Annual Report | 2018

Center for Quantum Spintronics

QuSpin

Norwegian Centre of Excellence
The Research Council of Norway

NTNU
Norwegian University of Science and Technology

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Quantum Physics through the wave function Psi, describes the quantitative behavior of microscopic particles and their interactions.

Psi, the 23rd letter of the Greek alphabet, represents the wave function, used by the scientist Erwin Schrodinger in 1925. And was later interpreted by the Nobel Laureate in Physics, Max Born, as a "probability amplitude".

FOREWORD BY CENTER DIRECTOR ARNE BRATAAS

Welcome to our Quantum Future

Quantum physics has been around for more than a hundred years. It successfully describes atoms, light, and their interactions. Quantum physics, for the most part, remains a hidden gem that reveals itself just in dedicated laboratory experiments. Smoking guns only appear around tiny objects that are invisible in our daily lives. However, get yourself ready for a take-over and revolution, perhaps in even your handheld device.

Quantum physics is bizarre since the behavior of nature strongly differs from our perception. Schrödinger's cat is a provocative thought experiment that illustrates the novelty of quantum physics. Erwin Schrödinger published in 1935, after co-fostering the invention of quantum physics, the most widely used example identified with quantum physics - Schrödinger´s Cat Paradox. Strangely, the imaginary cat can be simultaneously both alive and dead. The faith of the cat depends on random events that may or may not occur.

Quantum physics, through the wave function Psi, describes the quantitative behavior of microscopic particles and their interactions. According to quantum physics, a system can be in a simultaneous superposition of two or more states. This appears to be at odds with nature we observe in our daily life. Schrödinger's cat illustrates what happens if a macroscopic object behaves as a single microscopic particle. Our naïve intuition tells us that the cat cannot be dead and alive at the same time, yet, for simple and small enough entities the analog of this is exactly what occurs.

The macroscopic world is also determined by quantum physics, although the quantum nature is seldom directly encountered. A macroscopic object consists of a vast number of microscopic particles. For the macroscopic object to exhibit measurable quantum features, all microscopic particles must be in coherently related states. For a huge number of microscopic particles that are the building blocks of a macroscopic object, macroscopic quantum behavior is often extremely unlikely. Usually, macroscopic quantum behavior is so rare that for all practical purposes, even by waiting for periods that equals the age of the universe, it is impossible to observe it. Besides, macroscopic objects are also coupled to other macroscopic objects that further decrease quantum coherence.

There are a few exceptions that QuSpin focuses on. Magnetism is a macroscopic quantum phenomenon where all spin degrees of freedom are aligned. Furthermore, the electron spin, the appearant rotation of the electron around its axis, has a quantum mechanical origin. Superconductivity, the manifestation of zero electrical resistance and no energy loss, is also caused by a macroscopic quantum state.

Our vision is to trigger a revolution in low-power information and communication technologies in an energy-efficient society.

Until now, the arrangements of the building blocks of matter where set by spontaneous developments in nature. While we throughout the last century started to see matter down to the atomic scale, the revolutionary new development is the unprecedented new control over these structures. We can build matter just like a child puts LEGO blocks together. We can choose the 'colors' and the 'sizes' of the elementary units. We can put the units at desired locations. An increasing number of developments in nanotechnology utilize quantum effects in new ways that greatly impact society at large. The developments of blue light-emitting diodes have dramatically changed the way we use light. We need significantly less energy than previously. Electronic devices use the quantum variable of the electron, spin, to enhance functionality. Spintronics was behind the introduction of Apple's iconic iPod and is central in the services provided by technology giants Google, Microsoft, Amazon, and Apple.

Technological needs and scientific curiosity drive the nano-scale creation of new artificial materials in which basic physics has still to be explored. Center of Quantum Spintronics uses the quantum playground to create new opportunities for the appearance of quantum effects. We focus on new ways to utilize the electron spin in more power efficient ways. In the not too far future, the technology might include the bizarre nature of quantum physics. On the way to such a paradigm, we will reveal new quantum phenomena and get a better understanding of quantum physics at a larger scale and with a higher degree of precisions than previously.

Our Energy Efficient Future with Big Data

Ever considered how much data over twenty-four hours the 1.5 billion daily users of Facebook consume as they chat, watch videos and navigate from Facebook to nearly ten million websites daily?

When then considering the usage statistics behind Apple, Google, YouTube, Netflix, data mining for Bitcoin, as just a few examples, data transfer, and storage needs compound into a staggering amount. Followed by their continuously increased energy consumption needs, new ways to handle this efficiently is pressingly needed.

What about the devices we use to access, process and store this data? Most of the devices waste energy by heating their surrounding environment. This excessive heat generation has limited the sizes to which we can reduce devices to.

At this juncture, our center, the Center for Quantum Spintronics (QuSpin), and the basic research we are engaged in comes into play. QuSpin's research addresses the fundamental challenge of power consumption and heat generation as electronic devices scale to quantum scales. Our motivation is the need for dramatic improvements in electronics devices. State-of-the-art electronics miniaturization has reached an incredibly small scale of almost 10 nanometers in length. Beyond a 5-year horizon, conceptually new ways of harnessing quantum phenomena become essential for ultra-power innovations.

Our goal through our research, and with partners across the world, is to harness new possibilities in how we understand and utilize the electron. We hypothesize that the waste of energy in conventional electronics can be circumvented by utilizing the dynamics of quantum entities other than the electron charge.

QuSpin's objective is to develop the basic science that uses quantum entities such as the electron spin as information carriers in radically different ways. We aim at groundbreaking basic research that is crucial to the development of fast, high-capacity, material systems and tools for smaller and more power-efficient electronic devices. In turn, new knowledge can be carried forward by other fields to advance data and devices with greater efficiency.

Our research will contribute to the unraveling of quantum mysteries and the discovery of new phenomena. We believe that data transport and storage, and electronic device energy consumption can be revolutionized on a quantum scale through solutions on a nano level utilizing new phenomena in new materials, material combinations, and processes.

By moving the frontier of our knowledge frontier in basic research, we want to enable low-power information and communication technologies in a sustainable society for future generations.

Illustration:

THE ELECTRON SPIN: *The electron spin, the electron's magnetic moment, is a prime example of a quantum entity. Classically, when the earth orbits around the sun, it has an orbital angular momentum. The spin is the electron's intrinsic angular momentum. It is as if something orbits around inside the electron. While such an analogue can be useful, it is not what really happens. Instead, the spin is an intrinsic property of the electron. Furthermore, in measurements, there are only two possible outcomes of the spin, clockwise rotation or counter-clockwise rotation. We denote these states as spin-up and spin-down.*

A Center of Excellence

The QuSpin center, recognized in 2017 as one of the ten new Centers of Excellence by the Research Council of Norway, carries the responsibility in providing the resources and space for international researchers, to delve into and unravel the beautiful complexities of condensed matter physics to further our understanding and control of quantum physics in the pursuit of future innovations.

To innovate in the field of Spintronics the center will, throughout the next ten years, be receiving part of the 1.5 billion Norwegian Kroner which will be funding all the Centers of Excellence.

By the end of 2018, the center developed into the more than sixty member strong team with members from twelve different countries. QuSpin now has eleven permanent professors and associate professors, four researchers, seven postdocs, twenty-six PhD students, twenty master students and one administrator.

QuSpin being an international research center, values having a highly professional international advisory board of researchers, as well as an experienced board with senior researchers from NTNU.

In bringing together Norwegian experts with their international counterparts, the center is putting Norway squarely on the forefront of quantum spintronics research. In turn, our research will enable innovative applications.

Having received the status as a Center of Excellence from the Research Council of Norway - Jacob Linder, Arne Brataas, Asle Sudbø and Justin Wells.

Members at QuSpin - Our research center at the Department of Physics at NTNU in Trondheim.

SFF QuSpin is important to NTNU. The basic research within spintronics falls within the strategy of the University of developing talented researchers and excellent research environments.

- Professor Tor Grande, Chair QuSpin

I congratulate the consortium and its leader for impressive progress compared to the kick-off last year. Not only the productivity and quality of the output is excellent, the PI's are highly motivated, and new synergy starts to kick in.

- Professor Gerrit Bauer, Advisory Board QuSpin

Physics Matters

Physics is a basic science; when understood, it is clear how important it is. Energy, matter, time and space are nebulous concepts when speaking in the most general of terms, and when delving deeper into the proper core of physics, much is lost by those not actively working or studying in the field due to how language is used to speak about it.

One key goal is to make our center and physics attractive for young students, to be enticed by and recruited into a rewarding academic carrier. Another goal QuSpin has is to reach the general public to share our work through accessible language and tangible examples to be inclusive to the general public, thus illustrating why this research is critical, and worth current and future funding.

One new avenue of outreach was during the annual NTNU Researcher's Night through a lecture called "Flying Superconductors and the Quantum Revolution." In bringing actual flying superconductors, a very real-world example of what physics can do was a clear way to educate through an exciting medium. This idea of 'edutainment' is one employed by some of the world's preeminent science educators and is something QuSpin hopes to harness. This particular lecture was part of the People's Program portion of the Marie Skłodowska-Curie Actions (MSCA) in the European Union.

We have had school children, age twelve, at our center to do the same experiment. This community engagement challenges us to be able to explain complicated physics through easy, understandable words and examples.

QuSpin is also actively engaged in communicating through traditional media which has led to being covered by leading newspapers, research magazines and on television, both here in Norway and abroad in Germany and the Netherlands.

QuSpin PhD candidates reaching out to high school students, giving the lecture "Flying Superconductors and the Quantum Revolution" at the annual NTNU Researcher's Night.

Curiosity Driven Basic Research

At the very root of research is the curiosity of a researcher. For some, research is an innate passion, while others develop it over time. The work at the center itself is one that does not have a definitive end, requiring all involved to focus on the long-term potential for the research.

QuSpin aims to develop new concepts around what the electron will be capable of in the future of data storage and electronics innovation and seeks to be a leader in focusing on the fundamental challenges in spintronics.

In retrospect, the frontier of research is often described as moving forward in giant steps by remarkable individuals, but many researchers acknowledge the numerous smaller and crucial wiggly steps by many groups as equally important. This sentiment is central to QuSpin. In our aim to realize the full potential of the electron, our researchers engage in creative ideas that sometimes set them in motion along seemingly random walks. By engaging on several high-risk projects in different directions, we believe our skilled personnel will find something extraordinary interesting, but we do not always know in which direction.

Our walks are not entirely random, though. We increase our chances of groundbreaking findings by extending current collaborations and cultivating new relationships with top international researchers. QuSpin, while developing this field, is also actively encouraging the focus of training the minds of those working with them to facilitate intuitiveness, presence to foresee the questions that lay ahead to answer and the possible directions that can be explored.

Our focus is to develop frontier knowledge in both theoretical and experimental disciplines. Nanoscale engineering facilitates the creation of new materials and material combinations where the electron spin and other quantum variables behave and can be controlled in new ways. We want to unravel the intriguing properties of these novel systems to further our understanding of quantum physics and enable new uses with less energy loss in electronic devices.

We are building up two new labs with advanced equipment. We want to be able to verify the theoretical models through experiment, as well as growing new materials with unprecedented and superior properties for transport of electric signals across longer distances. The synergetic interplay between theoretical developments and experiments will open new doors for the understanding and utilization of the bizarre nature of quantum physics in devices.

Spintronics is already pushing the data storage revolution. Through developments of new theories, data modeling, and experimentation, it is our goal to create new concepts for the utilization of spin and pseudo-spin quantum states in low-dissipation systems. The aim is to be pioneers in controlling these states electronically using nanostructured combinations of magnetic insulators, topological insulators, and superconductors.

One of the breakthroughs, covered in our Nature article, and once considered a near impossibility, is the passing of a spin current through hematite, the most common ingredient in rust, an antiferromagnetic insulator, and to have it re-emerge into another metal. Arne Brataas further elaborates, "This is far in the field of nanoelectronics. The research opens the door to the new use of antiferromagnetic insulators in spintronics and electronics with very little energy loss."

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Main Research Themes, Goals and Activities

The principal goal of the center is to describe, characterize and develop recently identified quantum approaches to control electric signals in advanced nanoelectronics, conceptually different from those existing today.

The research focuses on three judiciously chosen low-dissipation systems: magnetic insulators, topological insulators, and superconductors which correspond to three research themes: insulator spintronics, topological matter, and super spintronics.

Our unique competitive edge is addressing the ultra-low power innovations by uniting expertise from insulator spintronics, topological matter, and super spintronics. While these themes are individually exciting, we combine them to generate significant added value.

Electrons can move in free air. In materials, their motion can differ significantly. In metals, the collective flow of the electrons resembles that of particles, but with dramatically altered properties. Their mass, charge, and even spin can be modified. This dressed behavior resembles new particles, so-called quasi-particles, that requires new models and new concepts. We will address how such quasi-particles can convey spin information with exceptional tiny energy losses. Also, we will consider the dynamical evolution of the spin states for high-speed electronics. A supercurrent is a remarkable phenomenon where a current can flow in a supercurrent with no electrical resistance and no energy loss. New material combinations with such properties would revolutionize electronics and have a significant impact on society at large. We will consider how spin can flow via supercurrents.

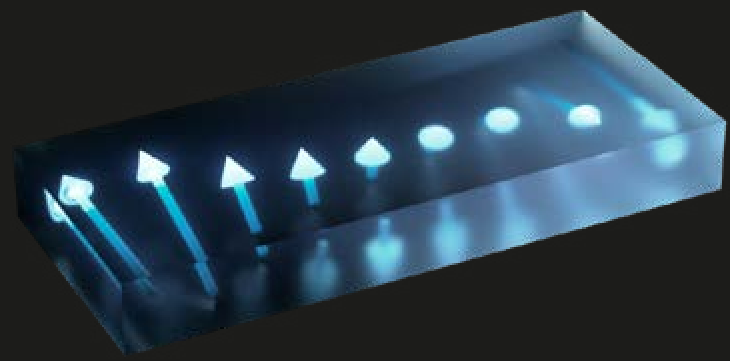
Successfully meeting these challenges has the potential to transform electronic data transmission, storage, and processing. Ultimately, dissipationless spin transport would solve the problem of energy waste to the environment with potential uses in disruptive technologies.

Illustration:

MAGNETIC INSULATORS: *Magnetic insulators are excellent conductors of spin while forbidding the energy-consuming process of charge transport. In magnetic insulators, the quanta of the spin vibrations can act as new low power dissipation information carriers.*

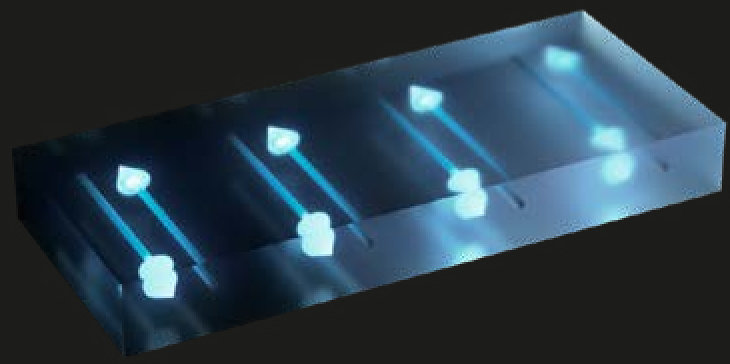
TOPOLOGICAL INSULATORS: *Topological insulators allow ultra-low dissipation transport of charge and spin at the surface but inhibit lossy processes in the bulk. An important aspect is the exceptional strong coupling between charge and spin signals.*

SUPERCONDUCTORS: *Superconductors have exactly zero electrical resistance and expel magnetic fields. Cleverly designed nanostructured superconductors in combination with magnetic materials exhibit intriguing new electrical and magnetic phenomena coupling charge and spin information.*

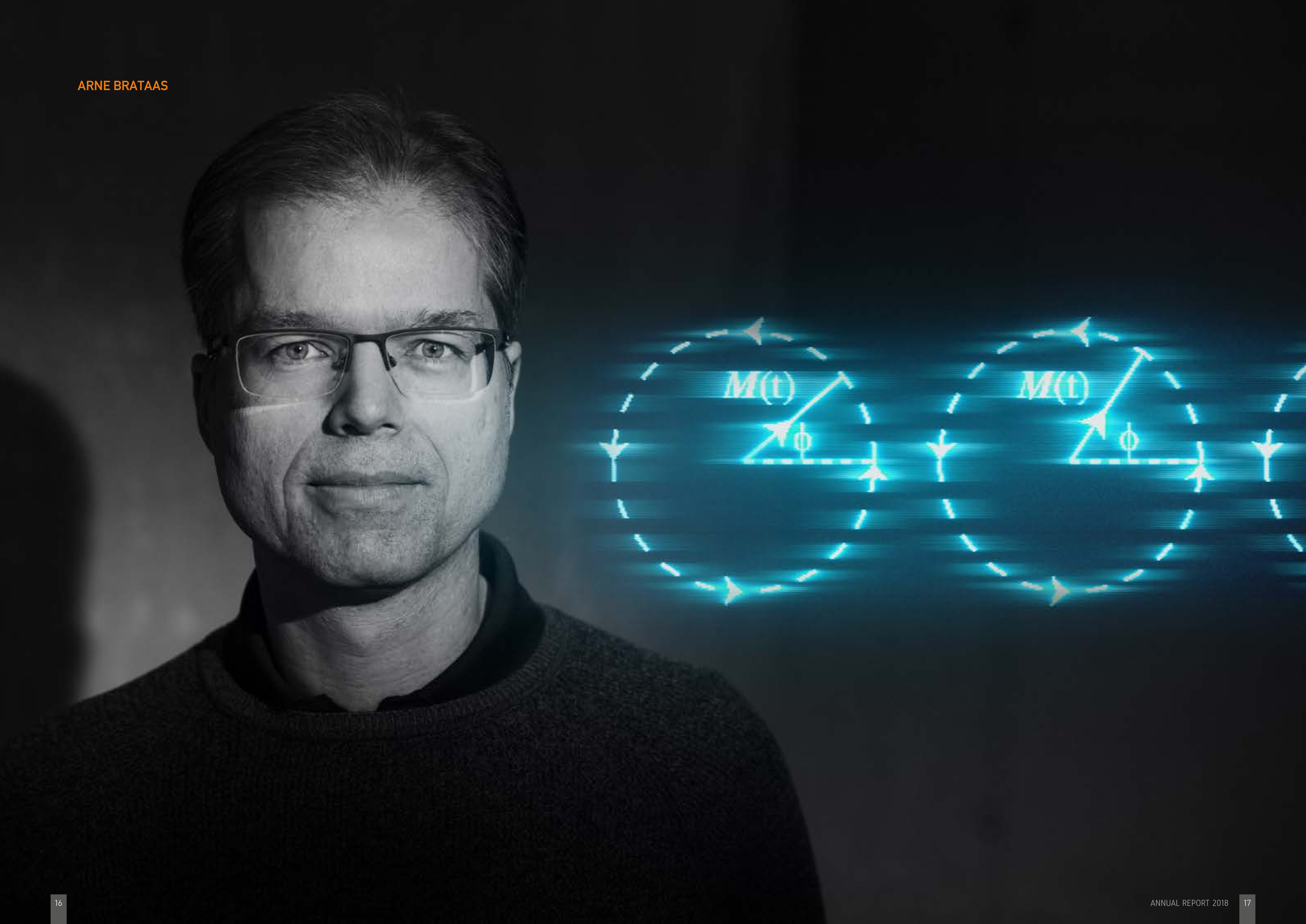


MAGNETIC INSULATORS

TOPOLOGICAL INSULATORS



SUPERCONDUCTORS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ARNE BRATAAS

Spin Insulatronics

Theme and goal

An electron has a spin as well as a charge. Conventional electronics and spintronics are based on the motion of mobile electrons in conductors. Spintronics, the utilization of spin in electronic devices, has revolutionized data storage and enabled Apple's iconic devices iPod, iPhone, and iPad. Spin Insulatronics is profoundly different because there are no moving charges that generate heat. In magnetic insulators, spin information can, nevertheless, propagate.

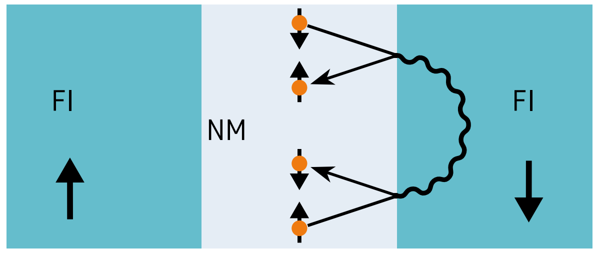
Controlling electric signals through the deployment of magnetic insulators can facilitate a revolution in information and communication technologies. We aim to determine to what extent spin in antiferromagnetic and ferromagnetic insulators couple to charge currents in adjacent conductors. We will utilize this coupling to control electric signals. Since spin signals in insulators have extremely low power dissipation, overcoming the limitations can enable low-power technologies such as oscillators, logic devices, non-volatile random-access memories, interconnects, and perhaps even quantum information processing.

Key questions

We focus on the fundamental challenges facing Spin Insulatronics. Key questions are how spin can transfer from electrical conductors to insulators, how far and how spin propagates in insulators, and how much power these devices consume.

Activity in 2018

While we consider a variety of insulators, we focus on surprisingly unexplored antiferromagnets. Antiferromagnets are magnetic, but you will not easily see these properties. The spins give rise to magnetic moments alternating in opposite directions, and these variations ensure that the material has no macroscopic magnetic moment. Antiferromagnets are potentially superior due to the thousand times faster spin response. This property can enable future THz electronics circuits, a thousand times speedier than state-of-the-art electronics.



A tri-layer consisting of a normal metal (NM) sandwitched between two ferromagnetic insulators (FI). The electrons in the NM interact via the magnons in the FIs.

At present, the dominant activity is in theoretical approaches, but we expand and combine this effort with an increasing experimental effort. Theoretically, we envision new approaches to conveying spin information in insulating materials. A conventional way is to transport spin information in the form of spin waves associated with the localized spins in the materials. This approach is analog to ripples on the surface of water. We also explore new ways where information can be transported with very little or zero energy dissipation. Certain magnetic insulators can behave like perfect spin superfluids, where spins flow without friction or viscosity. Magnetic insulators can also enable new forms of superconductors in adjacent conductors. In superconductors, a charge can flow without any resistance. Experimentally, we create new nano-scale materials and material combinations, connect them with electrical and thermal contacts, and explore the transport properties therein.

We have demonstrated long-range transport of spins in hematite, the main ingredient in rust. Hematite is an antiferromagnetic insulator. We inject spins into the antiferromagnetic insulators from platinum, a common metal, via a spin-to-charge phenomenon known as spin Hall effect. In turn, the spin signal is converted from the metal into the insulator via an exchange interaction at the interface. Inside hematite, the spin signal propagates as spin waves. The experiments were carried out at the Johannes Gutenberg University in Mainz, Germany under the leadership of co-PI Professor Mathias Klaeui. Other members of QuSpin contributed significantly to the fundamental understanding.

In a project that overlaps with our super spintronics activity, we have demonstrated how magnetic insulators can induce superconductivity in atomic-sized thick metal layers. Superconductivity requires pairing of electrons via an attractive interaction. In our case, the underlying pairing mechanism arises from the spin excitations and is unconventional. The research paves the way for controlled creation of new superconducting devices with unprecedented properties.

We have also carried a rich exploration of the spin-to-charge coupling across metal-insulator interfaces, new forms of magnetic excitations inside insulators, and how the spins information get lost in magnetic insulators.

ASLE SUDBØ

Topological Quantum Matter

Theme and goal

Superfluidity and superconductivity are the spectacular phenomena that fluids in the quantum regime may flow without any dissipation. Magnetism is the effect that an astronomical number of tiny magnetic dipoles of electronic, atomic, or molecular origin spontaneously organize themselves in an ordered state. Superconductivity, superfluidity, and magnetism are cooperative phenomena where enormous numbers of degrees of freedom spontaneously self-organize themselves into various ordered states of matter. This involves transitioning from one state of matter into another state of matter, so-called phase transitions.

Topology is a branch of mathematics that investigates global geometric properties of objects. These objects could be physical objects which we could hold in our hand, but also much more abstract objects defined in an abstract space of mathematical functions. In recent years, physics has seen a sharp rise of interest in topological matter and topological phase transitions.

Topological matter is a term denoting quantum system featuring extremely robust and very useful physical properties which are protected by some deep non-trivial topological properties of the energy spectrum of the system, i.e. a global property of the "geometry" of the energy spectrum. Topological phase transitions are phase transition where the ordered state cannot be characterized by a standard simple local order parameter (like the magnetization of a magnet).

Rather, the ordered state has a lack of topological defects (think of the hole in a doughnut compared to the lack of a hole in an orange), while the disordered states has proliferated large amounts of topological defects "ripping" the ordered state apart" (think of punching a large number of holes in an orange).

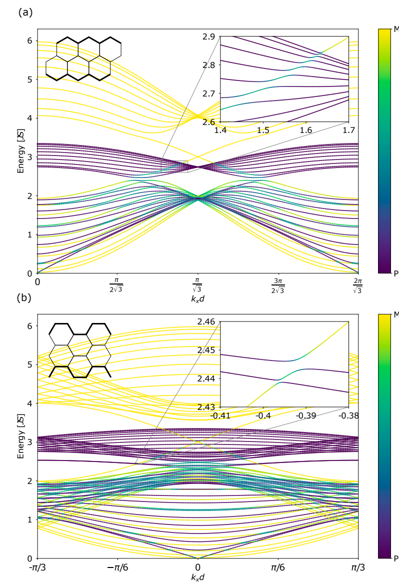
We are interested in the interplay between topological matter and various collective effects and broken symmetries such as superfluidity, superconductivity, magnetism, magnons (quantized magnetic fluctuations), phonons (quantized lattice vibrations), and photons (quanta of light). Could their interplay lead to novel and unexpected robust phenomena? Does the interplay lead to novel topological phase transitions? Can different types of topological order and different types of topological defects compete? Tangential to this, could such robust novel phenomena, were they to exist, also lead to interesting quantum-technological applications?

Key question

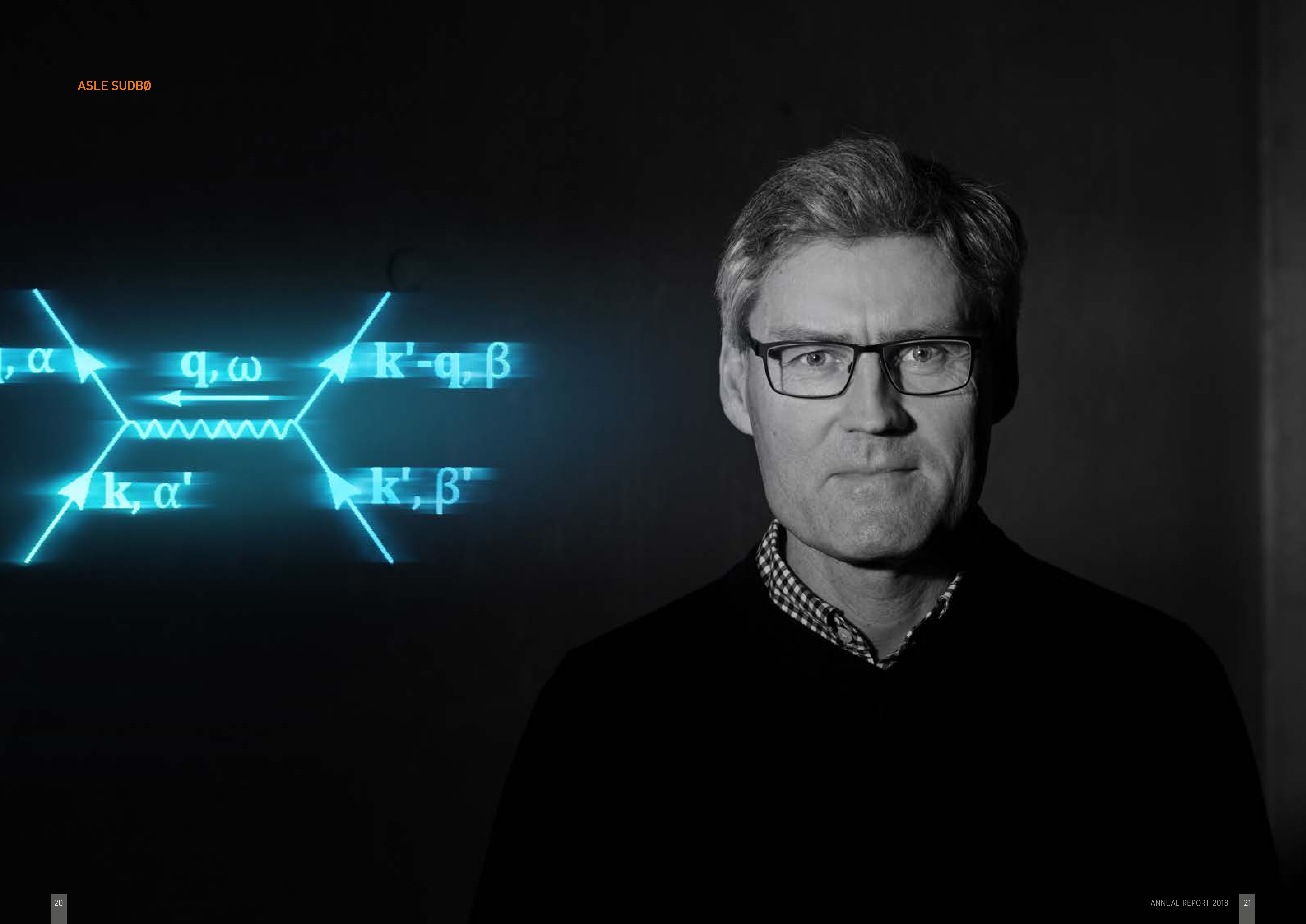
The overarching goal of our research is to understand how collective effects in quantum systems with topologically protected physical properties, both with and without strong correlation effects, conspire to produce novel and emergent physics. Such effects are of interest from a fundamental physics point of view, and the research is likely to shed light on other areas of physics as well, such as high-energy physics and high-temperature superconductivity. Systems that we study with this in mind are heterostructures of topological insulators and magnetic insulators, topological insulators, and superconductors, and chiral p-wave superconductors, to mention some.

Activity in 2018

In 2018, we have focused our research on collective excitations and collective phenomena in unconventional superconductors and heterostructures involving magnetic insulators, topological insulators, and superconductors. An overarching theme is the investigation of the crucial role that spin-orbit coupling plays in all of these systems, and how spin-orbit coupling leads to qualitatively novel collective effects. Superconductors develop domains of left- or right-handedness, with domains between them which host a rich set of novel phenomena when subjected to a magnetic field. Spin-orbit coupling also facilitates the control of vortices in superconductors in a dissipationless manner with electric fields.



Energy bands of mixed spin-and sound waves, rendering the sound waves on «armchair»-edges chiral, i.e. directed.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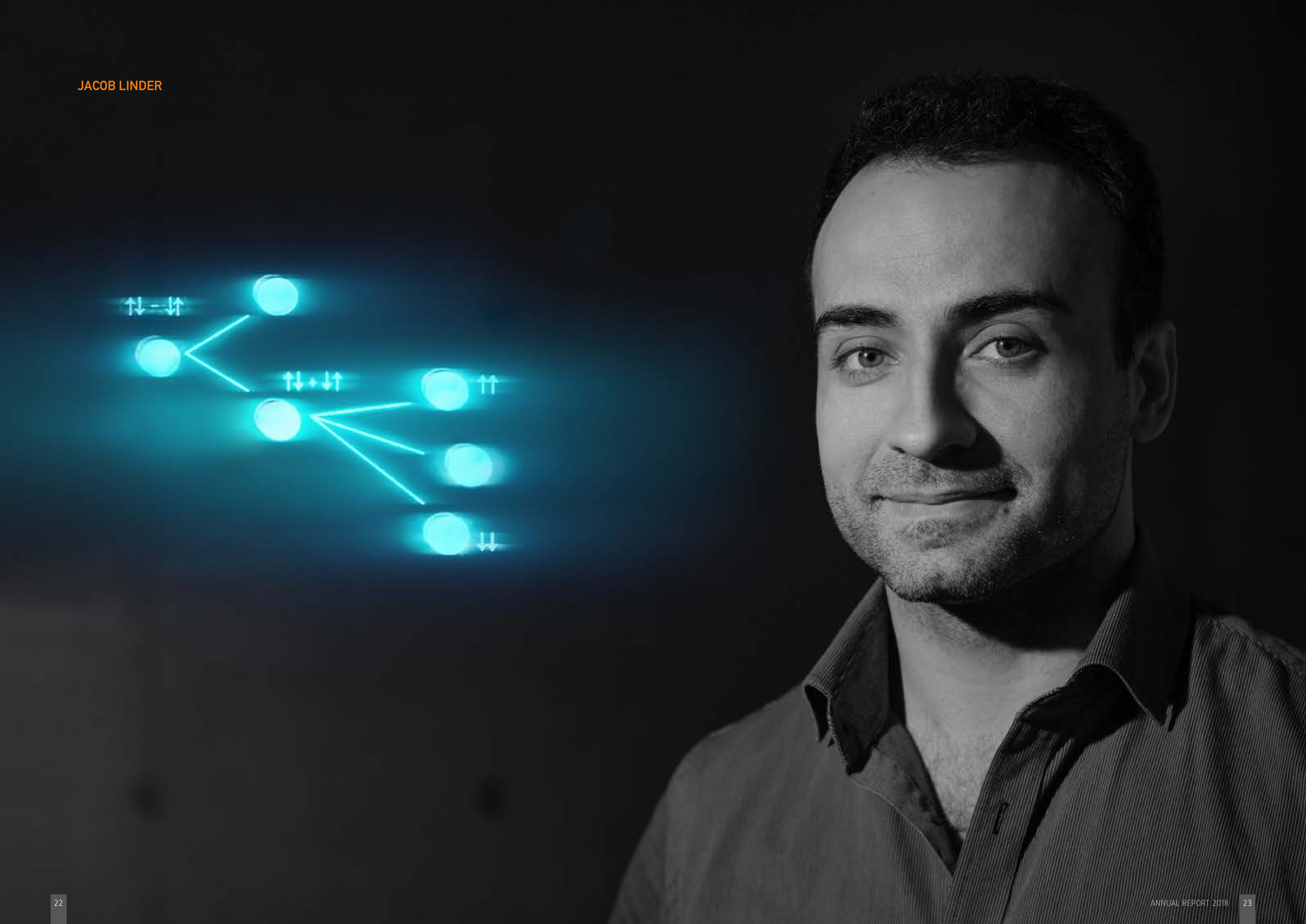
JACOB LINDER



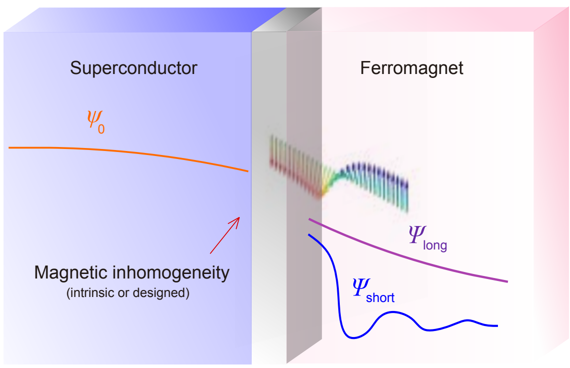
JACOB LINDER

Superconducting Spintronics

Theme and goal

In classical physics, matter exists in one of four different states: gas, liquid, solid, or plasma. However, this classification is too crude to capture the wealth of fascinating physics that emerges within each of these states. For instance, not all solid states behave in the same way. According to the quantum mechanical description of physics, various solid materials will behave in very different ways. Some materials are magnetic, some do not conduct currents of electric charge, while others can carry currents of not only charge but also a quantum property known as spin. This property is closely related to magnetism and is a fundamental trait of most elementary particles.

It turns out that some materials can conduct electric currents without any energy loss: so-called superconductors. The origin of superconductivity is quantum mechanical, but that does not mean superconductivity only occurs at microscopic length scales invisible to the naked eye. Large chunks of materials can be superconducting, making this phenomenon a macroscopic manifestation of quantum physics. Magnetism is another example of a phenomenon which originates from quantum physics. When materials such as superconductors and magnets, having very different properties, are combined, things get interesting. This is one of the core motivations behind the field of superconducting spintronics where one studies precisely what happens when magnets are placed in close proximity to superconductors.



When superconducting and ferromagnetic materials are combined, it is possible to generate new types of superconductivity which is spin-polarized and can survive for a long distance inside the ferromagnet. This happens for instance when magnetic disorder is present near the interface region of the materials.

Two main goals guide our research. Firstly, the most important goal is to discover new quantum mechanical phenomena that emerge when combining superconductors with other materials that have fundamentally different properties. A particular emphasis is on spin-dependent quantum effects that arise when magnetic materials are placed in contact with superconductors. Secondly, we focus on discovering specific phenomena that may be relevant to the development of memory technology and information transfer based on superconductors. This is closely related to how transport of charge, spin, and heat occurs in materials.

We use a variety of analytical and numerical tools to address the research questions above, depending on which method is the most appropriate for a particular research project. Some of our theoretical approaches include lattice models, quasiclassical Keldysh theory, Green function techniques, scattering theory, and Landau-Lifshitz-Gilbert phenomenology.

Key questions

The main challenges that we are attempting to solve are related to the functional properties of materials and how they can be controlled or altered by combining different materials. For instance, is it possible to use magnetic materials to control when superconductivity appears and even enhance its properties? Can one use superconductors to generate, control, and detect transport of not only charge but also other quantum degrees of freedom such as spin, without any energy loss? Finally, we are interested in understanding how superconductivity is manifested in unusual solid-state systems, such as atomically thin materials.

Activity in 2018

One of our research highlights from the past year is the prediction we made of how it is possible to create antivortices and giant vortices in non-superconducting materials without using magnetic fields. This provides an exciting opportunity to study the behavior of a type of quantum matter known as vortices in new environments where they do not naturally occur. We have also predicted the existence of a superspin Hall effect and its inverse, which in practice could solve the long-standing problem of how to measure the spin-polarization of a supercurrent. Finally, we have collaborated with an experimental group at Cambridge University and reported the observation of how spin-orbit interactions can be used to control the superconducting transition temperature of a material.

JUSTIN WELLS

Electronic structure

Theme and goal

The electronic band structure of a material contains information about all of the electrons in which are relevant for bonding and electronic properties in a solid. It also contains information on the electron spin, and the electrons interactions with each other, impurities, vibrations, spin waves, and more. It is of great interest to try to directly measure the electronic band structure, and hence to gain access to this information. Over the last decade, the instrumentation available has improved dramatically, thus it now possible to measure the electronic band structure with exceptional energy, momentum, and spatial resolutions.

The primary goals are to provide experimental competence to support the theoretical activities within QuSpin, to produce research contributions in important and topical fields, and at an internationally respected level. We also strive to bring interesting and up-to-date research work into the undergraduate classroom, to educate Master students, to contribute to the career development of young scientists and to enable high-quality Ph.D. theses to be produced.

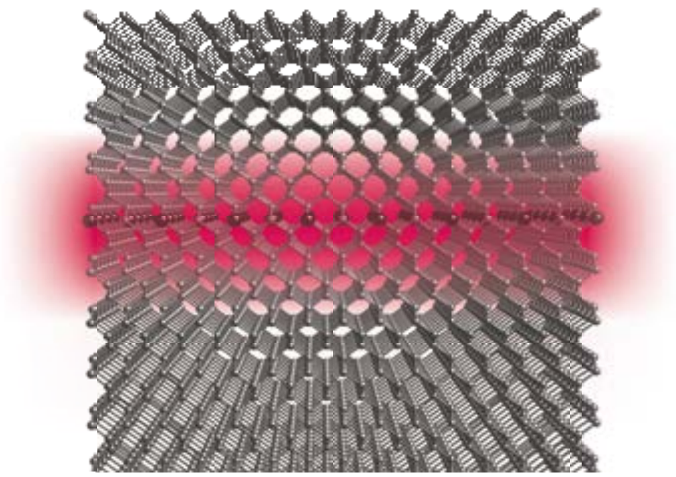
Key questions

Our research predominantly focusses on the interaction of electrons (especially their spin) within a solid. For example, the coupling of electrons with each other (mediated by vibrational waves or spin waves) can give rise to superconductivity, which allows an electrical charge to move without any losses. Unusual forms of coupling between spin and charge allow the efficient conversion of electrical signals into low loss spin signals - and this can also open new avenues for low loss (or lossless) signal transmission, storage, and manipulation. Finally, quantum confinement of charge and spin lies at the heart of the fast developing field of quantum computing.

Most of the methods we use come under the category of “photoelectron spectroscopy” and are based in Einstein’s photoelectric effect, for which he received the Nobel Prize in 1921. Using a refinement of this effect, it is possible to understand chemical bonding within a solid (a discovery which earned Kai Seigbahn the Nobel Prize in 1981), and more recently, it has also been shown that the same method can reveal the spectral function (closely related to the electronic band structure). Furthermore, this information can be resolved by energy, momentum, and spin and the newest instruments also facilitate good spatial resolution. We operate two instruments at NTNU which are based on various refinements of this method. We also make significant use of similar instruments at international synchrotron radiation facilities. In 2019 we will purchase and install a state-of-the-art spin-resolved photoelectron microscope to extend the range of possible measurements at NTNU.

Activity in 2018

Some highlights include studying the ubiquity of Dirac cones and topological states in transition metal dichalcogenides, many-body physics in graphene, growth of patterned structures of graphene, and the simultaneous quantization of the valence and conduction bands in a prototype quantum computer structure. This work has involved collaborations with the Shanghai synchrotron MAX synchrotron, the Swiss Light Source, and with research groups in Aarhus, St Andrews, London, Lund, Basel and elsewhere.



Model of electron confinement in a 2D electron gas in atomically sharp delta-doped silicon. This material garners much interest as a platform for silicon compatible quantum computing architectures.

JUSTIN WELLS

DENNIS MEIER

Topological Spin Textures

Theme and goal

The intriguing functional properties and nanoscale physics of magnetic skyrmions led to an explosion of interest in topological spin textures. Skyrmions are stable magnetic whirls that give rise to emergent electrodynamics, and their position and motion can be controlled at ultra-low energy costs. Due to these outstanding properties, skyrmions hold great promise as functional nano-objects for future spintronic devices including next-generation racetrack memories.

Up to now, either skyrmion lattices or skyrmions in a ferromagnetic background have been investigated. With our experiments, we have revealed that a much larger zoo of topological spin textures exists - even without the external magnetic field usually needed to stabilize skyrmions. In particular, we have observed that topological spin textures occur naturally in domain walls of helimagnetic order. These domain walls are distinctly different from conventional domain walls as encountered, for example, in ferromagnets. Instead, they share strong similarities with grain boundaries of liquid crystals as they can possess a microstructure best described in terms of dislocations and disclinations. In contrast to liquid crystals, these crystalline defects also correspond to topological spin textures and are endowed with an additional functionality.

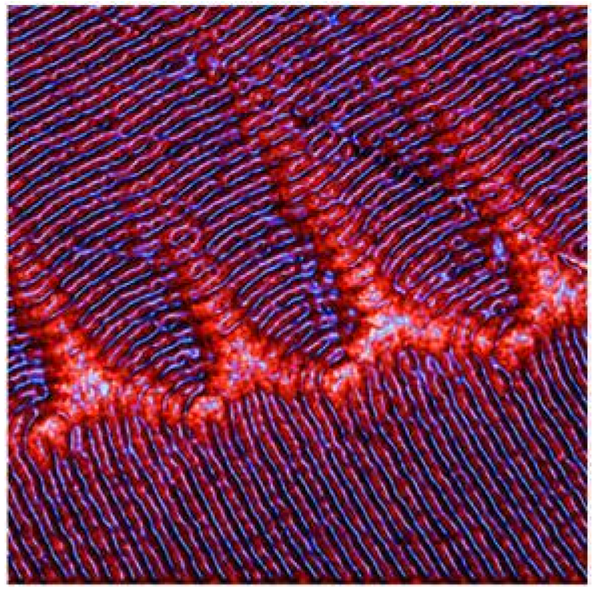
The goal of our research is to identify and demonstrate novel topological spin structures in chiral magnets that can be manipulated at ultra-low energy and allow device paradigms to be extended into new realms of magnetism.

Key questions

Our research explores functional properties in completely new types of topological spin textures, such as magnetic disclinations and dislocations, and helimagnetic domain walls. By applying state-of-the-art imaging methods, such as magnetic force microscopy, we aim to create fundamental knowledge about the physics of such spin textures: For example, we want to understand their formation process, topology-driven properties, and interactions. Furthermore, we study how electrical currents and magnetic fields control the position and movement of individual spin textures and investigate the dynamical nanoscale response. Ultimately, we want to understand if it is possible to utilize the new degrees of flexibility offered by the different topological spin textures to design next-generation spintronics devices.

Activity in 2018

2018 was an exciting year for us during which we managed to significantly expand and intensify our research activities related to topological spin textures. The number of group members working on related projects grew from two to five, we teamed up with the group of Christoph Brüne to combine nanoscale characterization and materials design, and explored novel experimental approaches involving state-of-the-art nano-structuring methods at NTNU NanoLab. Scientifically, we made a breakthrough in the classification of helimagnetic domain walls and disseminated our first results in high-impact journals as well as articles for the general public.



Topological zigzag domain wall observed in the helimagnetic iron-germanium (FeGe) using magnetic force microscopy.

CHRISTOPH BRÜNE

Molecular Beam Epitaxy of Antiferromagnets

Theme and goal

The QuSpin molecular beam epitaxy (MBE) group is a new experimental group that is still in the build-up process. Our primary goal is to develop the synthesis of new high-quality materials with potential for spintronics research and application. Our primary method to achieve this goal is called "molecular beam epitaxy." This technique uses an ultra-high vacuum environment to guide atomic or molecular beams onto a target, where a crystalline layer will grow. Using this method, we can create very high-quality crystals with thicknesses down to a single atomic layer. It is also possible to combine different materials to create new physical properties and control them in detail or to create nano-objects like quantum wires and quantum dots. Using MBE growth for magnetic materials will enable us to create, control and investigate new, high-quality materials that can be used in spintronics research and applications. Furthermore, the control down to single atomic layers will enable us to tailor the material properties such that we can enhance important characteristics or even create new ones. We will use this to search for model systems, which can for example realize the properties found in QuSpins theory groups, as well as develop materials with relevance for device application.

Key questions

Our initial research will revolve around the growth of so-called antiferromagnetic semiconductors and helimagnetic materials. Antiferromagnetic semiconductors are central to our research since they combine the potential for new spintronics applications with the possibility to manipulate the material characteristics by using electric fields (similar to today's semiconductor technology). This would enable the integration of established semiconductor technology principles and spintronics applications. Our research in this part will therefore focus on developing the growth of suitable materials, in which we will search for ways to manipulate and use their spin properties.

Helimagnetic systems will be the second research area of our group. These materials are very interesting because of their complex magnetic structure. They can host for example so-called 'Skyrmions'. These are, simply said, stable magnetic whirls inside the material and are promising due to their potential as nano-objects for future low energy memory devices. We will develop the growth of materials that host helimagnetic or skyrmionic structures even at room temperature and which are therefore interesting for room temperature applications.

Activity in 2018

The group was established late in 2018 with the arrival of three PhD students and a Postdoc researcher. Our focus in 2018 was mainly on establishing our lab space and starting to set up the equipment.

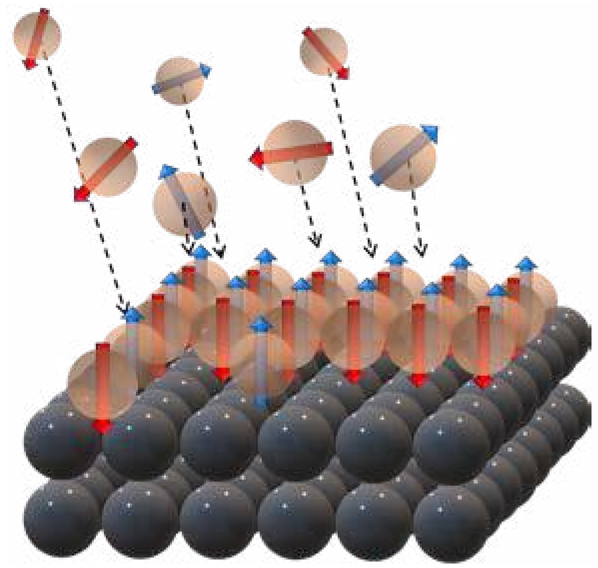


Illustration of molecular beam epitaxy growth of an antiferromagnetic layer on a non-magnetic substrate.

JOHN OVE FJÆRESTAD

Frustrated quantum antiferromagnets

Theme and goal

Our group's research centers around lattice models of quantum antiferromagnets, especially models with competing (aka "frustrated") interactions. In combination with strong quantum fluctuations, frustration may prevent magnetic order and instead lead to other, magnetically disordered phases that possess more exotic types of order that are of great fundamental interest.

Of particular interest are phases known as quantum spin liquids, whose order is not described by broken symmetries but may instead be of a topological nature. In recent years new materials have been discovered which exhibit evidence of unconventional behaviour pointing towards spin-liquid physics.

In recent years it has also been realized that various concepts and quantities originating in quantum information theory, like entanglement entropy and fidelity, may be very useful for characterizing quantum many-body phases and the quantum phase transitions between them. Different types of order may give rise to characteristic "signatures" in such quantities and their behavior as a function of various parameters.

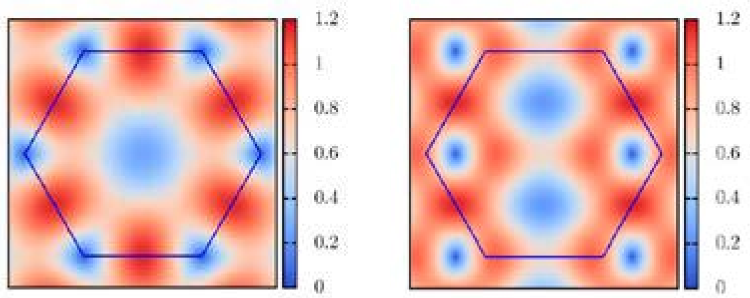
The overall goal is to get a better understanding of the "zoo of phases" that may arise in frustrated quantum anti-ferromagnets, and contribute towards their description and classification.

Key questions

Key questions include whether/where quantum spin liquids arise the phase diagram of various lattice quantum spin models, what types of quantum spin liquids can arise, and how various types of order can manifest themselves through signatures in quantities like entanglement entropy (including both orders that are and are not described by broken symmetries).

Activity in 2018

We have investigated the Renyi entropy in two-dimensional quantum Heisenberg models with non-collinear (coplanar) magnetic order in the ground state. Preliminary results were presented at the 2018 American Physical Society March meeting. We have also developed a bosonic coherent state path integral representation for spin systems based on a projection operator implementation of the Schwinger boson number constraint. Results were presented in a master thesis.



Schwinger-boson mean-field theory prediction of "spinon" dispersion in two neighbouring phases in the ground state phase diagram of a triangular-lattice quantum antiferromagnet.

ERIK WAHLSTRÖM

Local and Global Magneto-dynamic Properties of Oxides

Theme and goal

The primary goal is probing and understanding physics at the atomic scale. The primary method for this is through developing scanning probe techniques and experiments that provide insights into the fate of charge and spin in materials.

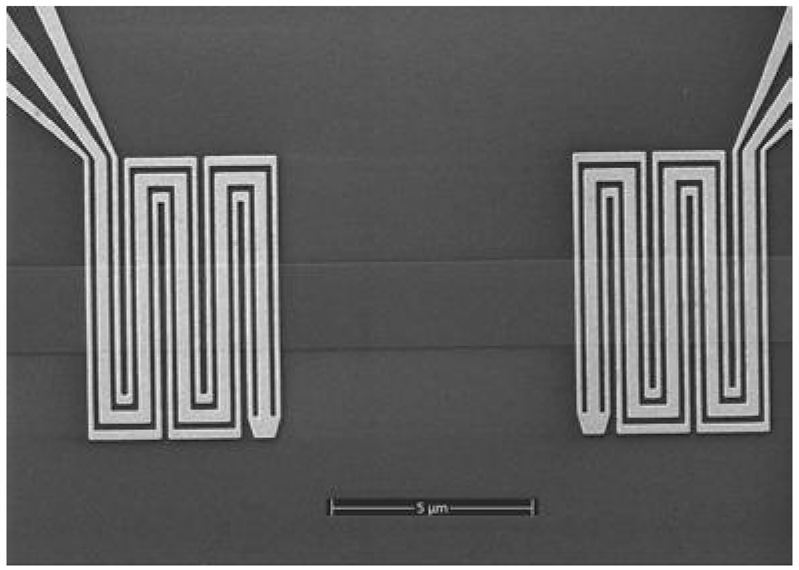
The short scale goal is to explore the magneto-electronics and magnonics of oxide materials and antiferromagnets. The longer-term goal is to develop STM based point-contact techniques to explore mesoscopic and magnetodynamic physics at a very local scale.

Key questions

We want to develop STM -based point contacts as a local characterization tool down to the nm-scale for studies of charge transport, excitations and dynamics at low energies. And to understand and control the magnetostatic, magnetodynamic and magnetotransport properties of perovskite magnetic oxides.

Activity in 2018

In 2018 the activity was somewhat limited due to duties as department head. However, we have proceeded with our collaboration with Thomas Tybell in the electronics department, with the primary aim to map out basic spin wave propagation properties in the perovskite magnetic oxide LSMO. Here we have continued to set up and prepare for pulse propagation measurements. We have also concluded an investigation of interface modes at the substrate (STO) / film (LSMO) interface of the 111 oriented film, where we for the first time can give evidence for the formation of magnetodynamic interface modes in a perovskite system. We have also started collaborations on diamond oxygen vacancy based lateral mapping of magnetodynamic wave propagation with our collaborators in Japan Toshu An (School of Materials Science, Japan Advanced Institute of Science and Technology (JAIST).



Gold antenna structures for sending and receiving magnetodynamic waves in a magnetic stripline. Work in progress for characterisation of magnetodynamic wave propagation in LSMO striplines.

JEROEN DANON

Quantum Computation with Multi-spin Qubits

Theme and goal

The quest for the optimal physical qubit (it should be stable, controllable, and scalable) is at full speed, and by now the research has been narrowed down to a handful of very promising approaches. My research is theoretical, but focuses on practical aspects of such qubit implementations, usually in close collaboration with experimentalists. Most problems my group is working on are related to questions such as: How could we improve qubit initialization, control, or read-out in a specific setup? What processes dominate qubit decoherence (loss of the quantum aspect of the information)? How could we reduce the effect of these processes?

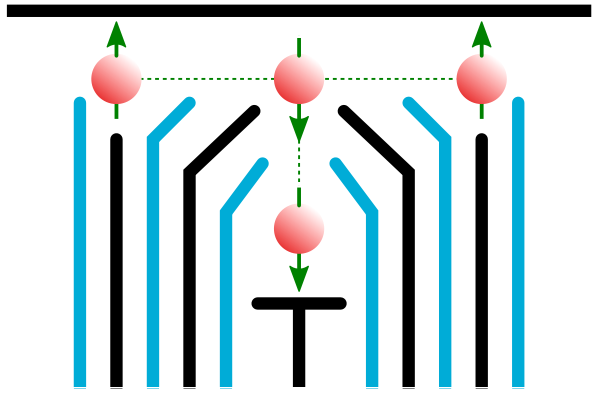
A large part of this work is in the field of spin qubits in semiconductor quantum dots (small potential traps inside a semiconductor), where the basic idea is to use the spin degree of freedom of the electron as a qubit basis. A recent and particularly interesting proposal is to create such qubits out of multi-particle spin states of electrons localized inside a semiconductor. These so-called exchange-only qubits are conceptually simple and scalable, they rely on well-developed experimental techniques, and can be operated fully electrically. The first attempts to create and operate such a qubit were promising, but also identified obstacles to further progress: Apart from being relatively sensitive to charge noise, exchange qubits couple to the fluctuating spins of the atomic nuclei of the host semiconductor. This coupling leads to decoherence, typically on the scale of tens of nanoseconds.

Key questions

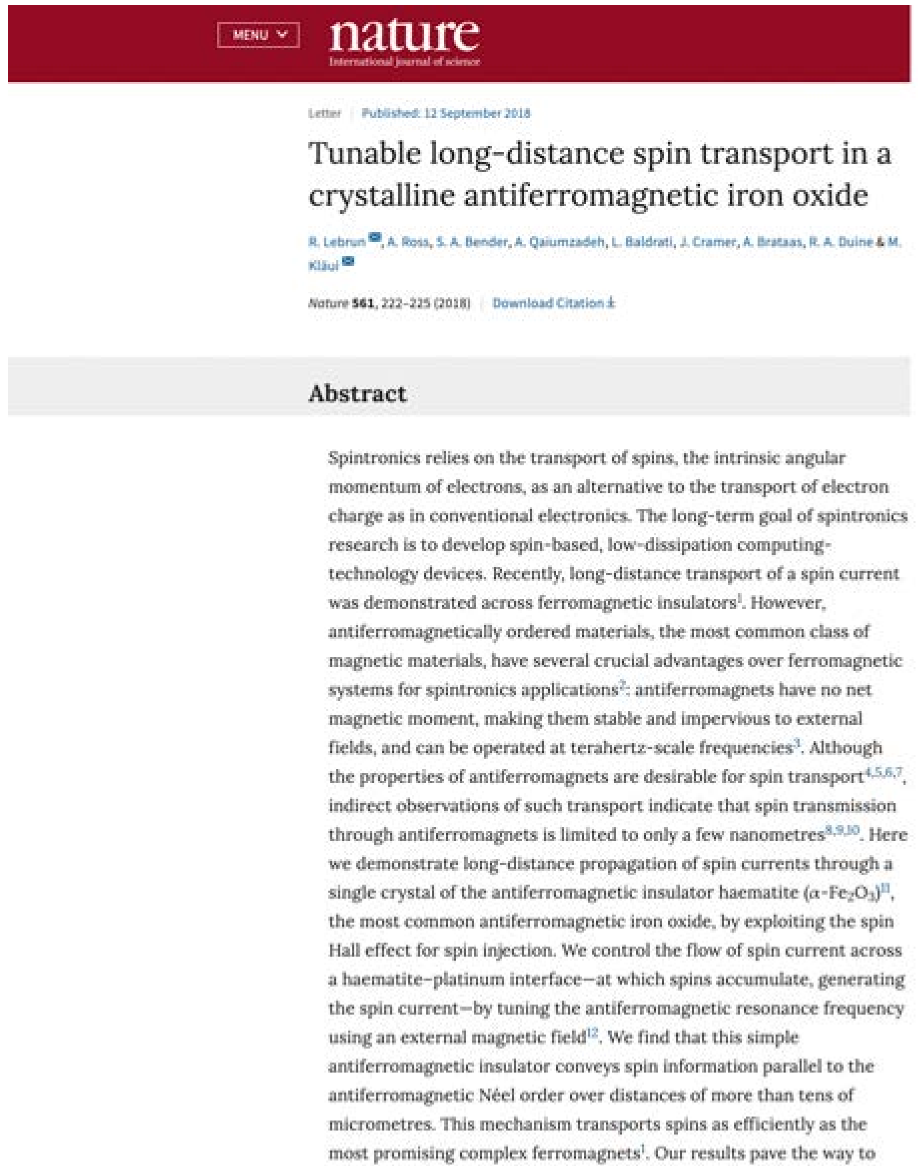
The goal is to solve the intrinsic problem of the nuclear spins and identify the optimal way forward for the exchange-only qubit. Roughly speaking, I am currently investigating two approaches. The first is to find a way to suppress or circumvent the effect of nuclear spin fluctuations in the commonly used III-V materials while keeping the qubit as much protected from charge noise as possible. The second is to determine the optimal implementation of such a qubit in (nuclear-spin-free) silicon.

Activity in 2018

Ph.D. student Arnau Sala has been working in this direction since he started in August 2016. So far, he proposed a four-particle spin qubit that should be intrinsically insensitive to the fluctuating nuclear spins and he investigated qubit relaxation and decoherence in the most common Si-based spin qubit. Since August 2018, funding from a Young Researcher Talent grant from the RCN allowed for team expansion with another Ph.D. student (Jørgen Holme Qvist, started in August 2018) and a postdoc (Vasil Saroka, started in December 2018).



Sketch of a structure of gate electrodes that produces a T-shaped quadruple quantum well, hosting the proposed four-spin singlet-only qubit that is insensitive to nuclear spin fluctuations.



MENU
nature
International journal of science

Letter | Published: 12 September 2018

Tunable long-distance spin transport in a crystalline antiferromagnetic iron oxide

R. Lebrun, A. Ross, S. A. Bender, A. Qaiumzadeh, L. Baldrati, J. Cramer, A. Brataas, R. A. Duine & M. Kläui

Nature **561**, 222–225 (2018) | Download Citation

Abstract

Spintronics relies on the transport of spins, the intrinsic angular momentum of electrons, as an alternative to the transport of electron charge as in conventional electronics. The long-term goal of spintronics research is to develop spin-based, low-dissipation computing-technology devices. Recently, long-distance transport of a spin current was demonstrated across ferromagnetic insulators[1]. However, antiferromagnetically ordered materials, the most common class of magnetic materials, have several crucial advantages over ferromagnetic systems for spintronics applications[2]: antiferromagnets have no net magnetic moment, making them stable and impervious to external fields, and can be operated at terahertz-scale frequencies[3]. Although the properties of antiferromagnets are desirable for spin transport[4,5,6,7], indirect observations of such transport indicate that spin transmission through antiferromagnets is limited to only a few nanometres[8,9,10]. Here we demonstrate long-distance propagation of spin currents through a single crystal of the antiferromagnetic insulator haematite (α-Fe_2O_3)[11], the most common antiferromagnetic iron oxide, by exploiting the spin Hall effect for spin injection. We control the flow of spin current across a haematite–platinum interface—at which spins accumulate, generating the spin current—by tuning the antiferromagnetic resonance frequency using an external magnetic field[12]. We find that this simple antiferromagnetic insulator conveys spin information parallel to the antiferromagnetic Néel order over distances of more than tens of micrometres. This mechanism transports spins as efficiently as the most promising complex ferromagnets[1]. Our results pave the way to

Facsimile from Nature Scientific Journal. We are particularly proud of our feature in this journal which casts a spotlight on our breakthrough research.

Our Co-Primary Investigators Professor Rembert Duine and Professor Mathias Kläui.

International Partners and Research Network

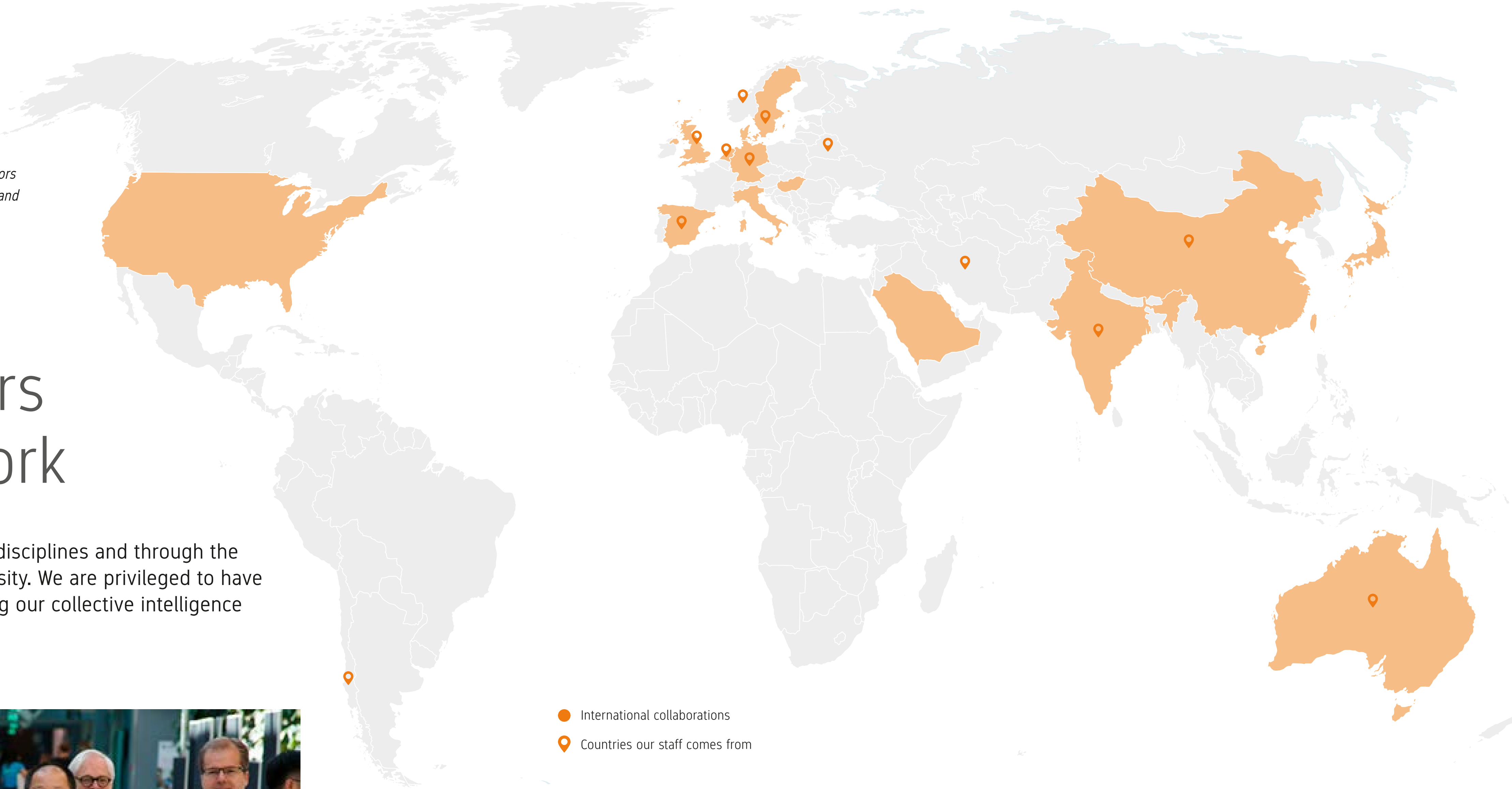
Research is a collaborative effort that often carries across disciplines and through the cooperation that extends globally in unified scientific curiosity. We are privileged to have working relationships across the world that add to elevating our collective intelligence and are adding to the work in our field.

Visiting researchers Andrew Kent, Oleg Kurnosikov, Mikhail Titov and Flavio Nogueira.

Visit from Beijing. Asle Sudbø (QuSpin), Hai-Qing Lin (CSRC), Alex Hansen (Porelab) and Arne Brataas (QuSpin).

We have a long-term collaboration with the centers of our Co-Primary Investigators; Professor Mathias Kläui at the Institute of Physics, at the University of Mainz in Germany, and the with Professor Rembert Duine, at the Institute of Physics, at the University of Utrecht, in the Netherlands.

QuSpin is proud to have recruited Kläui, a world-leading scientist, as a Professor II to build up our experimental activities to a robust level in Norway. Together, with the young and dynamic experimentalists in Trondheim, and supported by the excellent theory activity, QuSpin will raise the standards of the experimental activity considerably. The collaboration with JGU Mainz gives QuSpin access to material growth, characterization, and transport measurements.



Duine is a leading theoretician in the quantum-many body physics of spin transport and spin excitations. Landmark publications by Duine and his collaborators have led to the opening of new sub-fields of physics, such as magnetic skyrmion spintronics, antiferromagnetic spintronics, and cold spintronics. The insights gained in these developments give QuSpin complementary expertise in theoretical developments on magnetic insulators and topological matter.

This year we have established a new collaboration stemming from a visit from Computational Science Research Center (CSRC) from Beijing, China. Alex Hansen, Porelab and Asle Sudbø, QuSpin hosted the visit in hope to establish an exchange program for both research and Ph.D. levels, in the area of computational physics related to our spintronics activities.

The QuSpin center is happy for the opportunities it has to host visiting researchers and has been host to thirty-five researchers in the recent year. These visits allow for interactions on a personal level that bolster the professional work and exposure, going both ways, to new, ongoing and past projects. Often the visits are in tandem with the initiation of a new project.

This global cooperation adds to the richness in the diversity of people and experiences, outward dialogue, increases spirits and vibrancy of the center. It also introduces Trondheim to the broader research community in a way that allows for a lasting and tangible connection.

We have a collaboration with internationally leading theoretical and experimental groups in the United Kingdom, Denmark, Sweden, Hungary, Germany, the Netherlands, USA, Italy, Spain, Japan, China, India, Saudia-Arabia and Australia.

We have regular seminars given by our researchers and visiting researchers on various topics for discussions.

Research Training and Creativity Along the Way

It is our strategy to work actively with research training amongst our younger researchers.

We wish to train the next generation of researchers within our field, to take on leadership for new projects of their own, as well as getting experience by co-supervising our Ph.D. and master students.

We give a range of workshops and seminars at the center. We have regular seminars given by our researchers, and our visiting researchers, where they present their work, share ideas and discuss the challenges. Our regular Journal Club is where there is training in presenting a scientific article and its essence for discussion. These are valuable experiences in the process of their work and in writing articles for publication.

We also have a self-organized forum for the younger researchers, where projects, ideas, and research challenges are shared, stimulating collaboration across both the theoretical and experimental field, as well as between PhDs, Post Docs and researchers.

The professors teaching, supervision, and curriculum is still the primary source for each Ph.D.'s research training. However, we see that all the other activities have a significant added value.

At times we can connect physics with other disciplines to make it more accessible and fun; like combining physics with music, or physics with "Walking on Ice." The latter being a gateway into understanding how to move on icy pavements in Norway for those coming from countries where the sun is always shining.

In dialogue with Haakon Thømt Simensen, Payel Chatterjee, Håkon Ivarssønn Røst, Sol H. Jacobsen and Alireza Qaiumzadeh.

Collective Participation

Article based on a group dialogue with Haakon Thømt Simensen, Payel Chatterjee, Håkon Ivarssønn Røst, Sol H. Jacobsen and Alireza Qaiumzadeh.

What is the definition of success early on in a project or organization? For many, it might be a significant milestone reached or an epic breakthrough. However, what if you look more deeply? If you take that approach with the QuSpin center, you'll find a clear winner if you speak to those involved – connection.

When you approach the unassuming door to the QuSpin center and enter the quiet hall, there is an immediate sense of ease and purpose. The seeming stillness masks a hive of activity going on inside. The team is working hard to blend the two major facets of physics, and different interdisciplinary specialties, into a unique environment of cultural understanding and professional collaboration to drive spintronics forward.

The professional collaboration side, which one expects at a center such as this, is bolstered by the organic diversity in the team members. During lunch in the QuSpin room, you can see this perfectly illustrated in the blend of topics of conversations and by the faces filling the comfortable room. You'll find those who are fixtures, those who've left and returned, and new faces drawn in by this compelling work and exciting environment.

It was here that Sol H. Jacobsen, Alireza Qaiumzadeh, Payel Chatterjee, Håkon Ivarssønn Røst and Haakon Thømt Simensen sat down to talk about the center and why this is the place they, and others, should and want to be.

Collectively, and with candid honesty, they openly spoke about how what they do is a challenge as they work on the basic research being done, and writing new chapters in the field of physics and spintronics as they go. It cannot escape anyone listening that there is another driver behind all this which is far more personal and one that is helping change the face of academia -their own histories and social interactions with each other.

All but one are the first in their immediate families to hold a Ph.D. and for most, to be in scientific research. In the QuSpin center, they are surrounded by like-minded and focused peers. However, given there are twelve countries represented in the mix, it is the activities that have them going for meals, having game nights, and a Journal Club for example, that allow them to experience each other in a meaningful way outside of their work, yet still fueling it.

Theoretician Haakon Thømt Simensen sees the center as a superorganism, where what each member is doing is of benefit to someone else and putting time into helping each other is worth it. Theoretician Sol Jacobsen cites the various activities that the center encourages, and the newcomers which excite the creativity and interactive enthusiasm. "There are generally more initiatives, and everything is adding something extra."

There is an insatiable curiosity in the people here that is both in work and, by a happy byproduct, in those around them. The group heartily agrees this pushes them forward to do more and keep at it, even when things get hard.

One of the initiatives at the center is the SpinMaster of the Week. It is one individual who is responsible for the QuSpin room, the heart of the center for her, and keeping it tidy, organizing a special treat on Friday and generally looking after the wellbeing of the space. It provides a sense of ownership and connection to what otherwise could be another room.

On the professional side, this idea of connection sees theoreticians and experimentalists working side-by-side to advance the field of spintronics, even when they don't exactly understand what the other is doing or sometimes saying, in a way which is something of a novelty in the field. No more is the isolation of specialties inside this space. It is a quiet sentiment, almost a background note, that this is the new norm and a welcome one.

Ten years ago, Alireza Qaiumzadeh, came to NTNU. Before coming to NTNU, when studying in his home country of Iran, he learned a valuable lesson which only backs up his opinion of the necessity of this blended environment at

QuSpin. Qaiumzadeh took classes which were not part of his specialty to have a broader base for working from in his area of focus. "It has become a way of life here, a habit, to learn and listen to different topics in physics and not only our specific topic," explains Qaiumzadeh. He remembers the time when it wasn't so and that he was part of what he considered a 'Norwegian' research team as opposed to now being part of a world-class team made from global representatives.

Håkon Ivarssønn Røst, having the two disciplines sitting side-by-side (he shares an office with three theoreticians) to push the science forward and one other is a particular characteristic, which made NTNU win out over the adventure of working abroad. "For some reason, I stayed on, but what is that big reason? I had a lot of fun doing my masters here with my supervisor. I would point to that first." Røst explains, "I also had an excellent offer with a collaborator; we have similar facilities, but having this opportunity here characterized by having one common and well-defined focus (beyond condensed matter physics in general) that we have with spintronics, so if one is to point to any differences then that is the obvious one."

For newcomer Payel Chatterjee, is an example of how the center is drawing in talent that is passionate about the whole concept. Chatterjee is the first academic in her family, and QuSpin provided the opportunity for her to make her first voyage outside her native India and do what is uncommon for young Indian women; live and work independently. Although still a challenge, what could have brought a significant culture shock, if not environmental, has been counteracted by the fact she feels right at home. "I want to know how Europeans do things, how they research," she says, "...but the hunger to explore new things, this brought me here." She speaks to the fact that the personal environment, the seamless blend of twelve nationalities around her, makes her part of something that doesn't leave her feeling foreign at all. She also thinks that being here in the very start means she will be contributing to something in a way that is deeply meaningful and unique to being here now.

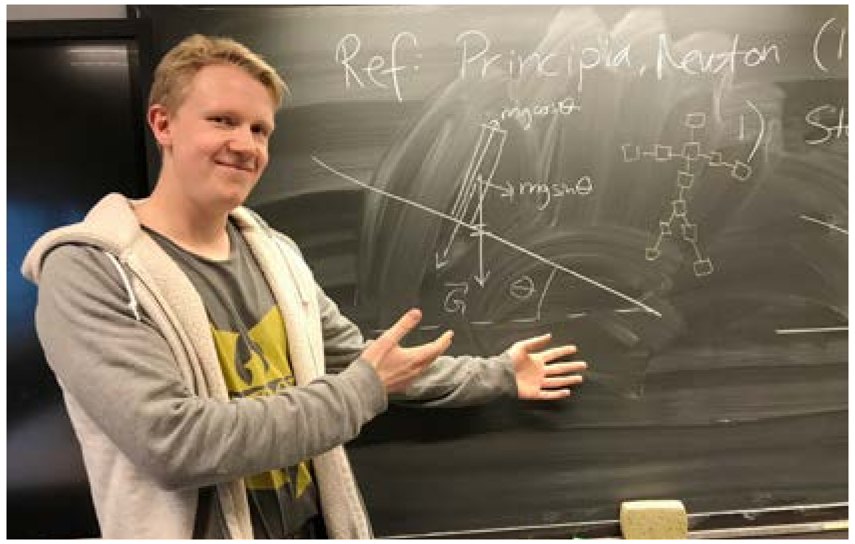
Haakon Simensen, a prior master student at NTNU, says it was an education he came for and then the opportunity he couldn't resist that made him stay. This opportunity to connect with his own intuitions and with those around him gives him the chance to understand things in a face-to-face manner. "Reading another's paper outside your field is often not that illuminating. Most often than not, it isn't illuminating at all." The group shares a laugh in acknowledgment. "You find yourself sitting there thinking, I didn't understand anything of that, but here you can ask those inside that field, and they can explain it to you, and that is what I really like about having so many people around doing separate, focused things."

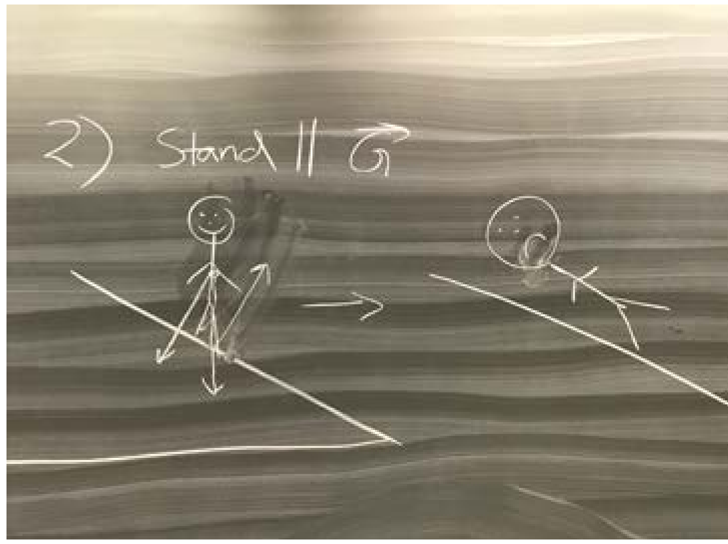
> *It still wins. It is such a good center to be part of that all of the hard things aren't hard enough to make me stop.*
>
> *- Researcher Sol H.Jacobsen*

Sol Jacobsen, a four-year veteran of the department, didn't intend to end up in physics. "It was only in my last year when I had to pick my specialization project that I chose something that was really, really interesting in quantum theory and I got bitten by the bug." Jacobsen recounts, "I took a year off to consider my options. I was a science teacher in Nepal and interacting with those kids who didn't have an option to do a Ph.D. in physics, and I thought if I have the opportunity to do this, I should try it." She stuck it out and found herself with a Ph.D. and a further postdoc position. It was the pull of coming home to Norway, after many years away, and QuSpin offering her an environment which continually fosters interest despite how hard and demanding it is, that she is still here. Like most who have not yet become a professor, she still finds herself evaluating, from time to time, if it is still interesting enough? But she smiles as she says, "It still wins. It is such a good center to be part of that all of the hard things aren't hard enough to make me stop."

The center might be walls, doors, laboratory work and such, but to sit with its people is to know that it is so much more. It is the passion, curiosity, integrity, and comradery that fuels and pushes these researchers past the hard part, the not knowing, and towards building the foundations that tomorrow's innovations will be built. It might not happen overnight, but rest assured this dynamic group of people will reshape our knowledge of spintronics and watching them will never cease to be fascinating.

GLIMPSES FROM SOCIAL ACTIVITIES AT OUR CENTER





Giving a lecture on"Walking on Ice".

Our Leadership, Diversity and Pro-social Mission

Diversity leadership is about the strength we find in our differences and harnessing that potential.

Diversity and different perspectives are an essential factor when approaching challenging questions, in our research center. Each researcher and student that comes to the center brings their unique experience to the group dynamic, and we see their individualities and experiences as adding additional value to our research.

Our center has researchers coming from twelve different countries of origin; Norway, Sweden, Netherland, Germany, Spain, Chile, Iran, India, China, Belarus, England and Australia. Also, from different walks of life, culture, ethnicity, and language, male and female.

“We spend time and resources on developing a prosocial and robust culture,” says Center Coordinator Karen-Elisabeth Sødahl. “We need places and arenas where people can meet, create and exchange. As a young center just in the start-up phase, we have the privilege to create and develop a culture where people want to come to visit and, then, stay”.

One place this clearly is in action is in the QuSpin heart, our QuSpin room. This room is the hub for our joint research fora, workshops, seminar, Journal Club, leader group and section meetings, evening gaming, lunches, and celebrations.

One person, our SpinMaster, has the weekly responsibility to keep the room and kitchen in good shape and offer all the colleagues a special treat Friday lunch. We have had many good conversations and laughter, or just a good cup of coffee.

We need places and arenas where people can meet, create and exchange. As a young center just in the start-up phase, we have the privilege to create and develop a culture where people want to come to visit and, then, stay.

- Center Coordinator Karen-Elisabeth Sødahl

QUANTUM SPINTRONICS 2018

Our Annual International Workshop

It is critical to gather in with leading international professionals outside QuSpin. Targeted workshops allow for inspiration, discussions around current challenges and findings, and a strengthened environment for focused peer discussions.

The eighteen speakers, representing both the theoretical and experimental areas, came to share with us their perspectives and work with our nearly seventy attendees. In moving forward, this state-of-the-art field needs hands-on and intensive workshops. This year we focused on our close network. Over the next years, we plan to broaden our participants as well.

The pro-dean for research at NTNU, Bjarne Foss, and our chair Tor Grande were also present, when the Research Council by special advisor Liv Furuberg, officially handed over the center of excellence plaquette. An important and memorable moment for us all!

Our workshop does not need to be all work and no play, and so our city also hosted to further type of connection and learning opportunity for those attending. The workshop was held at the mouth of the Nidelven, a point where history meets modernity, at the Scandic Nidelven Conference Centre. Through a guided tour of the city, our strong history in trade, culture, cultivation of knowledge and local food was introduced to our guests.

Invited speakers at our workshop. From bottom left: Markus Munzenberg, Maxim Mostovoy, Jairo Sinova, Arne Brataas, Katharina Franke. From top left: Aurelien Manchon, Akashdeep Kamra, Manuel Houzet, Vincent Cros, Karsten Rode, Stefano Bonetti, Romain Lebrun, Mario Cuoco, Isabella Giertz and Sol H.Jacobsen.

GUIDED TOUR OF THE CITY

2018 Scientific Publications

We are privileged to have the work of our researchers published in journals such as Physical Review Letters, Physical Review B, Nature, Nature Physics and the following listed publications. We are particularly proud of our feature in Nature Scientific Journal which casts a spotlight on our breakthrough research. Our center has had twenty-eight publications over the last year, and we look forward to continuing to add to our library of published research.

1. Ado, I. A.; Qaiumzadeh, Alireza; Duine, Rembert; Brataas, Arne; Titov, M.
Asymmetric and Symmetric Exchange in a Generalized 2D Rashba Ferromagnet.
Physical Review Letters 2018; Volume 121. (8) p. 086802-1-086802-7

2. Amundsen, Morten; Ouassou, Jabir Ali; Linder, Jacob.
Field-free nucleation of antivortices and giant vortices in non-superconducting materials.
Physical Review Letters 2018; Volume 120. (20)

3. Gao, Tenghua; Qaiumzadeh, Alireza; An, Hongyu; Musha, Akira; Kageyama, Yuito; Shi, Ji; Ando, Kazuya.
Intrinsic Spin-Orbit Torque Arising from the Berry Curvature in a Metallic-Magnet/Cu-Oxide Interface.
Physical Review Letters 2018; Volume 121. (1) p. 017202-1-017202-6

4. Mazzola, Federico; Wells, Justin; Pakpour-Tabrizi, Alex; Jackman, Richard; Thiagarajan, Balusubramanian; Hofmann, Philip; Miwa, Jill A.
Simultaneous Conduction and Valence Band Quantization in Ultrashallow High-Density Doping Profiles in Semiconductors. ***Physical Review Letters*** 2018; Volume 120. (4) p. 046403-1-046403-5

5. Qaiumzadeh, Alireza; Ado, Ivan A.; Duine, Rembert; Titov, Mikhail; Brataas, Arne.
Theory of the Interfacial Dzyaloshinskii-Moriya Interaction in Rashba Antiferromagnets.
Physical Review Letters 2018; Volume 120. (19)

6. Johansen, Øyvind; Brataas, Arne.
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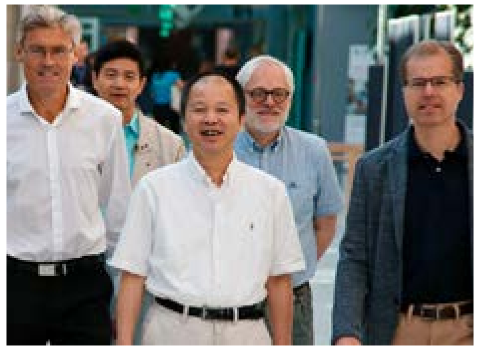
Highlights

JUNE

Our new QuSpin Room

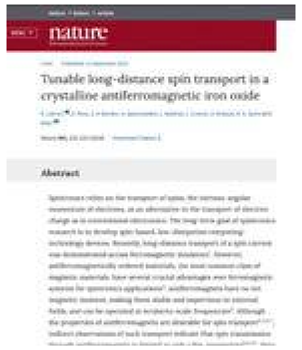
JUNE

Visit from the Computational Science Research Center (CSRC) Beijing, China



SEPTEMBER

Publication in Nature Scientific Journal



SEPTEMBER

Outreach lecture at Researchers Night, NTNU

SEPTEMBER

Revised/new QuSpin logo

OCTOBER

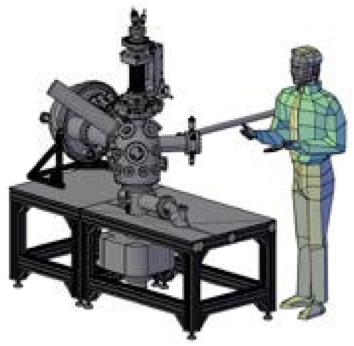
QuSpin receiving the SFF plaquette from The Research Council of Norway by Special Advisor Liv Furuberg

OCTOBER

Quantum Spintronics 2018 Annual international workshop in Trondheim

DECEMBER

Deciding on supplier of ARPES experimental equipment



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35
VISITING RESEARCHERS

28
PUBLICATIONS

*Note: In addition, one 20% finance position.

Funding

FUNDING 2018 (NOK)

The Research Council of Norway, Center of Excellence	6 168 000
Norwegian University of Science and Technology	5 051 000
SUM	**11 219 000**
The Research Council of Norway, Center of Excellence	10 502 000
International Funding	5 160 000
Other Public	717 000
SUM	**16 379 000**
TOTAL FUNDING	**27 598 000**

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3D Illustrations:
Alexander Somma, Helmet AS: Page 4, 7 and 15

Layout:
Skipnes Kommunikasjon AS
Karen-Elisabeth Sødahl/Center for Quantum Spintronics

Print:
Skipnes Kommunikasjon AS

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