)–Italy. Five years. Final grade: **96/100**.

Stays abroad

August 2012 – present

Groningen, The Netherlands. Study stay (M.Sc.).

September 2009 – August 2010

Dublin, Ireland – Study stay + summer research at UCD.

Summer 2002

Brighton, UK. Language study stay.

Personal skills and competences

Mother tongue(s)

Italian

Other languages

English, Spanish

Self-assessment
European level(*)

	Understanding		**Speaking**		**Writing**
	Listening	Reading	Spoken interaction	Spoken production	
English	C2 Proficient user	C2 Proficient user	C2 Proficient user	C2 Proficient user	C2 Proficient user
Spanish	A1 Basic user	A1 Basic user	/	/	/

(*) *Common European Framework of Reference (CEF) level*

Dutch

Will be attending a Dutch course of 50 hrs from 11/02/2014 (projected level: A2)

Technical skills and competences	Familiarity with the most advanced and cutting-edge physics laboratory equipment and nanofabrication processes, in particular: vacuum technologies, CVD, sputtering and related; optical microscope, XPS, UPS, SEM, AFM, EBL, X-ray Powder Diffraction, Molecular Absorbtion-Emission Spectroscopy in UV-VIS; fabrication of Organic Solar Cells and Organic Transistors, building of Ti:sapphire optically pumped solid-state laser.
Computational	Knowledge of standard algorithms for: interpolation, linear systems solving, numerical derivation and integration, numerical solution to differential equations, minimization, fits, Monte Carlo simulations, *etc...*
Programming	Good knowledge of languages C, C++, ForTran95 and tcl. Knowledge of the simulation package ESPResSO (Extensible Simulation Package for the Research on Soft matter) gained in the UCD research experience. Basic knowledge of Labview. Good aptitude for quick learning of new programming languages.
Operating Systems	Good knowledge of GNU/Linux based distributions and Windows O.S.
Softwares	Excellent knowledge of a wide range of programs for data analysis, among others: Gnuplot and ROOT (on GNU / Linux), Matlab and Mathcad; software designed ad hoc by myself if necessary and / or useful in the programming languages I know. LyX and LaTeX for writing professional documents. GIMP and Photoshop for image processing. Mathematica for math expressions manipulation.
Experiments	Good skills in setting up experimental apparatus, organizing and rationalizing data acquisition, solving general problems, DIY and hand-work.
Math	Good skills in working with all Maths related to Physics, handling expressions, *etc...*
Social skills and competences	At ease with teamwork and with leadership (I was group leader of five people, involved in the organization of a science symposium).
Organisational skills and competences	Always had a genius, in every social context, for responsibility roles, performed with the due organization not sacrificing nevertheless creativity.

Memberships

2011–2013	Invited member of the Italian Physics Society (SIF).

Additional information

Licenses	B and A3

I hereby declare that the information in this Curriculum Vitæ is exact and truthful.

Detailed academic career

Personal information

Surname(s) / First name(s)	**Pozzi, Alessio**
Address(es)	Permanent: via S. Angelo 11, 65019 Pianella (PE), Italia Term: A. P. Fokkerstraat 51, 9713JK Groningen, The Netherlands
Telephone(s)	+31 6 2333 2635 (NL)
Email(s)	maglevitation@gmail.com
Nationality(-ies)	Italian
Date of birth	23/02/1988, born in Pescara (PE)–Italy
Gender	M

Master degree (M.Sc.)

Top Master Programme in Nanoscience

Zernike Institute for Advanced Materials
University of Groningen
Groningen – The Netherlands
www.rug.nl/research/zernike/education/topmasternanoscience

A.Y. 2013/14	*M.Sc. Thesis*. Final grade: to be obtained. *PhD Proposal*. Final grade: to be obtained. *Quantum Field Theory*. Final grade: extra-curriculum. *Advanced Quantum Mechanics*. Final grade: extra-curriculum.
A.Y. 2012/13	*Physics of Lasers*. Final grade: **9/10**. *Theoretical Condensed Matter Physics*. Final grade: **10/10**. *Mathematical Methods of Physics*. Final grade: **10/10**. *Statistical Methods in Physics*. Final grade: **10/10**. *Paper*. Final grade: **7.5/10**. *Small Research Project and Symposium*. Final grade: **7.5/10**. *Preparation of Nanomaterials and Devices*. Final grade: **7/10**. *Characterization of Nanomaterials*. Final grade: **8.5/10**. *Fundamental and Functional Properties of Nanomaterials*. Final grade: **8/10**. *Tutored Self Study (Inorganic and Organic Chemistry)*. Final grade: **9/10 and 9/10**.

Bachelor's (B.Sc.)

110/110 magna cum laude

Physics

Università Degli Studi Dell'Aquila
L'Aquila (AQ) – Italy
http://cdlfisica.aquila.infn.it/CAD/270/Eng-L30-Fisica-AQ.html

Average grade	**29.095 / 30 (97.0 %)**
Weighted average grade	**28.912 / 30 (96.4 %)**
A.Y. 2009/10	B.Sc.Thesis. Final grade: **30/30**

Astrofisica (Astrophysics). Final grade: **30/30 cum laude**.
Fisica dei fluidi (Physics of fluids). Final grade: **30/30**.
Istituzioni di fisica teorica (Institutions of theoretical physics). Final grade: **30/30**.
Laboratorio di elettronica (Electronics laboratory). Final grade: **30/30**.
Laboratorio di elettronica digitale (Digital electronics laboratory). Final grade: **30/30**.
Metodi matematici della fisica (Math methods of physics). Final grade: **30/30**.
Microfisica quantistica (Quantum microphysics). Final grade: **30/30**.

Examinations approoved by the Physics C.D.C.S. (teaching professors council) of the University of L'Aquila given the obtained results, the exams and their grades, according to the ERASMUS criteria. Here are original courses attended at UCD in Dublin:

Foundations of Quantum Mechanics. Final grade: **A+**.
Foundations of Fluid Mechanics. Final grade: **A+**.
Functions of One Complex Variable. Final grade: **A+**.
Nuclear Physics. Final grade: **A+**.
Introductory Quantum Mechanics. Final grade: **A+**.
Quantum Mechanics. Final grade: **A+**.
Thermodynamics and Statistical Physics. Final grade: **A+**.
Stellar Astrophysics. Final grade: **A+**.
Advanced Laboratory I. Final grade: **A+**.

A.Y. 2008/09

Analisi matematica II (Mathematical analysis II). Final grade: **27/30**.
Elettromagnetismo (Electromagnetism). Final grade: **28/30**.
Introduzione alla fisica moderna (Intr. to modern physics). Final grade: **27/30**.
Lab. di fisica computazionale (Computational physics lab). **30/30 cum laude**.
Chimica (Chemistry). Final grade: **30/30**.
Meccanica classica e analitica (Classical & analytical mech.). Final grade: **27/30**.
Lab. di elettromagnetismo (Electromagnetism lab). Final grade: **26/30**.

A.Y. 2007/08

Geometria (Geometry). Final grade: **28/30**.
Introduzione alla fisica (Introduction to physics). Final grade: **30/30**.
Analisi matematica I (Mathematical analysis I). Final grade: **30/30**.
Lab. di mecc. e termodinamica (Mech. & thermodynamics lab.). Final grade: **30/30**.
Laboratorio calcolatori I (Computers lab. I). Final grade: **30/30**.
Meccanica e termodinamica (Mechanics & thermodynamics). Final grade: **28/30**.

I hereby declare that the information in this transcript is exact and truthful.

university of groningen / faculty of mathematics and natural sciences / zernike institute for advanced materials

Version 3 Dec. 2013

Declaration of hospitality and financial support for research costs

Appendix to the Proposal for a PhD research position
in the NWO Graduate Programme Advanced Materials, deadline 2 Feb. 2014

Name of the applicant: Alessio Pozzi

Title of the proposal: Novel materials and transport phenomena with classical and quantum skyrmions

By signing this document the staff member declares that she/he is willing to host and supervise the PhD research project that is mentioned above. In addition, the staff member declares that she/he has and makes available the materials, infrastructure and the funding that is needed for covering the research costs (the costs in addition to the salary of the PhD student some funding for travel and training), as described in the proposal.

The signing staff members must be affiliated with the Zernike Institute for Advanced Materials (including the associate members).

Signatures

Applicant (the student applying for the PhD grant)

Date: 01/02/2014 Name: ALESSIO POZZI Signature:

Daily PhD supervisor (only needed if applicable, in case of supervision by an assistant professor or UD/UHD without ius promovendi)

Date: Name: Signature:

1st Promotor (staff member with ius promovendi)

Date: 01-02-2014 Name: Prof. M. Mostovoy Signature: