Annual Report | 2020

Center for Quantum Spintronics

QuSpin

Norwegian Centre of Excellence
The Research Council of Norway

NTNU
Norwegian University of Science and Technology

Our vision

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

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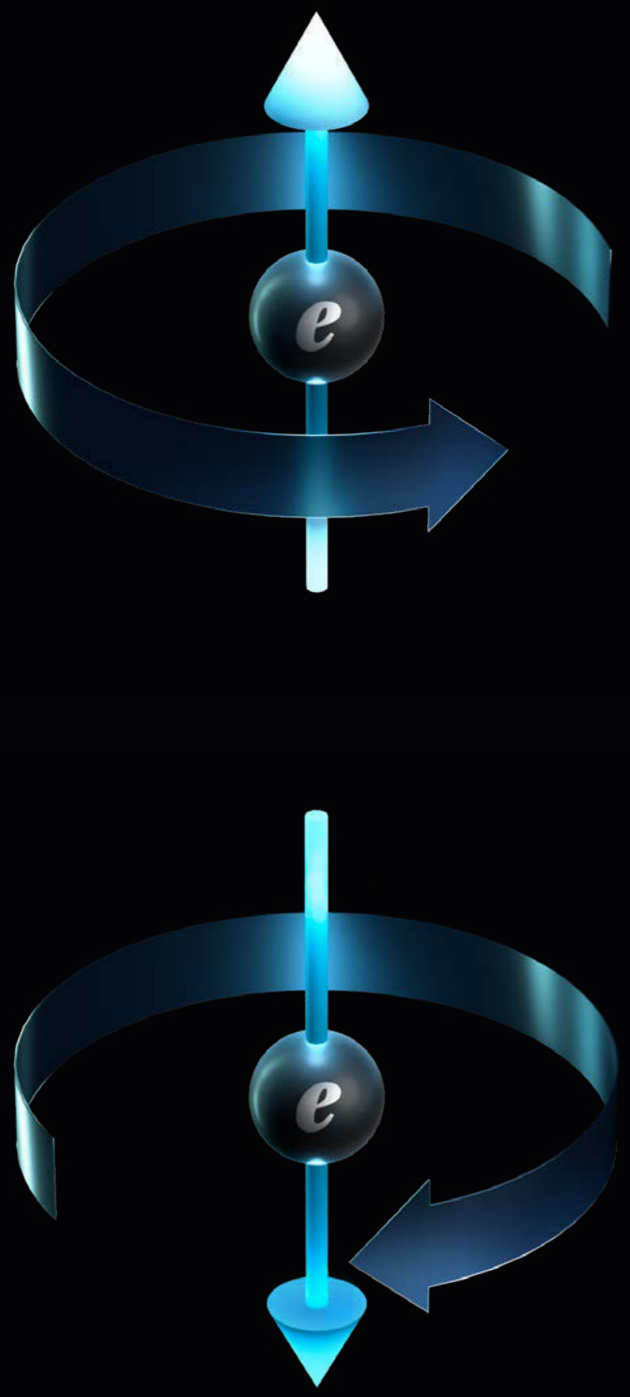


THE ELECTRON SPIN: *The electron spin, the electron's magnetic moment, is a prime example of a quantum entity. Classically, when the earth orbits around the sun, it has an orbital angular momentum. The spin is the electron's intrinsic angular momentum. It is as if something orbits inside the electron. 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.*

CENTER DIRECTOR ARNE BRATAAS

Foreword

QuSpin is a Center of Excellence funded by the Research Council of Norway and the Norwegian University of Science and Technology. After three years of building up QuSpin, we have reached a peak in the number of postdocs and Ph.D. positions. This number will remain stable over the next years. Like all Centers of Excellence, in line with international recommendations, QuSpin will have a midterm evaluation during the fall of 2022. If proven successful, our Center will continue beyond six years for another four years. The last years of the activity will include a downsizing so that all Ph.D. students will be able to defend their theses within the Center´s lifetime.

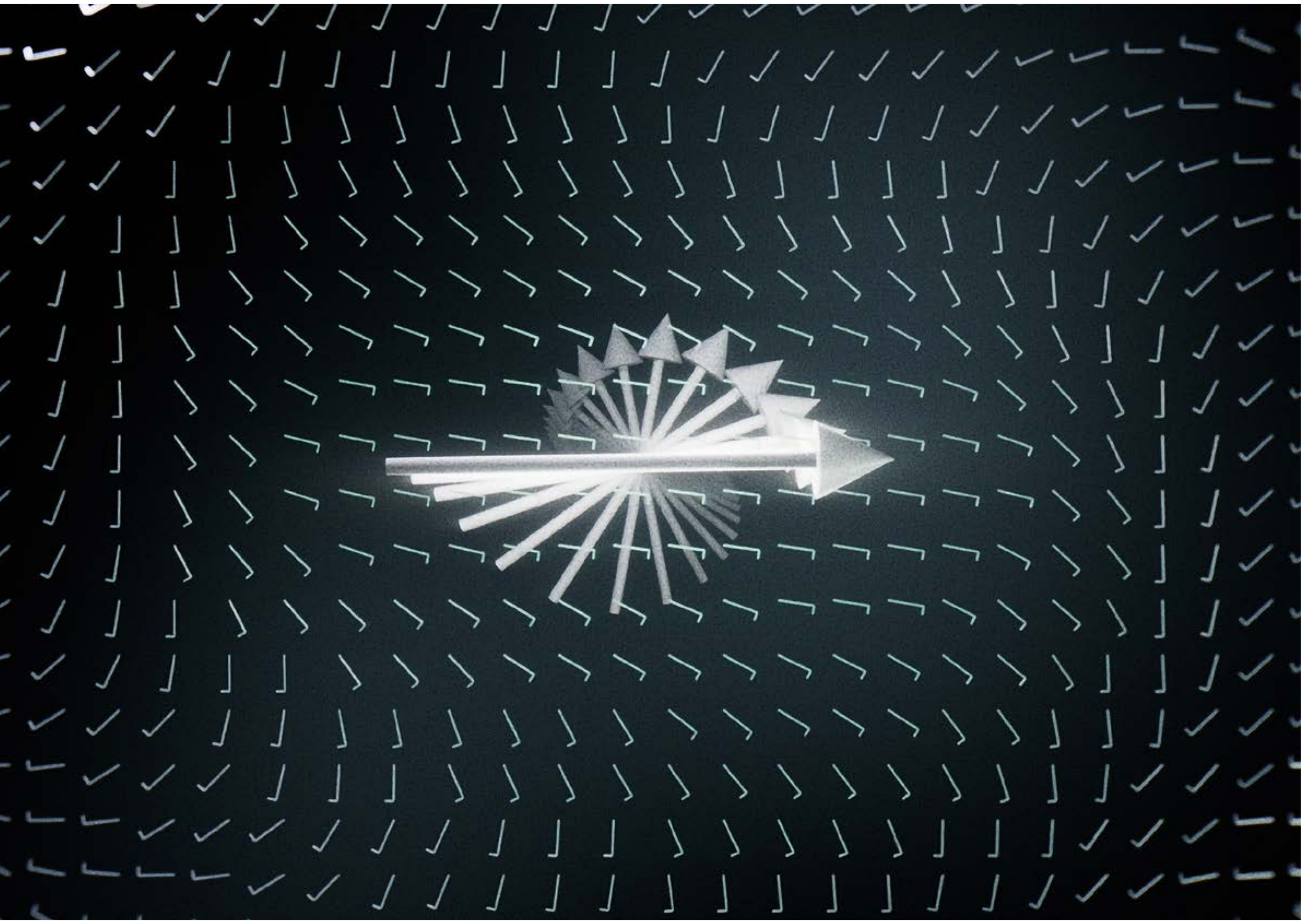
At the moment, QuSpin is at full speed. We are happy to see that several young talents emerge from QuSpin to continue in academia and the industry, benefiting from our environment. In the end, QuSpin´s success is the qualifications and experience gained by the people we educate and train. QuSpin members have been active and successful in acquiring new research grants. We have received grants from the Research Council of Norway (RCN), EEA GRIEG grant, Peder-Sæther grant Berkeley, and NTNU Nano. We are particularly happy that we will receive significant funding through the RCN Balance Project to improve the gender balance at our Center and among the talents we train that will become qualified for permanent positions.

In late February 2020, academic life was as it used to be, despite the news of the growing infection rates of Covid-19 worldwide. Many of us arrived in Denver in the USA to attend the annual American Physical Society March Meeting. However, the organizers had to suddenly cancel the welcoming of ten thousand attendees on March 1. Although the decision was made very late in retrospect, it was wise to cancel this event to prevent a further escalation of the pandemic. This cancellation has become a symbol of the sudden changes in our lives and the profoundly altered academic interactions.

At the moment, QuSpin is at full speed. We are happy to see that several young talents emerge from QuSpin to continue in academia and the industry, benefiting from our environment.

Interactions and collaborations are central to scientific progress and vital for QuSpin. The pandemic implied that we could neither organize our international workshop Quantum Spintronics nor our internal and our scientific collaboration workshops. Also, we had to put our international visitor program on hold. As a partial replacement, we organized an international online seminar series. We also moved all our regular activities, such as seminars and journal clubs, to become available online. We are grateful for the many initiatives by group members to cope and support others during the pandemic. While it is clear that new initiatives and the collaborative environment have suffered since the outbreak in March, we are grateful that the publication rate has been steady. We also have a positive trend in the number of collaborations within the Center, as reflected in the co-authorships in our publications. The spin ARPES is installed and running. The functional topological systems laboratory has developed new methods for the detection of magnetic structures at the nanoscale, and the MBE lab is making its first nano-scale controlled materials.

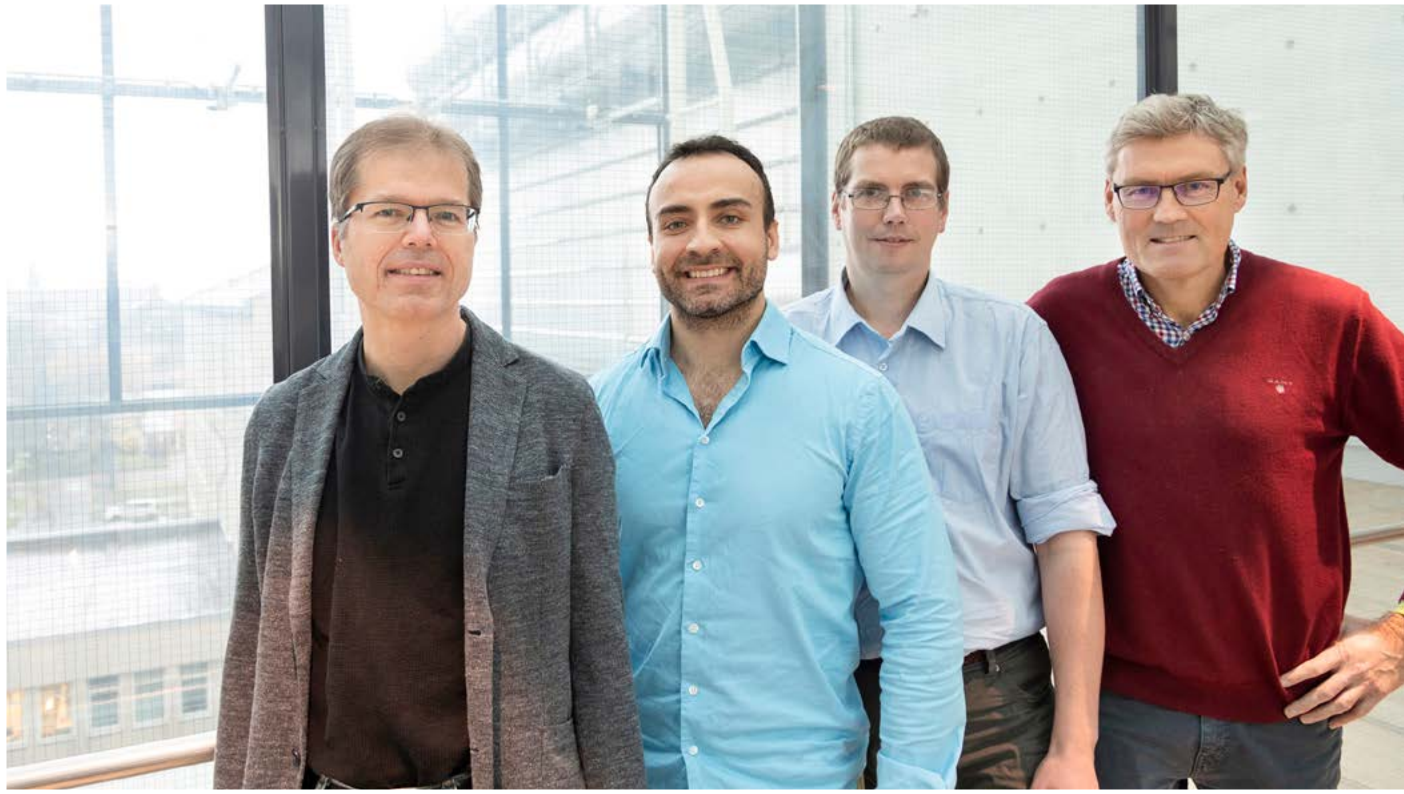
We are grateful to our collaborators, the Scientific Advisory Board, and our Board for support and suggestions during the past year. We also would like to thank all our members for their outstanding work and enthusiasm.



THE QUANTUM SPIN: *We are training a new generation of scientists to discover new phenomena involving the quantum spin and exotic quantum properties.*

Center of Excellence

QuSpin, recognized in 2017 as one of ten new Centers of Excellence by the Research Council of Norway, carries the responsibility to provide 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 innovations.



Principal Investigators Arne Braatas (Center Director), Jacob Linder, Justin Wells and Asle Sudbø.

To innovate in the field of spintronics, our research center will be receiving funding throughout its ten-year lifetime. QuSpin will receive part of the total funding of 1.5 billion Norwegian Kroner for the Centers of Excellence.

By the end of 2020, our Center had developed into the more than sixty-people strong team with members from thirteen different countries. QuSpin now has nine permanent professors and associate professors, four researchers, seven postdocs, twenty-seven Ph.D students, twelve master's students, and one administrator. In addition we have three positions on twenty-percent as Co-Principal Investigators and Associate Professor II.

As an international research center, QuSpin values its 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 puts Norway at the forefront of quantum spintronics research. In turn, our research will enable innovative applications.

Outlook from the QuSpin Advisory Board

Our role as the International Advisory Board for QuSpin is to advise the leadership team on management, cutting edge research themes, defining milestones, and international communication. Normally, we have annual in-person meetings for dialogue. Because of the pandemic, our 2020 meeting took place on Zoom.

Milena Grifoni
Chair

Geritt E.W. Bauer

Daniela Pfannkuche

Jason Robinson

We have noted the impressive publication track record over this past year, which also demonstrates an increase in collaborative research across the groups within QuSpin. The research strategy plan, reviewed against the original objectives of QuSpin, shows a massive increase in experimental activities, including the hiring-in-process of a part-time female Professor II. This new post is an exciting opportunity for QuSpin and creates critical mass for the Spin ARPES activity.

The Center has also been granted an RCN Balance Project, aimed at attracting female scientists to improve the gender balance, and supporting women on their road to qualify for top academic positions.

We welcome this effort to increase Equality, Diversity and Inclusivity. The Board has contributed with a number of suggestions to boost support for both female and male members of QuSpin, including an enhanced appraisal process.

QuSpin has been concerned about the negative impact of the Covid-19 pandemic on the general well-being of its members and research output. Foreign personnel have been particularly vulnerable. The Center has successfully supported the team through Zoom scientific meetings and virtual social events. QuSpin aims for a long-term benefit from this experience and plans to organize virtual seminars and a hybrid international workshop in 2021. It is very well possible that meetings will continue to take place on these platforms in the future.

In brief, we are happy to see that QuSpin, despite the challenges associated with the pandemic, continues to increase its scientific impact and develop its internationally leading research programs.

One day we can be able to transport and store data in entirely new manners.

From Basic Ideas to Proof-of-concept Devices

How observations of small “defects” may guide us towards new technology.

Dialogue between Professor Dennis Meier, Postdoc Mariia Stepanova and Ph.D. candidate Erik Lysne. Facilitated by Karen-Elisabeth Sødahl.

Erik Lysne, Dennis Meier and Mariia Stepanova.

Background and motivation

“It all started with a scientific discussion with a colleague at a conference more than a decade ago,” Dennis says. “She was working on the theory of a new magnetic phase that had just been discovered. The discussion sparked my interest in the underlying physics. At that time, I was doing experimental work on remotely related topics and immediately had ideas for first experiments, which then of course did not work out right away. But that is how it goes: Science demands a good mixture of curiosity and patience to tackle the more complex problems. Today, things look different. The initial ideas have evolved into successful fundamental research projects, exploring new opportunities for future nanotechnology.”

The goal of the research team around Dennis is to understand and utilize new discoveries in magnetism at the nanoscale to develop solutions for more efficient low-energy devices. “If you take the memory of a computer, for example, it is basically nothing but a really fancy kind of *rock* into which you *engrave* the information you want to store,” Erik says. “We are exploring novel physics that potentially allow us to *engrave* the 1s and 0s on which modern information technology relies in new ways.”

“It is crucial to understand the underlying physics,” Mariia adds. “We are studying magnetic objects through different imaging techniques at the nanoscale to learn how they behave under different experimental conditions, and how we can control them. One important question is whether or not the magnetic nano-objects we find can be written and erased on demand, so that they can eventually serve as data bits.”

Dennis continues, “But it is also crucial to always keep an eye open for new, unexpected things when doing this kind of research. New discoveries very often start with an observation in an experiment that was actually supposed to test or verify something totally different. This makes fundamental research so exciting and important.”

The latter can be seen from the team’s current project, where scientific curiosity and unexpected discoveries have led them to the development of new concepts for memory technology, which they could not even imagine themselves just three years ago.

The research process

“We got inspired by an emergent and rapidly evolving field of research and performed rather target-oriented experiments. But these experiments did not go as we had hoped,” Dennis says. “Unexpected outcomes, however, are quite often the most interesting ones, and step by step we realized that we had discovered something new instead, which nobody had looked at in detail before. Thus, what we first considered a non-successful experiment turned out to be the beginning of a new and exciting journey away from the mainstream. In a sense, this was a lucky coincidence, but also the natural consequence of carefully performed experiments, frequent brainstorming, and dedicated work in the laboratory.”

> *The three of us are part of a much bigger team. We could name so many who are contributing. If you take a piece out of the puzzle, it is not complete anymore and that`s the same with our work. - Dennis*

What the team had found was a novel type of magnetic defect structure that arises at the nanoscale. “The more data we took,” says Dennis, “the more we realized how exciting this was and that these magnetic nano-entities had never been studied before. While publishing our first articles on their fundamental physics, we already developed ideas how our observations could be utilized in devices and started dreaming a little of how they might even improve existing technologies.”

That was the starting point of several scientific proposals the team submitted, which enabled the systematic studies they performed over the past four years at NTNU. These studies allowed them to develop the necessary understanding and expand their skillset, which was essential in order to bring the new discoveries closer to applications and devise first proof-of-concept experiments.

What did we discover and why is it important?

“Usually, when we hear the word *defect* in our daily life, it has a negative connotation. The same used to be true in materials science and especially in information technology, where defects are truly unwanted companions because they are one of the main reasons for failure,” Erik explains. “But this typically refers to defects in the structure of a material, like a missing atom or an atom in the wrong place,” Mariia emphasizes. “What we are studying are defects in the magnetic order, where some of the electrons have a spin that is pointing in the wrong direction. Such magnetic imperfections can be extremely small, down to the length scale of a few atoms. Despite their smallness, these defects cannot just vanish and are thus very robust. This is exactly what we want in our search for objects that we can use to store information: they need to promote ultra-small feature size for high storage density and, of course, non-volatility so that we do not lose our data.”

The idea to make use of magnetic defects – or magnetic solitons, which is the same but sounds more positive – was already established when the team got started and scientists around the world were intensively studying tiny magnetic whirls, so-called skyrmions, as next-generation information carriers.

Dennis elaborates, “Originally, we tried to do the same, but did not manage to observe the magnetic whirls in our model material. This forced us to constantly improve our setup and the experimental strategy, and eventually we measured a large variety of exotic magnetic defects beyond skyrmions which we hadn`t expected.”

Over time, they realized that they had discovered a zoo of novel magnetic defects which share many of the physical properties with the whirls most of the other researchers in the field were investigating. “Although we did not really find what we were looking for, we were kind of lucky and, instead, observed completely new nano-entities that added promising and unforeseen aspects to the existing research.”

Based on these defects and other magnetic imperfections at the nanoscale the team measured later on, they developed different ideas for novel device concepts, which they are currently trying to realize in their laboratory.

How would you describe this joint process of developing new knowledge?

“I would describe it as an interactive process,” Erik explains. “You can start to work in one direction and then you see something weird. First you check that it is not just an artefact and if others have seen the same thing. Sometimes they have, sometimes they haven’t.” Mariia continues, “We build up on the knowledge from previous research, our experience, and collaborations with others. We start our own experiments and go one way, then possibly sideways; every now and then you don’t really know anymore what to measure next and get new input to try new things you did not consider before.”

Dennis adds, "The exchange with other scientists is really crucial. Very often, we measure things at the nanoscale that we do not understand right away, because the physics at this length scale can be truly counterintuitive. In the really complex cases, the data we collect can serve as input to develop a first model together with our colleagues in the theory field, which we then test again in the laboratory and refine step by step until we are sure what`s going on. That's why it is great to be part of a vibrant Center like QuSpin, where such synergetic scientific work and discussions are basically the daily business, allowing to answer complex research questions much more efficiently."

As a Ph.D. student and a Postdoc, you think you know everything, but you really don't. So every now and then it is good to have a professor who has more experience around who tells you, "this is not how you do it", or reminds you that you forgot an effect or something. - Mariia

What is your approach when meeting challenges?

Mariia and Erik joined the project in 2017, when the basic physical properties of the new magnetic defects which Dennis and his collaborators had discovered were already fairly well understood. The plan was to start controlling their motion in the next step, which is one of the key requirements when it comes to applications. But while preparing samples for the experiment, they met a problem: the surface of the material degraded much too fast during nano-structuring – on the timescale of hours – which made it impossible to build the envisioned test devices before the material was magnetically *dead*. But how to protect the surface of a material without covering up the already hard-to-detect magnetic nano-objects the team was interested in? What started out as a seemingly straightforward microscopy study suddenly turned into a materials engineering problem...

"After we realized that, we sat down and discussed new strategies," Dennis explains. "Erik had the idea to shift the focus to another material, which he had already investigated a little together with Markus Altthaler, who is doing his Ph.D. at the University of Augsburg and partly with us at NTNU. This is one of the international collaborations we have with researchers in Germany, Switzerland, Japan and the US, through which we have access to the important high-quality materials needed for our work and to conjointly realize measurements we couldn`t do just by ourselves."

"In parallel, I teamed up with a collaborator at the University of Stuttgart to identify possibilities to continue the originally intended line of research," Mariia mentions.

Thus, once again, an unforeseen challenge required an adjustment of the team's original research plan. "At first, this always feels like a throwback," Dennis says, "but it rarely is – in fact, occasions like this can be very beneficial for the research as we are enforced to take a step back, brainstorm, critically re-think the experiments, and develop new ideas. For me, this problem-solving as a team is one of the most enjoyable tasks in our job – a kind of trivia game that we can only master together."

"Yes, although Erik and I went in different directions, we still asked each other for advice, discussed with Dennis and the other team members," Mariia adds. "We performed simulations together, communicated about the open challenges and the progress. Collaborations are so important, and in our group, they happen naturally, which is very helpful whenever a challenge comes up."

From millimeter-sized little rocks to concepts for future technology

When asked a bit more in depth about their recent findings and how one can understand them, Erik says, "I brought this," and puts a small unremarkable stone on the table. The stone is greyish and is about one millimeter in diameter – at first glance, nothing that would catch our attention, but Erik knows better. "This is the material I started studying as an alternative to the one that degraded too fast. Out of this little stone, we are cutting tiny rings with a width that is 100 times thinner than a human hair. Because the magnetic order in the material strongly depends on shape and size, we can control it by cutting such rings. We have learnt how to make the rings with nanometer precision to influence the magnetic order in exactly the way we want, achieving the small and stable magnetic defects it takes to store information."

Presenting the illustration (see next page), Erik explains further, "This is an example of one of the rings and the microscopy measurements we are performing on them. The two colors represent the magnetic order. When regions appear bright, we know that the magnetization points up and when they are dark, the magnetization points down. In reality, the interpretation is more complex, but this is essentially how we visualize magnetic order at the nanoscale and find the tiny magnetic defects Dennis talked about."

Mariia also has a success story to tell. She has found a solution to stop the degradation of the material she and Erik started out with. In addition, together with her international colleagues and with support from Professor Arne Brataas and researcher Alireza Qaiumzadeh at QuSpin, she has demonstrated a conceptually new method for reading out magnetic nanoscale defects, which the team is currently writing up for publication.

"I think this nicely exemplifies what we mentioned before," concludes Dennis, "Progress in science is usually not *linear* and we may have to adapt our ideas several times and make adjustments, but not giving up and looking for solutions always pays off."

Is this how we will store data in the future?

"Well, that's what we are trying to find out," Erik responds. "What you see here is where we left off the day the COVID lockdown hit us. In my simulations, it already works – so theoretically it should definitely be doable. The experimental results are also highly reproducible, the magnetic structures are stable at room temperature and way above, and upscaling is possible, too."

Dennis continues, "This means that, in principle, all ingredients needed to make a proof-of-concept device are in place and I am also convinced that we will be able to do so in the next months. However, this does not mean that you will be able to buy our device next year or that it can really outperform existing technology. Our job is to demonstrate and explain the new physics that enable novel device concepts and show that it is feasible to go this way. We are still doing fundamental science, but with a clear technological motivation."

What's next?

Until recently, the team focused on a *top-down* approach, cutting their nanostructures out of a much larger material. "This is not how it is done when producing actual devices," Erik says, "Instead, one would synthesize optimized thin films with the desired physical properties."

I still think it is fun and I believe that it will be possible to realize our initial vision. - Erik

In order to go in this direction, the groups of Dennis Meier and Christoph Brüne have teamed up. In QuSpin's new laboratory for molecular beam epitaxy (MBE), led by Christoph, Payel Chatterjee and Longfei He are exploring possibilities to grow the materials of interest with atomic-layer precision. Bringing these two lines of research together and combining thin-film and lithography methods would be a major breakthrough, establishing a scalable approach for the fabrication of their test devices.

All this is happening on campus at NTNU and, as Dennis points out, reflects the outstanding infrastructure the team has access to, allowing them and their collaborators to realize projects that bridge materials synthesis, characterization, and device fabrication. "It is not just what we have available in our laboratories; in addition, there is NTNU NanoLab which is crucial for us and where we can become really creative," says Dennis and continues with a smile, "So maybe I was wrong earlier and you will be able to buy our device next year after all".

Magnetic domain pattern in a nano-structured ring. The contrast indicates the direction of the magnetization (dark: up; bright: down).

QUSPINERS 2020:
QuSpiners working from their home offices during the pandemic.

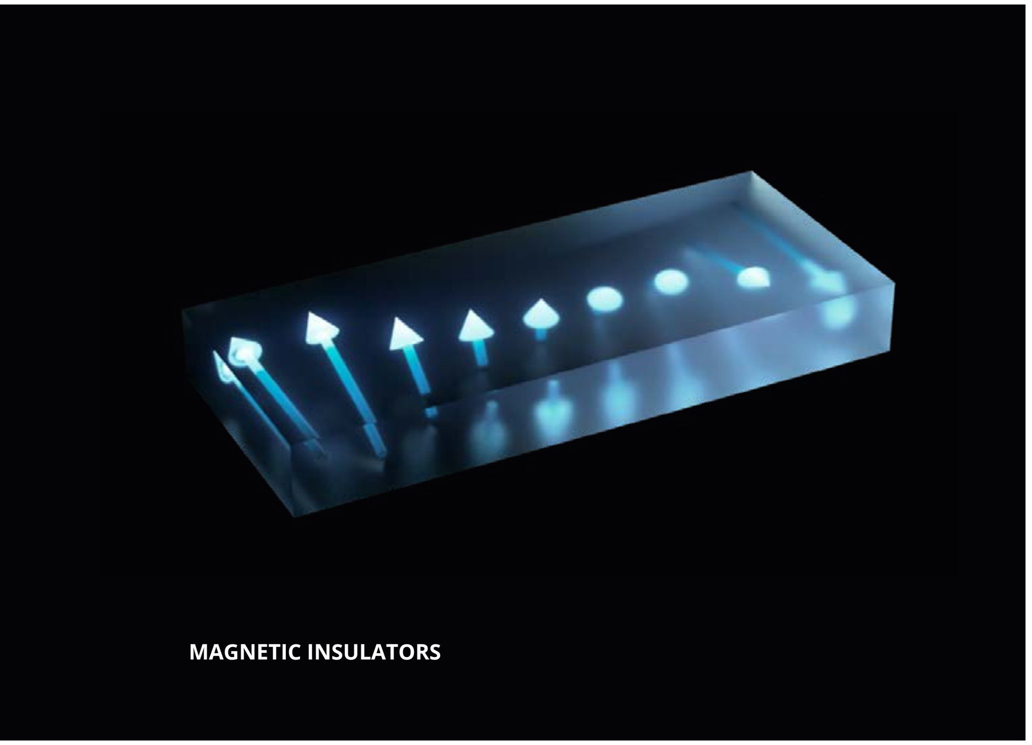
Main Research Themes, Goals and Activities

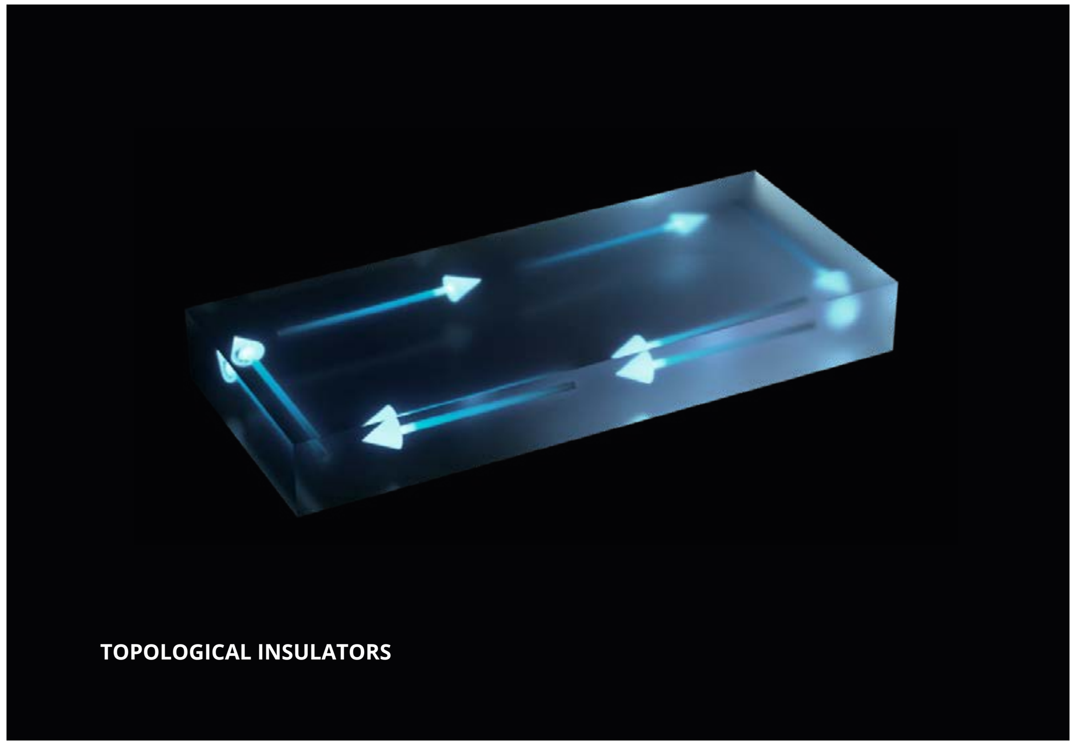
The principal goal of the Center is to describe, characterize and develop recently identified quantum approaches to control electric signals in advanced nanoelectronics, conceptually different from those existing today.

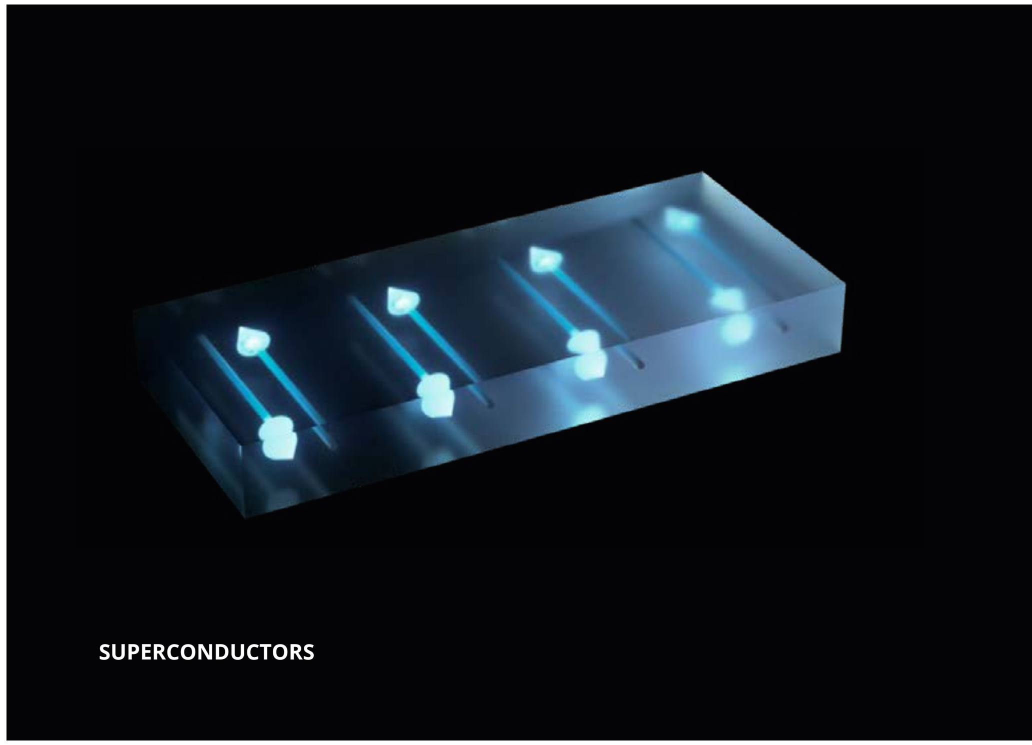
The research focuses on three judiciously chosen low- dissipation systems: magnetic insulators, topological insulators, and superconductors which correspond to three research themes: insulator spintronics, topological matter, and super spintronics.

Our unique competitive edge is addressing the ultra-low power innovations by uniting expertise from insulator spintronics, topological matter, and super spintronics. Although 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 require new models and new concepts.







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.*

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.

ARNE BRATAAS

Spin Insulatronics

Theme and goal

An electron has a spin in addition to its electric charge. The spin is the source of magnetism. The motion of the mobile charge carriers is the basis of conventional electronics and spintronics. In metals and semiconductors, electric fields induce currents. In magnetic materials, a spin current occurs naturally as well. Spin currents also appear in non-magnetic materials where the spin significantly couples to electron motion.

Spin Insulatronics is profoundly different because there are no moving charges. In magnetic insulators, spin information can, nevertheless, propagate. While electrons are immobile in insulators, another entity conveys information. At equilibrium, the electron spins become ordered. In response to external forces, the ordered pattern of the spins can be disturbed. The disturbance can take on forms such as waves, spin waves, or other dynamical spin textures.

Controlling electric signals through the deployment of magnetic insulators can facilitate a revolution in information and communication technologies. We aim to determine the extent to which spin in antiferromagnetic and ferromagnetic insulators couple to mobile electrons in adjacent conductors. We will utilize this coupling to control electric signals. We will replace moving charges with dynamical low-dissipation coherent and incoherent spin excitations in magnetic insulators. These features also imply that we can enable unprecedented control of electron-electron correlations. In turn, these features can open the doors towards the creation of new paths for magnon and exciton condensation, superfluidity, and superconductivity. 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

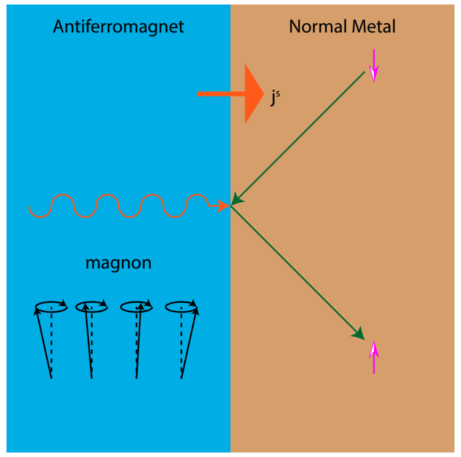
We focus on the fundamental challenges facing Spin Insulatronics. Key questions are how spin can transfer from electrical conductors to insulators, how and how far spin propagates in insulators, how we can control correlations that cause new states of matter, and how we can detect these phenomena's signatures.

Activity in 2020

The use of antiferromagnets in spintronics is mainly passive; the exchange bias in contact with ferromagnets controls the latter's orientation. However, antiferromagnets are promising in a more active role since the spin dynamics is orders of magnitude faster than in ferromagnets. Spin transfer torque and spin Hall effects, combined with their reciprocal phenomena spin pumping, and inverse spin Hall effects, enable reading and controlling magnetic moments in spintronics. The direct observation of these central effects remained elusive in antiferromagnetic-based devices until this year.

Enrique del Barco's experimental team at the University of Florida in Orlando, with assistance from our theoretical input, observed the desired effects this year, and published the results in Science. We reported subterahertz spin pumping at the interface of the uniaxial insulating antiferromagnet manganese difluoride and platinum. The measured inverse spin Hall voltage from spin-charge conversion in the platinum layer depends on the chirality of the antiferromagnet's dynamical modes, which is selectively excited and modulated by the handedness of the circularly polarized subterahertz irradiation. Our results open the door to the controlled generation of coherent, pure spin currents at terahertz frequencies.

Additional activities are the developments of a theory of spin Hall effect in antiferromagnets, the generalization of the description of current fluctuations driven by spin dynamics to arbitrary junctions and antiferromagnets as well as ferromagnets, the development of a theory of Bose-Einstein condensation of nonequilibrium magnons in confined systems, and the observation of magnon polarons in a uniaxial antiferromagnetic insulator.



ASLE SUDBØ

Topological Quantum Matter

Theme and goal

In the words of the Russian author and Nobel Laureate Aleksandr Solzhenitsyn: "Topology! The stratosphere of human thought! In the twenty-fourth century, it might be of possible use to someone". At QuSpin, we aim to make good use of topology for a better world long before that.

Topology is a branch of mathematics that investigates global geometric properties of objects. These can be physical objects, 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 properties of matter in the quantum domain.

Topological quantum matter features certain robust and very useful physical properties which are protected by deep non-trivial topological properties of the quantum states of the system, involving the "geometry" of the quantum states in topological phase transitions, the ordered state cannot be characterized by a standard simple local order parameter. Rather, the ordered state lacktopological defects, while the disordered state has proliferated large amounts of topological defects "ripping" the ordered state apart".

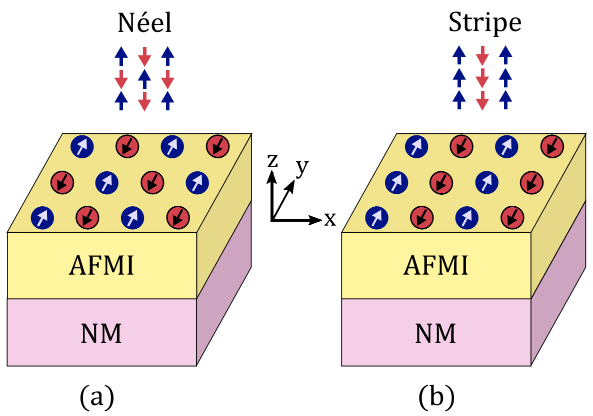
Superfluidity and superconductivity are the phenomena that make it possible for fluids in the quantum regime to flow without any dissipation. Superconductivity, superfluidity, and magnetism are cooperative phenomena where enormous numbers of degrees of freedom spontaneously self-organize themselves into various ordered states of matter. This involves the phenomenon of spontaneous symmetry breaking.

Key questions

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.

Activity in 2020

A major aspect of the research carried out in 2020 has been an extension and continuation of what we investigated in 2019, namely to compute and predict how magnetic quantum fluctuations at the interface between metals or topological insulators on the one hand, and ferromagnets or quantum antiferromagnets on the other hand, may induce superconductivity in the metal or topological insulator. These investigations continue to be extended into the realm of strong-coupling superconductivity using Eliashberg theory. Moreover, a new undertaking of 2020 has been in the area of low-dimensional magnetic systems, so-called van der Waals magnets. A long-standing problem in condensed matter physics has been how to measure and detect the universal properties of the topological phase transition that takes place in two-dimensional magnets with easy-plane ansitropy, the Kosterlitz-Thouless-Berezinskii transition. We have proposed a detailed experimental setup to measure a specific universal feature of this transition, drawing on the broad expertise at QuSpin on topological phase-transitions and charge-spin conversion in transport processes.



JACOB LINDER

Superconducting Spintronics

Theme and goal

In classical physics, matter exists as a gas, liquid, solid, or plasma. However, this classification is too crude to capture the fascinating physics that emerges within each of these states. For instance, not all solid states behave the same way. According to quantum physics, various solid materials will behave very differently. Some are magnetic, some do not conduct electric currents, 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 different materials such as superconductors and magnets are combined, things get interesting. This is one of the motivations behind the field of superconducting spintronics where one studies spin-dependent quantum effects in superconductors.

Two main goals guide our research. The main goal is to discover new quantum phenomena that emerge when combining superconductors with materials that have very different properties, in particular magnetic ones. Secondly, we focus on discovering phenomena that may be relevant to the development of memory technology and information transfer based on superconductors. This is closely related to the transport of charge, spin, and heat.

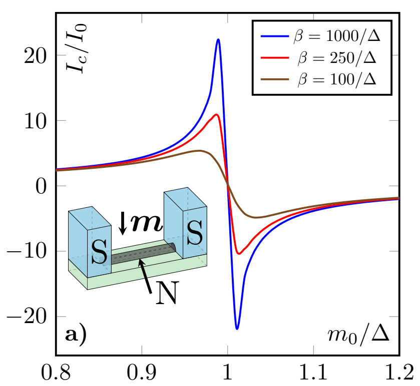
We use a variety of analytical and numerical tools to address the research questions above, depending on which method is the most appropriate for the system at hand. Some of our theoretical approaches include lattice models, quasiclassical Keldysh theory, Green function techniques, scattering theory,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

Key questions

The main problems we are attempting to solve are related to the functional properties of materials and how they can be controlled or altered by combining several materials. For instance, is it possible to use magnetic materials to control when superconductivity appears and even enhances its properties? Can one use superconductors to generate 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 2020

One of our research highlights from 2020 is the development of a theoretical framework allowing for the study of ultrafast and non-periodic time-dependent problems in superconducting heterostructures. We have utilized this to predict a strongly enhanced supercurrent via the abrupt onset of a spin-splitting field. Moreover, we have predicted that the phase transition of a superconductor can be controlled by rotating an inversion symmetry-breaking axis in a neighboring material. In collaboration with experimental groups, we have published work on quantum Hall states in magnetized graphene and a superconductivity-induced change in the magnetic anisotropy of Fe/MgO/V layers. Other research activity includes the prediction of a non-equilibrium spin accumulation induced by singlet Cooper pairs, RKKY interactions mediated by zero-energy states in unconventional superconductors, and the Josephson effect in rippled graphene. Our publications in 2020 include two papers in PRL and three papers in PRB Rapid Communications.



Strongly enhanced supercurrent via the abrupt onset of a Zeeman-field m_0.

JUSTIN WELLS

Electronic Structure

Theme and goal

The electronic bandstructure of a material contains information about all the electrons which are relevant for physical and electronic properties in a solid. It also contains information about the electron spin, and interactions of electrons with each other, impurities, vibrations, spin waves, and more. It is therefore of great benefit to be able to directly measure the electronic band structure, and hence gain access to this information. Over the last decade, the instrumentation available has improved dramatically. During 2020, we have been part of this revolution in instrumentation: We have been involved in the development and installation of a new type of photoelectron spectromicroscope which boasts ultra-high efficiency spin-resolved, momentum-resolved, spatially-resolved and energy-resolved bandstructure imaging.

Having completed the construction and installation of the new suite of instruments, the primary goal is now to demonstrate mapping of electron interactions, including electron-phonon and electron-magnon interactions. More specifically, to understand how to modify the strengths of these interactions, and to evaluate their potential role in driving novel forms of unconventional superconductivity. We also strive to bring interesting and up-to-date research work into the undergraduate classroom, to educate Master's students, to contribute to the career development of young scientists and to enable the production of high-quality Ph.D. theses.

Key questions

Our research predominantly focuses on the interaction of electrons (especially their spin) within a solid. For example, the coupling of electrons with each other 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.

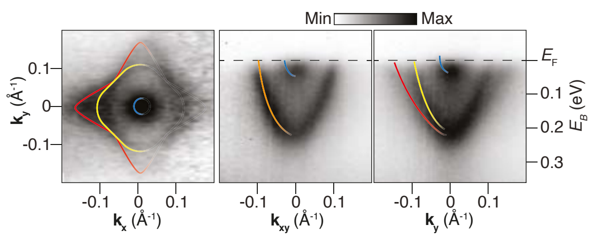
Most of the methods we use come under the category of "photoelectron spectroscopy" and are based in Einstein's photoelectric effect, for which he received the Nobel Prize in 1921. More recently, it has been shown that the same method can reveal the spectral function (closely related to the electronic band structure). Furthermore, this information can be resolved by energy, momentum, and spin and the newest instruments also facilitate good spatial resolution. We operate multiple 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.

Activity in 2020

Highlights from 2020 include the completion of our new flagship instrument. Our focus has been on the growth and bandstructure mapping of 2D materials, such as graphene, to facilitate the electron-phonon coupling to be extracted under a range of realistic degrees of doping.

A particular highlight from 2020 is our publication in NPJ Quantum Materials in which we show how extreme downscaling of silicon electronics results in a dramatic enhancement of the dielectric constant such that additional bands appear in the occupied bandstructure which have never before been predicted or observed. We show how this enhancement can be used to control the energy separation of the bands in a quantum device platform, and hence how this can potentially be used to develop quantum devices.

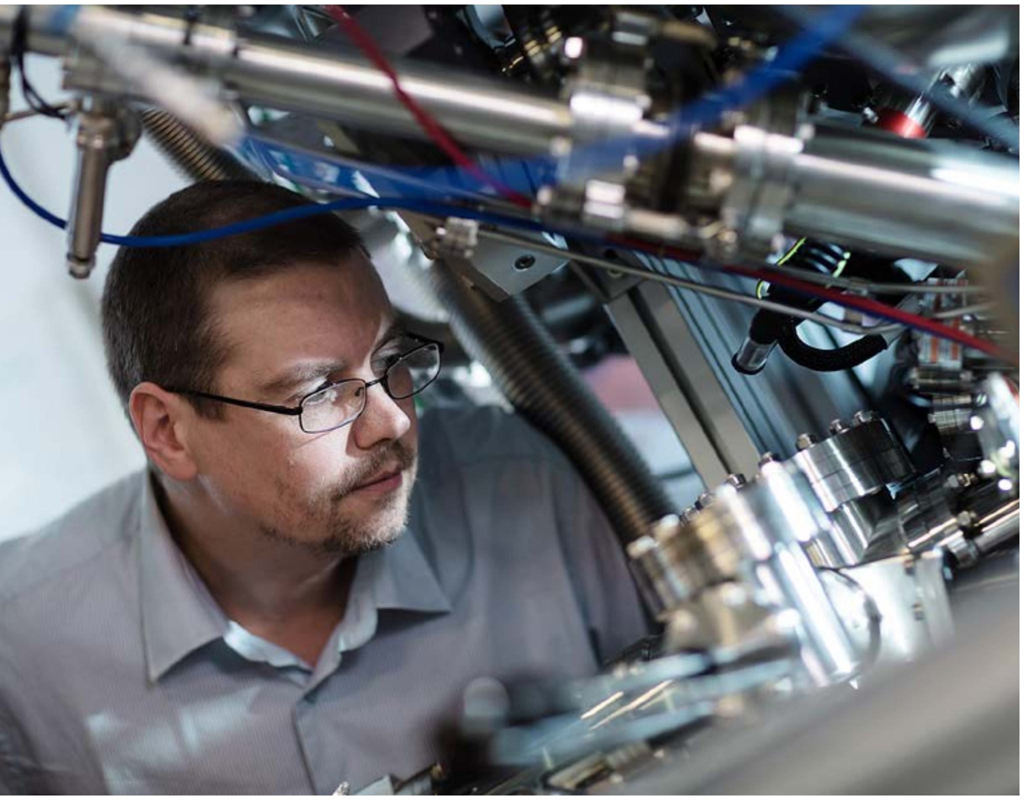
This work is carried out in collaboration with the Quantum Computation and Communication Technology at UNSW in Australia.

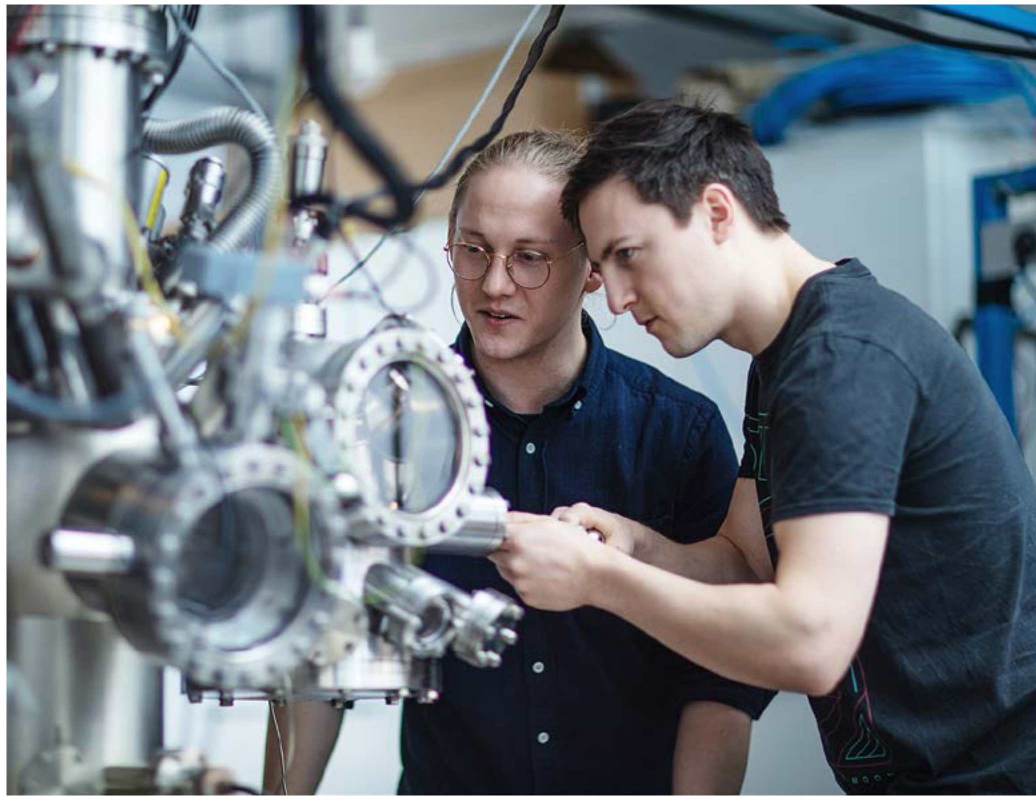


The sub-band structure in an atomically sharp dopant plane in a silicon-phosphorus "delta layer", used as a platform for silicon quantum electronics. The figure shows the Fermi surface and electronic structure along the kxy and ky directions for a Si:P layer with a P concentration slightly higher than 25%. The active part of the structure is 1.5 nm thick. Blue, red, and yellow lines serve as a guide for the eye. ARPES measurements are performed using hv=36 eV at the Swedish synchrotron "MAX IV laboratory". [see "The sub-band structure of atomically sharp dopant profiles in silicon" Mazzola et al., npj Quantum Materials 5:34 (2020)]

SPIN-ARPES LAB

Here we are working with our spin-ARPES instrument and multi-purpose preparation and characterisation chamber.





CHRISTOPH BRÜNE

Molecular Beam Epitaxy of Antiferromagnets

Theme and goal

The QuSpin Molecular Beam Epitaxy (MBE) group's goal is to develop the synthesis of high-quality materials with potential for spintronics research and application. We have recently started up our new lab and are now synthesizing the first materials.

To do this, we rely on so-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 nano-wires and quantum dots. Using MBE growth for magnetic materials will enable us to create, control and investigate materials that can be used in spintronics research and applications. Furthermore, the control down to single atomic layers will allow us to tailor the material properties so that we can enhance desired characteristics or even create new ones.

Key questions

Our first project area is the growth of so-called antiferromagnetic semiconductors. These materials combine the potential for new spintronics applications with the possibility to manipulate the material properties using electric fields (similar to today's semiconductor technology). This will enable the integration of established semiconductor techniques and spintronics applications. This work is done in close collaboration with Arne Brataas' and Mathias Kläuis' groups.

Helimagnetic systems are the group's second research area. These materials are very interesting for their complex magnetic structures, based on a spiralling (helical) order of the spins in the material. This includes so-called 'Skyrmions', stable magnetic whirls inside the material. Skyrmions are promising for their potential as nano-objects for future low-energy memory devices. We will develop the growth of materials that host helimagnetic or skyrmionic structures at room temperature for future applications.

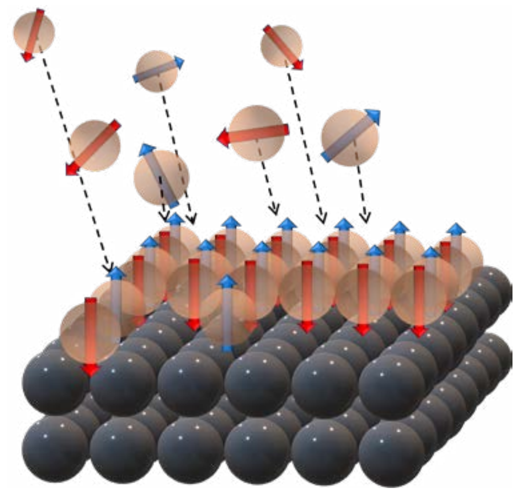


Illustration of molecular beam epitaxy growth of an antiferromagnetic layer on a non-magnetic substrate.

These investigations are conducted in close collaboration with Dennis Meiers' group, with two Ph.D. candidates shared between the two groups.

We have recently also started activities towards the synthesis and investigation of hybrid systems that combine antiferromagnets and superconductors. This work will initially focus on the antiferromagnetic semiconductor MnTe and is a collaborative effort with the theory groups at QuSpin and partners at the IF PAS in Warsaw, Poland.

Activity in 2020

The central activity in 2020 was the first growth development of the antiferromagnetic semiconductor CuFeS2 and the helimagnetic FnSn material system. Even though we experienced some delays here related to the Covid-19 situation, we successfully grew crystalline thin films of both materials. We also began with structural investigations of these materials using high resolution X-ray diffraction, scanning electron microscopy and atomic/magnetic force microscopy.

The planned installation of a further growth chamber was unfortunately delayed due to the pandemic, but we will hopefully get it up and running in 2021.

JEROEN DANON

Spin-based Quantum Computation

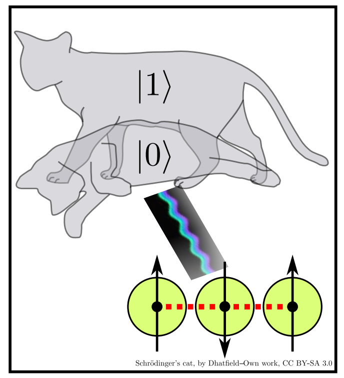
Theme and goal

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 can 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 can 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, we are 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 2020

My group consisted for most of the year of three Ph.D. students and one postdoc. In 2020, we published (1) an improved proposal for a multi-particle singlet-only spin qubit, which is intrinsically insensitive to the fluctuating nuclear spins, (2) the discovery of a quite general mechanism that provides a way to actively suppress the nuclear field fluctuations in a multi-dot setup, simply by applying a DC electric current, (3) an elegant proposal of how to create bosonic qubits that are based on so-called Schrödinger cat states and how to transfer quantum information between such a qubit and a spin qubit, (4) a discovery of very general symmetry properties of the conductance matrix of a three-terminal superconducting junction, which was a collaboration with the Niels Bohr Institute in Copenhagen, and (5) the first experimental demonstration of well-controllable few-electron quantum dots in an InAs-based two-dimensional electron gas with weak spin-orbit interaction, which resulted from a collaboration with the ETH Zürich.

In the course of the year, we also shifted part of our focus to so-called hole-spin qubits, where the spins are carried by "missing" electrons in the valence band of a semiconductor. Due to the underlying structure of their wave function, these holes are intrinsically coupled much more weakly to the nuclear spins than the electrons in the conduction band. So far, we have addressed an open issue concerning several basic hole parameters in silicon and we have investigated effects of the residual coupling to the nuclear spins. Apart from that, we have started thinking about other possible experiments that could be performed to access the more intricate properties of these holes.

SCANNING PROBE MICROSCOPY LAB

Here we are studying functional topological systems.

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 behavior pointing towards spin-liquid physics.

In recent years it has also become clear 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.

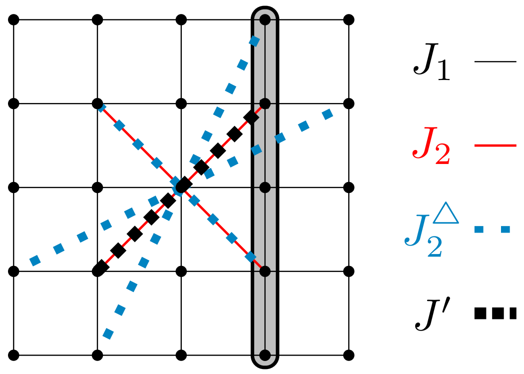
The overall goal is to get a better understanding of the "zoo of phases" that may arise in frustrated quantum antiferromagnets, and contribute towards their description and classification.

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 2020

Research activities were mainly focused on investigations of crossover phenomena in entanglement properties of quantum XXZ antiferromagnets based on modified linear spin wave theory, shortcomings in the ability of Schwinger-boson mean-field theory to describe entanglement properties of ordered quantum Heisenberg antiferromagnets, and bosonic and fermionic coherent-state path integral representations of quantum spins.



Examples of model interactions for calculations of entanglement entropy of magnetically ordered frustrated quantum Heisenberg antiferromagnets (subsystem in grey).

ERIK WAHLSTRÖM

Local and Global Magneto-dynamic Properties of Oxides

Theme and goal

Our primary theme is to probe and understand excitations in the charge, spin and lattice, and their interactions at the atomic scale. Our primary method is through developing excitation spectroscopy techniques, primarily scanning-based probe techniques and other experiments that provide insights into the fate of charge and spin in materials.

Our short-term goal is to explore the magneto-electronics and magnonics of oxide ferromagnets and antiferromagnets. In a more applied context, the long-term goal is to understand and control coupling in the thermal energy scale in order to contribute to the use of thermal energy to communicate information. The longer-term goal on the method side is to develop STM-based point-contact techniques to explore mesoscopic and magnetodynamic physics at a very local scale.

Key questions

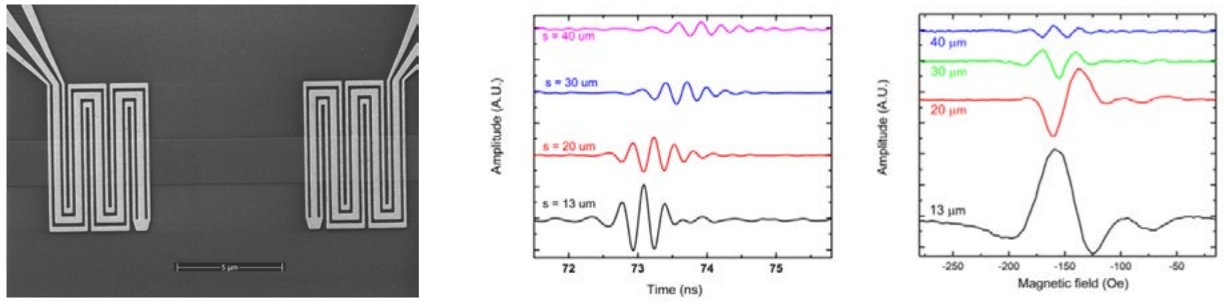
Our primary aim is to understand and probe the excitations and coupling between magnons, phonons and charge carriers at an energy scale that ranges from sub-thermal energies to electron volts. In the spin domain, the prime motive is to understand magnons, and the expression in the form of interacting and propagating magnons and their interaction with charge and phonons.

In the phonon regime, we are interested in understanding size and material control and tunability in coupling to the charge and spin excitations.

We are primarily investigating model systems in oxide materials, developing an understanding of perovskite-type ferromagnets and antiferromagnets, mainly collaborating and seeking collaboration with groups on the material synthesis side to address our key questions.

Activity in 2020

In 2020 we finalized our work on developing a continuous wave version of pulsed wave spectroscopy, assessing propagating properties of magnetodynamic waves between antennas through a field sweep protocol. This has been used for test samples employing both NiFe and Co2FeAl. A small collaborative work comparing a series of 1D magnonic lattices with a magnetodynamic simulations and a simple analytic model was also brought to finalization. Funding was secured for a project through the FRIPRO program supporting the main goals of the group, where we in the course of the next four years will explore and control magnon-phonon interactions in oxide systems with the aim to thermally pump the magnon system. This is an internationally collaborative effort where THz imaging (Stefano Bonetti, Stockholm), PEEM imaging of excited structures (Ferran Macia, Barcelona) and development of point contact spectroscopy (NTNU and Toshu An, Kanasawa) will be used to probe structures grown in collaboration with the oxide electronics group at NTNU.



Left: Gold antenna structures for sending and receiving magnetodynamic waves in magnetic striplines; (middle) time-domain pulses used for pulse-based characterization for thick films (150 nm NiFe); (right) field domain data for continuous wave characterization of superior quality for thin films (15 nm NiFe).

MBE LAB

Here we specialize in the growth of magnetic thin films with thicknesses ranging from single atomic layers to several 100 nm.

DENNIS MEIER

Topological Spin Textures

Theme and goal

Topologically non-trivial spin textures, such as skyrmions, dislocations, disclinations and domain walls, display emergent electrodynamics and can move coherently over macroscopic distances. Their outstanding properties and nanoscale feature size make them excellent candidates for next-generation spintronics technology. Application opportunities range from logic gates and race-track memory to artificial synapses for neuromorphic computing, where the topological spin textures are utilized to process or store information.

Our research studies the fundamental physics that gives rise to the formation and unique behaviors of topological spin textures in insulators, half-metals and metals. We are particularly interested in the unusual local responses of these special magnetic defects, their scaling behavior and how they can be created on demand, controlled and read-out. For this purpose, we apply advanced microscopy and nano-structuring tools which allow us to investigate the topological defects spatially resolved in device-relevant geometries.

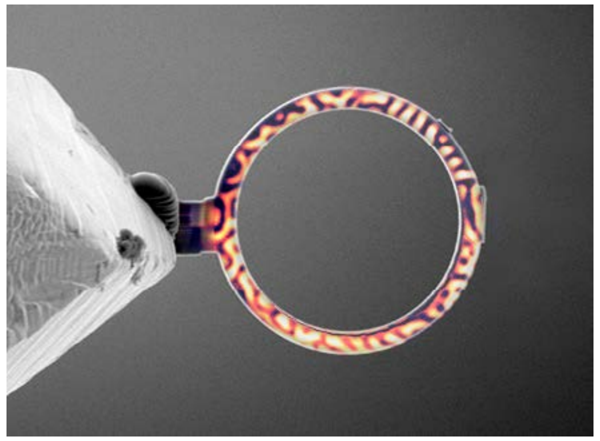
The goal of our research is to understand and utilize the emergent functional phenomena associated with topological spin textures, developing current device paradigms into new realms of magnetism.

Key questions

By applying microscopy and nano-structuring methods, such as magnetic force microscopy (MFM) and focused ion beam (FIB), we aim to create fundamental knowledge about the physics of these nanoscale spin textures. We want to understand their formation process in confined media and the emergent topology-driven interactions that distinguish them from the surrounding material. For example, we investigate how electrical currents and magnetic fields control the position and movement of individual spin textures, tracking their quasi-dynamical response. Ultimately, we want to understand the new degrees of flexibility the different topological spin textures can offer and demonstrate new application opportunities that arise for future low-energy electronics.

Activity in 2020

In 2020, we achieved several breakthroughs regarding the preparation, characterization and understanding of device-like architectures, focusing on different materials that promote the formation of magnetic dislocations and domain walls. Working closely together with Alireza Qaiumzadeh, Arne Brataas, and our international partners, we showed that pronounced nonlinear magnetic interactions occur at topological spin textures in chiral magnets, facilitating new possibilities for their detection and innovative read-out schemes for related device applications. In addition, in collaboration with Christoph Brüne's team, we have begun to synthesize and measure new systems of interest that are not yet available as thin films. In the next step, we will expand our activities to include an even wider variety of materials to identify the most promising model systems for the development of test devices, using the MBE and microscopy infrastructure available within QuSpin and in close collaboration with NTNU NanoLab.



Magnetic order in a nano-structured ring with diameter of about 7 μm. (Courtesy of Erik N. Lysne & Erik D. Roede)

SOL H. JACOBSEN

Triplet Spintronics

Theme and goal

Superconducting spin-polarized triplets carry coherent quantum information. A component of their correlation does not decay in either ferromagnets or superconductors, even with impurities. This makes them a primary candidate for low-dissipation information transport in spintronics. We examine the interplay of magnetism and superconductivity in a range of systems using theoretical and numerical techniques.

The goal of this research is to show that superconducting triplets are useful low-dissipation information carriers in emerging spintronic systems.

Key questions

Our research considers atypical geometries and model setups for examining the conversion mechanisms and manipulation of superconducting singlets and triplets, and aims to identify their experimentally accessible signatures. By challenging the geometrical constraints of conventional spintronics, we hope to enable new superconducting spintronic device design and control.

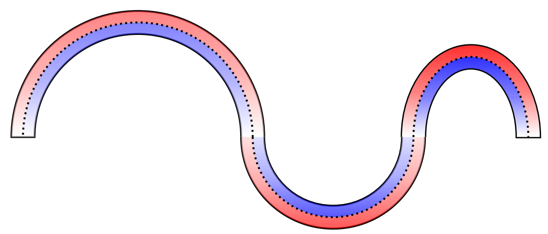
One of our key research directions exploits recent experimental advances in creating spintronic devices with curvature. It is known that curvature affects the spin-orbit coupling that can yield singlet-triplet conversion. We will determine the potential and scope of curvature to generate and control triplet populations in diffusive systems.

We aim to challenge the conventional paradigm of direct proximity between superconducting and magnetic elements in spintronic devices, and hope to show that the proximity constraint can be circumvented for triplet devices, via their photon-mediated effects on magnons, or other spintronic readout mechanisms. In the longer term, we also aim to apply the advances of superconducting triplet spintronics to other areas of solid-state quantum computing, such as entanglement optimisation and transmission.

Activity in 2020

In 2020, we started up the TripletSpin project funded by a Young Research Talents grant from the Research Council of Norway. We were joined by Ph.D. student Tancredi Salamone from Italy, and Henning Hugdal will join as a postdoc in February 2021. It is not easy to start a new group during a pandemic, but we have made some good progress. Andreas Janssønn and co-workers at QuSpin successfully showed the macroscale non-local transfer of singlet signatures to a ferromagnet in a cavity, and Tancredi is well underway with the first curvature models in the diffusive regime. We are also joined by master's students Mariell Breivik and Mathias Svendsen, working on aspects of superconducting triplets in nanowire systems.

We have established collaborations with postdoc Morten Amundsen from the NORDITA institute in Sweden, and also continue working with QuSpin members on aspects of superconducting spintronics with antiferromagnets. The pandemic meant colleagues further afield had to be reached through attendance and discussions at digital conferences, and traditional outreach activities also had to be moved online. This year I was interviewed by college students in Australia, and quizzed by theatre producers in the UK. I also joined and presented at the inaugural meeting of the Grete Hermann Network for women working in condensed matter, and acted as discussion partner in the now successfully funded QuSpin Balance project.



Curved nanowires may hold the key to new device designs, control and capabilities. Fig. by T. Salamone.

AKASHDEEP KAMRA

Transistors of the Future

Theme and goal

The different phases of electronic matter that emerge due to interactions are the cornerstones of solid-state physics and digital technologies. Two diametrically opposite phases – superconductor and magnetic insulator – constitute the focus of our research. A superconductor is an ideal conductor with zero resistance, hosting dissipationless and unhindered flow of electrons. A magnetic insulator is comprised by immovable electrons, which interact via their spins and can transport spin without actual motion. We aim to understand these electron and spin flows, and exploit them for future technologies.

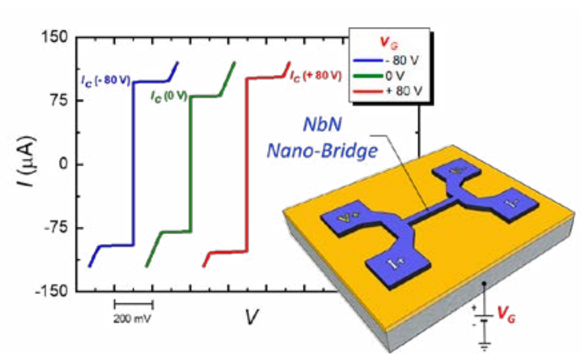
Key questions

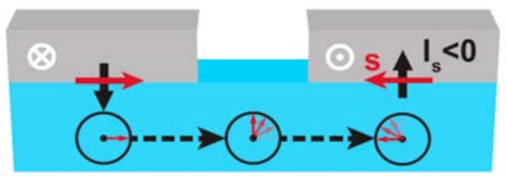
How can one transport information via supercurrent in a superconductor and spin current in a magnetic insulator? Is it possible to use these currents for not just transporting information, but enabling its active control and manipulation in a transistor action?

Activity in 2020

Our digital electronics uses as a building block a "switch" that connects or disconnects a circuit depending on the voltage at a gate lead. This is achieved by realizing the circuit with silicon constrictions, which are electrically insulating. Application of gate voltage creates charge carriers in the constrictions making them conducting and thereby closing the circuit. Using similar devices made of superconducting films, collaborators at MIT (USA) succeeded in increasing the maximum supercurrent that can flow through the constrictions. This opens fresh application opportunities based on the control, and especially an increase, of the dissipationless supercurrent. Further, it defies decades of research suggesting that such a gate voltage should not affect a good conductor. In an oversimplified comparison, the observed effect looks like turning the water of an entire lake orange by adding a bucketful of orange juice. Check out Nano Letters 21, 216. Precocious master's student Marius K. Hope will present further theoretical analysis in an upcoming manuscript.

Our electronics relies on information being encoded in the electronic charge. An emerging paradigm based on magnets relies on the spin angular momentum carried by emergent quasiparticles – magnons. These quasiparticles are much more flexible than elementary particles such as electrons. Experimentalist colleagues at TU Munich and Walther-Meissner-Institute have succeeded in exploiting this flexibility, and managed to bend the spin of antiferromagnetic magnons to their will. See Phys. Rev. Lett. 125, 247204 and Phys. Rev. B 102, 174445. Soon after, our QuSpin colleagues in Mainz found the same magnon Hanle effect in a different material and present findings in Appl. Phys. Lett. 117, 242405.





ALIREZA QAIUMZADEH

2D Quantum Spintronics

Theme and goal

Recent discovery of two-dimensional (2D) ferro- and antiferromagnetic materials in metallic, semiconducting, and insulating phases is a paradigm shift in spintronics. In low dimensions, quantum fluctuations and interactions are strong, and thus techniques used in conventional spintronics are not useful anymore. The primary focus of our current research is on exotic magnetic and topological phases, nonequilibrium phenomena, and emergence phenomena in novel 2D quantum systems. In general, we are interested in phenomena such as ultrafast manipulations of spin interactions, quantum magnonics, topological magnetic solitons, topological orders and topological phases, and unconventional quantum transport. Our goal is to develop theories and formalisms for understanding exotic phases of materials, mechanisms behind non-equilibrium phenomena, and consequently design and control quantum devices on demand beyond the current state-of-the-art.

Key questions

Effects of different interactions, such as electron-electron, magnon-magnon, electron-magnon, magnon-phonon, etc., on nonequilibrium 2D systems are challenging problems for which we need to develop sophisticated analytical and advanced numerical techniques. We are also interested in studying the effect of quantum and thermal fluctuations in stabilizing different magnetic phases and exotic spin transport in 2D magnets. Developing theoretical frameworks beyond conventional approaches for describing these phenomena on a microscopic level is an important topic in our group.

Activity in 2020

In 2020, we received two grants to study novel quantum materials: "2Dtronics" funded by EEA and Norway grants, and "Micromagnetic Simulation of Antiferromagnetic Nanostructures" funded by NTNU Nano's Enhanced Impact Fund. The 2Dtronics project is a collaboration between our group and our Polish partner, Dr. Anna Dyrdał's group. In this project, we study novel low-dimensional quantum materials. In 2020, we had collaborations with several world-leading experimental and theoretical groups. We had close collaboration with the experimental group of Prof. Mathias Kläui in Germany on magnon transport in antiferromagnets. We are going to extend this collaboration to other mutual research interests. In collaboration with Prof. Burkard Hillebrands's group in Germany, we discovered the possibility of high temperature Bose-Einstein condensation of magnon in geometrically confined ferromagnets. Using first-principal calculations, in collaboration with Prof. Reza Asgari's group in Iran, we studied the effect of strains and electric fields on 2D magnets. Furthermore, in collaboration with Prof. Jamal Berakdar's group in Germany, we studied spin-orbit torques in topological insulator-ferromagnet junctions (Fig. 1). Developing formalisms to compute magneto-resistance in 1D antiferromagnetic solitons (Fig. 2) and antiferromagnetic-superconductor junctions were other research results in 2020. In another project, our postdoc Dr. Marion Barbeau has, in collaboration with Prof. Mikhail Katsnelson's group in the Netherlands, developed a new non-quasiparticle formalism for magnons excited by hot electrons in a metallic antiferromagnet under strong laser irradiation.

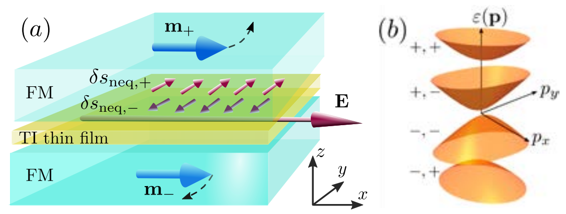


Fig 1. (a) Schematic of a topological insulator thin film sandwiched between two ferromagnetic layers in the presence of a dc electric field (b) Chiral band dispersion of topological insulator thin film. [adapted from PRL 125, 196801 (2020)]

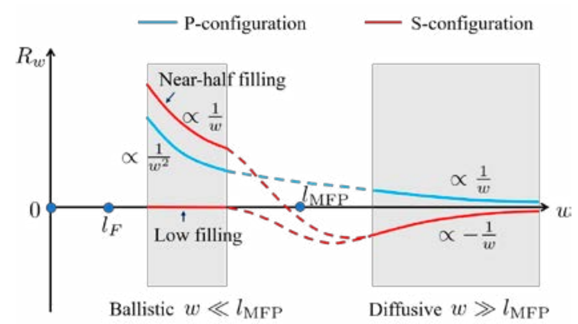
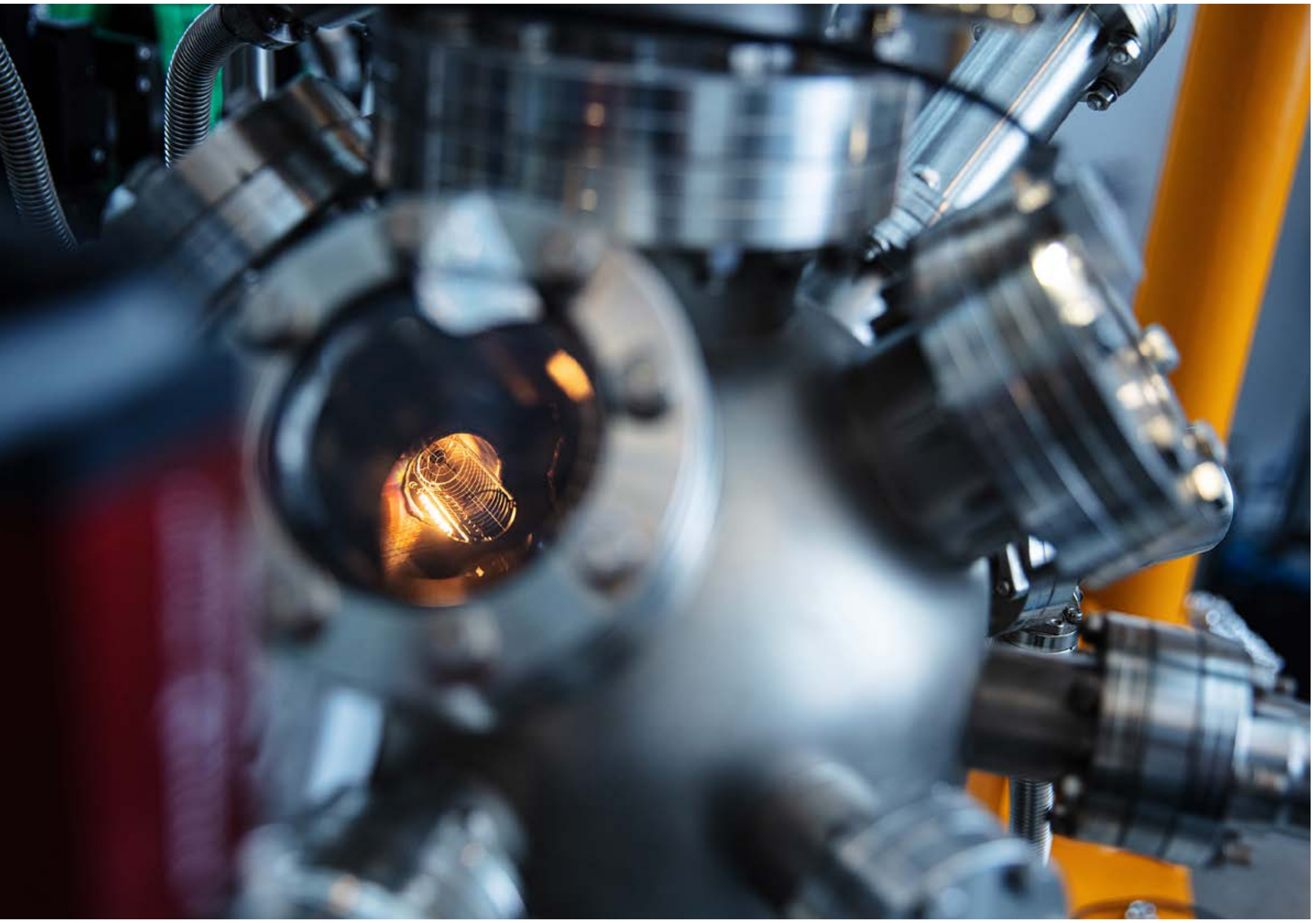


Fig. 2. Domain-wall magnetoresistance as a function of domain-wall width for different antiferromagnetic configurations. [adapted from PRB 102, 184413 (2020)]

ILLUSTRATION: *We are discovering fundamental properties of new materials to control quantum variables.*



International Partners and Research Network

Research is a collaborative effort that often carries across disciplines and strengthens scientific curiosity. We are privileged to have working relationships across the world that elevate our collective intelligence and add to the work in our field.

Professor Rembert Duine

Professor Mathias Kläui

We are continuing the long-term collaboration with our Co-Primary Investigators and their groups, Professor Mathias Kläui at the Institute of Physics at the University of Mainz in Germany, and Professor Rembert Duine at the Institute of Physics at the University of Utrecht in the Netherlands.

QuSpin has the leading experimental scientist Professor Mathias Kläui as Professor II. Combined with the work of young and dynamic experimentalists in Trondheim, and supported by our excellent theory activity, QuSpin is taking its experimental activity to the next level.

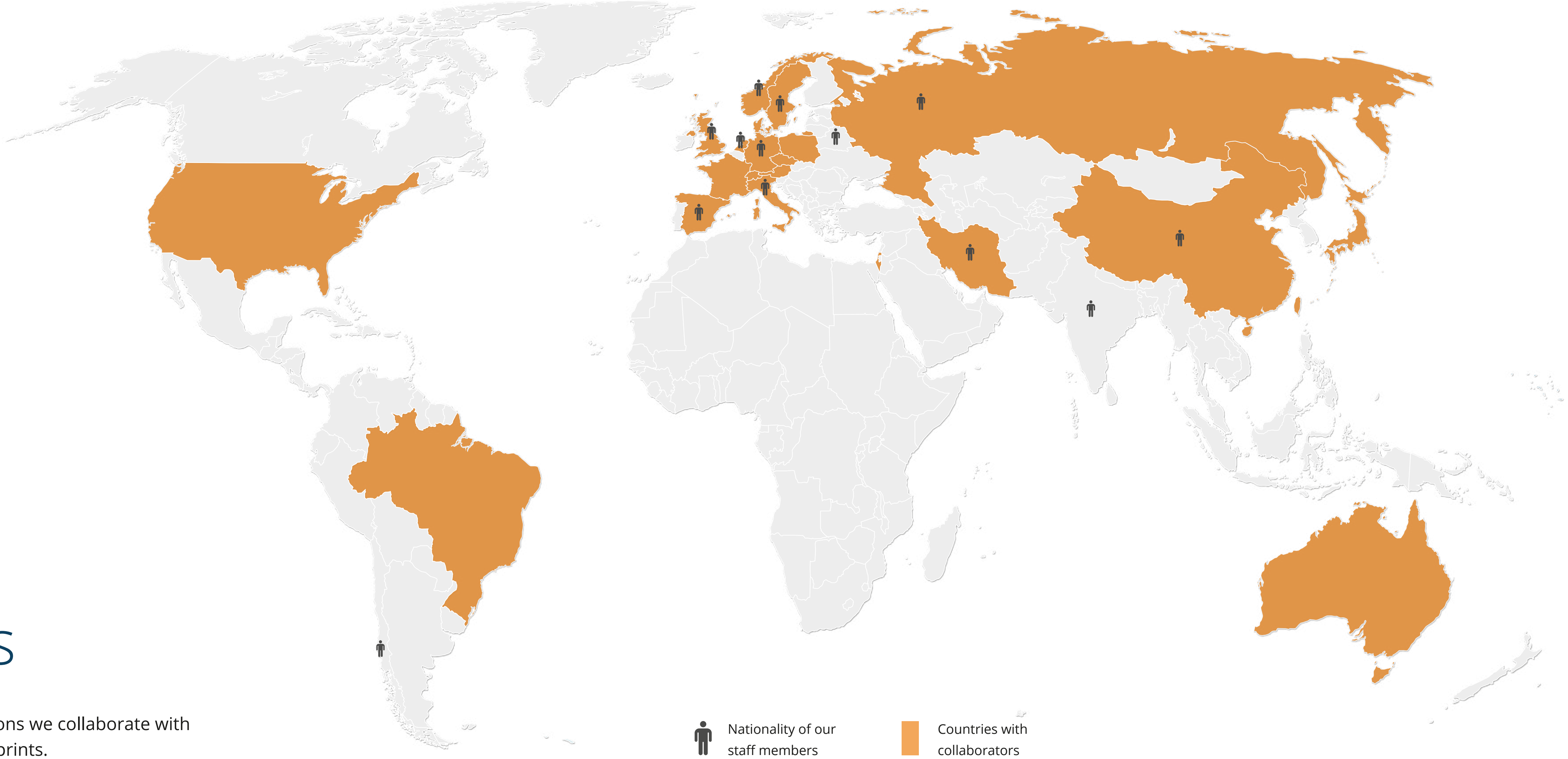
The collaboration with JGU Mainz gives QuSpin access to material growth, characterization, and transport measurements. A central theme of the collaboration has been spin transport in antiferromagnetic insulators, where we have established fruitful synergies between experimental and theoretical developments.

Professor Rembert Duine is a leading theoretician in the quantum-many body physics of spin transport and spin excitations, and a Professor II at QuSpin. Landmark publications by Rembert 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. Professor Duine´s activities last year extend QuSpin´s research in the direction of the new field of spin angular momentum transferred by phonons.

The QuSpin Center is grateful for its opportunities to host visiting researchers that allow for interactions on a personal level, bolstering the professional work and exposure to new, ongoing, and past projects.

Due to last year’s – and ongoing - international travel restrictions, the visits have been significantly reduced. Instead, we invited guests to hold scientific talks online on the Zoom platform. The talks were given by speakers from collaborating universities in the UK, Italy, Germany, the Netherlands, and the USA. These online talks have helped us keep up our interaction with the international research community during the pandemic and have added valuable input, knowledge, and inspiration to our ongoing research. However, we look forward to physical meetings and interactions as soon as the situation allows it.

In addition, we collaborate with internationally leading theoretical and experimental groups in many places around the world (See map overview next page).



Collaborators

The list below is an overview of the institutions we collaborate with as co-authors on published papers and preprints.

AUSTRALIA
Australian Synchrotron, Clayton
University of Monash, Clayton
University of New South Wales, Sydney

AUSTRIA
Graz University of Technology, Graz

BRAZIL
University of Brasilia, Brasilia
Federal Rural University of Pernambuco, Recife

CZECH REPUBLIC
Czech Academy of Sciences, Prague

CHINA
Central South University, Changsha
China Academy of Engineering Physics, Beijing
University of Chinese Academy Sciences, Beijing
Shanghai Institute of Applied Physics, Shanghai
Shandong University of Science and Technology, Qingdao
Zhejiang University, Hangzhou

DENMARK
University of Copenhagen, Copenhagen
University of Aarhus, Aarhus

FRANCE
Nancy Universitè, Nancy
Universite Grenoble Alpes, Saint-Martin-d'Hères
Universite Paris-Saclay, Saint-Aubin
Université de Strasbourg, Strasbourg
Unité Mixte de Physique CNRS/Thales, Palaiseau

GERMANY
Fritz-Haber-Institute of the Max-Planck Society, Berlin
Johannes Gutenberg University of Mainz, Mainz
Karlsruhe Institute of Technology, Karlsruhe
Leibnizs Institute, Dresden
TU Kaiserslautern, Kaiserslautern
Technical University of Munich, Munich
University of Augsburg, Augsburg
University of Cologne, Cologne
University of Konstanz, Konstanz
University of Mainz, Mainz
University of Regensburg, Regensburg
University of Würzburg, Würzburg
Walther Meissner Institute for Low Temperature Research, Munich

IRAN
Institute for Research in Fundamental Sciences, Teheran
Institute for Advanced Studies in Basic Sciences, Zanjan

ISRAEL
Hebrew University of Jerusalem, Jerusalem

ITALY
University of Genova, Genova
Universitá di Milano-Bicocca, Milan

JAPAN
RIKEN Center for Emergent Matter Science, Saitama

THE NETHERLANDS
Radboud University, Nijmegen
Utrecht University, Utrecht
University of Groningen, Groningen

NORWAY
University of Bergen, Bergen
University of Oslo, Oslo

POLAND
Polish Academy of Sciences, Warzaw
Adam Mickiewicz University, Poznań

ROMANIA
Technical University of Cluj-Napoca, Cluj-Napoca

RUSSIA
Russian Academy of Sciences, Moscow

SPAIN
Instituto de Física Fundamental, Madrid
Donostia International Physics Center, Donostia-San-Sebastian
Universidad Autónoma de Madrid, Madrid

SWITSERLAND
ETH Zürich, Zürich

SWEDEN
KTH Royal Institute of Technology, Stockholm
MAX IV Laboratory, Lund
Uppsala University, Uppsala

THAILAND
Synchrotron Light Research Institute, Nakhon-Ratchasima

UK
Aberystwyth University, Aberystwyth
Cambridge Graphene Centre, Cambridge
Hitatchi Cambridge Laboratory, Cambrigde
Loughborough University, Loughborough
University of Cambridge, Cambridge
University College London, London
University of St. Andrews, St. Andrews
University of York, York
Swansea University, Swansea

US
Clemson University, Clemson
Cubic Carbon Ceramics, Huntingtown
Purdue University, West Lafayette
University of California, Riverside
University of Central Florida, Orlando
University of Chicago, Chicago
Massachusetts Institute of Technology, Cambridge

Research Training of our Ph.D. Candidates and Postdocs

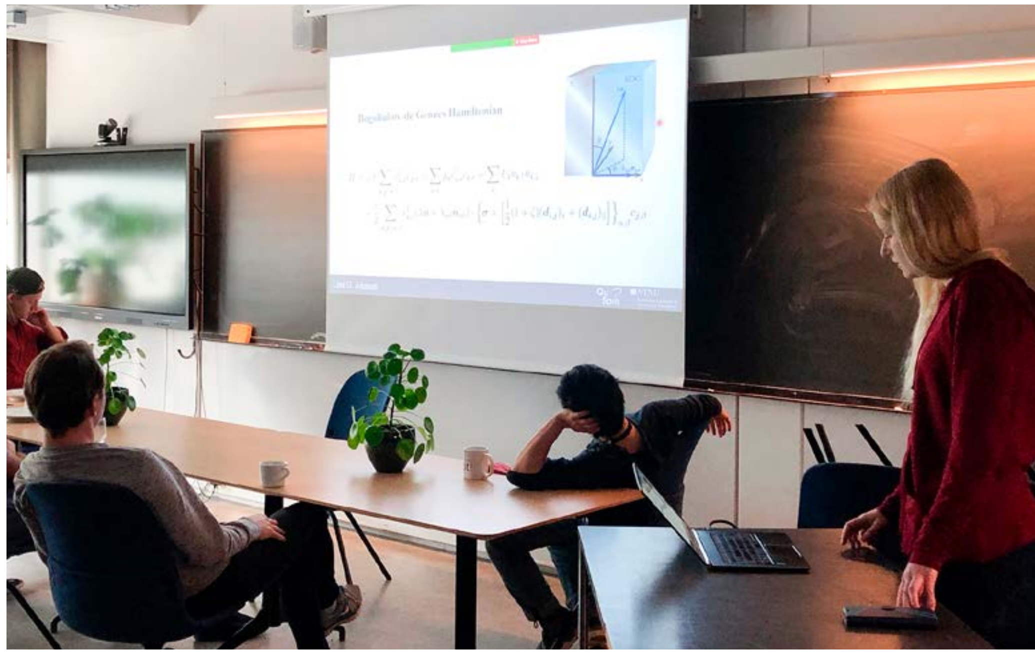
We wish to train the next generation of researchers within our field so that they can take on leadership for new projects of their own, as well as gain experience by co-supervising our Ph.D. candidates and Master's students.

QuSpin conducts excellent research that deserves excellent communication. The scientific presentations should be engaging and memorable. The goal of last year's pilot training project for young researchers was to strengthen their creative confidence and to develop their unique, personal presentation style, always with the memorability factor in mind.

– Marleen Laschet, International speaker coach and presentation trainer

Visiting guest Professor Dr. Manfred Fiebig from ETH Zürich giving a scientific talk.

Participating at our internal seminar series.



Ph.D. candidate Lina Grøvan Johnsen giving a scientific talk.

QuSpin went digital from March 2020. We normally give a range of workshops and seminars at the Center. Due to the ongoing corona pandemic, our annual international and our collaboration workshops have been cancelled. They were replaced by an online international seminar series on the Zoom platform where invited speakers gave their talks. This was successful, and also allowed us to reduce costs and travel time. However, this whole range of digital alternatives can never fully replace the benefits of physical meetings, where sharing ideas and knowledge takes place in a more open and spontaneous manner.

Our regular seminars and journal clubs have taken place online. The benefit of this solution was a larger audience. The speakers presented their work, shared ideas and discussed the challenges they face. Our regular Journal Club provides 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 Idea Forum for the younger researchers, where projects, ideas, and research challenges are shared, stimulating collaboration across both the theoretical and experimental fields, as well as between Ph.D. candidates, postdocs and researchers.

Researchers also need training in presenting their work and story in an efficient and compelling way. QuSpin has run a pilot project, training a small group of researchers. It was a fruitful learning experience. Our goal is to offer this training to our whole staff.

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

Ph.D. Defenses and Completed Master Theses

We congratulate our Ph.D. candidates who successfully completed their defenses and our Master's students who completed their theses. We wish them all the best in the next phase of their journey!

COMPLETED PHD'S

Amundsen, Morten. PhD Defence September 4th, 2020. Title: *Proximity effects in superconducting hybrid structures with spin-dependent interactions*. Supervisor: Jacob Linder.

Gulbrandsen, Sverre Aamodt. PhD Defense September 9th, 2020. Title: *Spin Transport in Antiferromagnets and Ferromagnets*. Supervisor: Professor Arne Brataas.

Sala, Arnau Cadellans. PhD Defence September 18th, 2020. Title: *Exchange-only, nuclear spin-free qubits in semiconductor quantum dots.* Supervisor: Professor Jeroen Danon.

Singh, Suraj Kumar. PhD Defence September 18th, 2020. Title: *Magneto-dynamic properties of thin films and interfaces.* Supervisor: Erik Wahlström.

COMPLETED MASTER THESES

Brekke, Bjørnulf. Title: *Diagrammatic Monte Carlo based on irreducible vertices for the Hubbard model in the strong-coupling limit.* Supervisor: Asle Sudbø.

Fossheim, Andreas Götestam. Title: *Exploring signatures of magnetic order in entanglement properties of finite-size two-dimensional quantum XXZ antiferromagnets at zero temperature-asymptotic behaviour and crossover phenomena.* Supervisor: John Ove Fjærestad.

Haug, Trond Hjerpekjøn. Title: *Ultrafast Two-Magnon Excitation in Two-Dimensional Antiferromagnetic Insulators.* Supervisor: Alireza Qaiumzadeh.

Mjøs, Andreas Halkjelsvik. Title: *Spontaneous Vortex Phase and Quantum Phase Diagram of Ferromagnetic Superconductors.* Supervisor: Jacob Linder.

Mæland, Kristian. Title: *Excitation Spectrum and Superfluidity of Weakly Interacting, Spin-Orbit Coupled Bose-Einstein Condensate.* Supervisor: Asle Sudbø.

Rygh, Jonas Halse. Title: *Study of the Quasiparticle Excitation Spectrum for the Ultracold, Two-Component, Synthetically Spin-Orbit Coupled, Weakly Interacting Bose Gas Residing on a Bravais Lattice.* Supervisor: Asle Sudbø.

Sund, Patrick Isene. Title: *Characterization of a proximity-mediated magnon–exciton coupling in a ferromagnet/transition metal dichalcogenide van der Waals heterostructure.* Supervisor: Jeroen Danon.

Syed, Shahzeb Talib. Title: *Superconductivity in the attractive Haldane-Hubbard model.* Supervisor: Asle Sudbø.

Ushakov, Ivan. Title: *Phase diagram of an extended Kane-Mele-Hubbard model in strongly correlated regime.* Supervisor: Alireza Qaiumzadeh.

Jacob Linder and Morten Amundsen.

Arne Braatas and Sverre Aamodt Gulbrandsen.

Jeroen Danon and Arnau Cadellans Sala.

Erik Wahlström and Suraj Kumar Singh.

Opponent on Zoom.

Celebrating a Ph.D. defense.

Glimpses from Our Center

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

When I saw the green lady dancing gracefully and fearlessly in the night sky, I came to think of a line from Khalil Gibran's The Prophet "Things move within you as lights and shadows in pairs, and when the shadow fades and is no more, the light that lingers becomes a shadow to another light".

– Payel Chatterjee, Ph.D. candidate

Diversity and different perspectives are essential factors in our approach of challenging questions in our Research Center. Each researcher and student who comes to the Center brings their unique experience to the group dynamic, and we can see how their individualities and experiences add value to our research.

Our Center's researchers come from thirteen different countries: Belarus, Chile, China, England, Germany, India, Iran, Italy, Norway, Russia, Spain, Sweden, and the Netherlands. They come from different walks of life, cultures, and ethnicities. They speak a variety of languages and are of diverse genders.

We normally spend time and resources on developing a prosocial and robust culture. We build arenas where people can meet, create and interact. But physical meetings have been a scarce resource last year. We had to comply with restrictions and form smaller cohorts.

Our newcomers have shown impressive flexibility coming onboard our Center. The use of home offices and digital meeting places have been the rule rather than the exception in 2020. Yet our new members grabbed every opportunity to get to know their peers little by little, at moments when physical presence at the Center was allowed.

Our Easter holiday feast was arranged on Zoom with soup and Easter treats distributed to everyone's home office. Children, spouses, cats and dogs were included, too. Christmas lunch was served partly at QuSpin, partly at home.

Our summer picnic in the garden, with delicious tapas and the two-woman NTNU band "The Peer Reviews", was a nice treat after several months in home offices.

People also enjoyed what nature could offer of walks, skiing and watching the amazing Aurora Borealis in our Nordic sky.

All in all, we had as much social interaction as we could, keeping up the good QuSpin spirit!

Honors and Grants

We had a great year with several honors and grants to our researchers. We highly appreciate the acknowledgment of our colleagues work, and the opportunities this represents for the further development of our center.

PEDER SÆTHER GRANT

Professor Dennis Meier (NTNU) and Professor Lane Martin (UCB) together received the Peder Sæther Grant for their proposal *on Ferroic domain walls for multi-level data storage and reservoir computing.* The Peder Sæther Center for Advanced Study supports projects carried out conjointly by researchers at UC Berkeley and universities in Norway.

GRIEG CALL, EEA AND NORWAY GRANTS

Researcher Alireza Qaiumzadeh has received the GRIEG Grant 2020-2023 by the Polish National Science Centre, together with researcher Anna Dyrdał from Adam Mickiewicz University in Poznań (AMU). The title of the project is *Spin and charge transport in low-dimensional novel quantum materials.* The GRIEG call is part of the Basic Research Programme operated by the Polish National Science Centre under the EEA and Norway Grants.

NTNU NANO GRANT

Researcher Alireza Qaiumzadeh received the Enhanced Nano Impact Fund 2020 for his work on *Real-world simulations of antiferromagnetic nanostructures.* NTNU Nano offers support to researchers at NTNU for a wide range of activities that are likely to raise the visibility and impact of NTNU's work in the area of nanoscience, nanotechnology and functional materials.

NTNU OUTSTANDING ACADEMIC FELLOWS PROGRAMME

Researcher Sol H. Jacobsen has become part of the NTNU Outstanding Academic Fellows Programme 2020-2023. The Outstanding Academic Fellows Programme aims to qualify some of NTNU's foremost young research talents for internationally leading research careers.

FELLOW OF THE AMERICAN PHYSICAL SOCIETY 2020

Co-PI Professor Mathias Kläui has been elected as a Fellow of the American Physical Society (APS) in recognition of his experimental research into magnetic materials, spin transport, and the dynamics and manipulation of spin textures on the nanoscale level.

RCN FRIPRO GRANT

Professor Erik Wahlström has received the RCN FRIPRO Grant for the project *Phonon-Magnon Pumping in Oxide Nano-structures - Creating condensates for Boson based computing.* The funding scheme for independent projects (FRIPRO) is an open, national, competitive arena that provides funding for basic, ground-breaking projects in all fields of research. The project ideas originate with the researchers themselves.

Highlights

JANUARY

NTNU Outstanding Academic Fellow Programme
Researcher Sol H. Jacobsen

NTNU
Norwegian University of Science and Technology

APRIL

Publication in Science

GRIEG call, EEA and Norway grants
Researcher Alireza Qaiumzadeh

AUGUST

First QuSpin 3D promofilm

Click QR-code to watch

SEPTEMBER

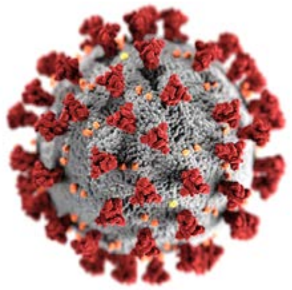
PhD Defense
Morten Amundsen

PhD Defense
Sverre Aamodt Gulbrandsen

PhD Defense
Arnau Cadellans Sala

PhD Defense
Suraj Kumar Singh

MARCH-DECEMBER



Covid-19 Pandemic

MAY-SEPTEMBER

zoom

QuSpin International Seminar Series on Zoom

JUNE

Peder Sæther Grant
Professor Dennis Meier (NTNU) and Professor Lane Martin (UCB)

OCTOBER

APS physics

Fellow of the American Physical Society 2020
Co-PI Professor Mathias Kläui

NOVEMBER

NTNU
Norwegian University of Science and Technology

NTNU Nano Grant
Researcher Alireza Qaiumzadeh

DECEMBER

The Research Council of Norway

RCN BalanseHub Grant
Females in Academia QuSpin

The Research Council of Norway

RCN FRIPRO Grant
Erik Wahlström

Scientific Publications

We are privileged to have the work of our researchers published in journals such as Science, Physical Review Letters and Physical Review B. Our center has had fifty-three publications over the last year, and we look forward to continuing to add to our library of published research.

1. Vaidya, Priyanka; Morley, Sophie A.; van Tol, Johan; Liu, Yan; Cheng, Ran; Brataas, Arne; Lederman, David; del Barco, Enrique.
Subterahertz spin pumping from an insulating antiferromagnet. ***Science*** 2020 ;Volume 368.(6487) p. 160-165

2. Ding, Shilei; Ross, Andrew; Go, Dongwook; Baldrati, Lorenzo; Ren, Zengyao; Freimuth, Frank; Becker, Sven; Kammerbauer, Fabian; Yang, Jinbo; Jakob, Gerhard; Mokrousov, Yuriy; Klaui, Mathias Michael.
Harnessing Orbital-to-Spin Conversion of Interfacial Orbital Currents for Efficient Spin-Orbit Torques. ***Physical Review Letters*** 2020 ;Volume 125.(17)

3. Johnsen, Lina G.; Svalland, Kristian; Linder, Jacob.
Controlling the Superconducting Transition by Rotation of an Inversion Symmetry-Breaking Axis. ***Physical Review Letters*** 2020 ;Volume 125.(10)

4. Li, Junxue; Simensen, Haakon Thømt; Reitz, Derek; Sun, Qiyang; Yuan, Wei; Li, Chen; Tserkovnyak, Yaroslav; Brataas, Arne; Shi, Jing.
Observation of Magnon Polarons in a Uniaxial Antiferromagnetic Insulator. ***Physical Review Letters*** 2020 ;Volume 125.(21)

5. Moghaddam, Ali G.; Qaiumzadeh, Alireza; Dyrdał, Anna; Berakdar, Jamal.
Highly Tunable Spin-Orbit Torque and Anisotropic Magnetoresistance in a Topological Insulator Thin Film Attached to Ferromagnetic Layer. ***Physical Review Letters*** 2020 ;Volume 125.(19)

6. Ouassou, Jabir Ali; Belzig, Wolfgang; Linder, Jacob.
Prediction of a paramagnetic Meissner effect in voltage-biased superconductor/normal-metal bilayers. ***Physical Review Letters*** 2020 ;Volume 124.(4)

7. Troncoso, Roberto; Brataas, Arne; Sudbø, Asle.
Fingerprints of Universal Spin-Stiffness Jump in Two-Dimensional Ferromagnets. ***Physical Review Letters*** 2020 ;Volume 125.(23)

8. Wimmer, Tobias; Kamra, Akashdeep; Gueckelhorn, Janine; Opel, Matthias; Gepraegs, Stephan; Gross, Rudolf; Huebl, Hans; Althammer, Matthias.
Observation of Antiferromagnetic Magnon Pseudospin Dynamics and the Hanle Effect. ***Physical Review Letters*** 2020 ;Volume 125.(24)

9. Ado, I. A.; Qaiumzadeh, Alireza; Brataas, Arne; Titov, M.
Chiral ferromagnetism beyond Lifshitz invariants. ***Physical Review B*** (PRB) 2020 ;Volume 101.

10. Amundsen, Morten; Linder, Jacob.
Spin accumulation induced by a singlet supercurrent. ***Physical Review B*** (PRB) 2020 ;Volume 102.(10)

11. Bauer, Dag-Vidar Krogstad; Fjærestad, John Ove.
Spin-wave study of entanglement and Rényi entropy for coplanar and collinear magnetic orders in two-dimensional quantum Heisenberg antiferromagnets. ***Physical Review B*** (PRB) 2020 ;Volume 101.(19)

12. Brataas, Arne.
Current fluctuations driven by ferromagnetic and antiferromagnetic resonance. ***Physical Review B*** (PRB) 2020 ;Volume 102.(5)

13. Ding, Shilei; Baldrati, Lorenzo; Ross, Andrew; Ren, Zengyao; Wu, Rui; Becker, Sven; Yang, Jinbo; Jakob, Gerhard; Brataas, Arne and Kläui, Mathias.
Identifying the origin of the nonmonotonic thickness dependence of spin-orbit torque and interfacial Dzyaloshinskii-Moriya interaction in a ferrimagnetic insulator heterostructure. ***Physical Review B*** (PRB) 2020 ;Volume 102.

14. Erlandsen, Eirik; Sudbø, Asle.
Schwinger boson study of superconductivity mediated by antiferromagnetic spin fluctuations. ***Physical Review B*** (PRB) 2020 ;Volume 102.(21)

15. Erlandsen, Eirik; Brataas, Arne and Sudbø, Asle.
Magnon-mediated superconductivity on the surface of a topological insulator. ***Physical Review B*** (PRB) 2020. Volume 101.

16. Fyhn, Eirik Holm; Amundsen, Morten; Zalic, Ayelet; Dvir, Tom; Steinberg, Hadar; Linder, Jacob.
Combined Zeeman and orbital effect on the Josephson effect in rippled graphene. ***Physical Review B*** (PRB) 2020 ;Volume 102.(2)

17. Gulbrandsen, Sverre A.; Espedal, Camilla and Brataas, Arne.
Spin Hall effect in antiferromagnets. ***Physical Review B*** (PRB) 2020 ;Volume 101.

18. González-Ruano, César; Johnsen, Lina G.; Caso, Diego; Tiusan, Coriolan; Hehn, Michel; Banerjee, Niladri; Linder, Jacob; Aliev, Farkhad G.
Superconductivity-induced change in magnetic anisotropy in epitaxial ferromagnet-superconductor hybrids with spin-orbit interaction. ***Physical Review B*** (PRB) 2020 ;Volume 102.(2) Suppl. https://journals.aps

19. Hafez-Torbati, Mohsen; Zheng, Jun-Hui; Irsigler, Bernhard; Hofstetter, Walter.
Interaction-driven topological phase transitions in fermionic SU(3) systems. ***Physical Review B*** (PRB) 2020 ;Volume 101.(24)

20. Holt, Ann Julie; Mahatha, Sanjoy K.; Stan, Raluca-Maria; Strand, Frode Sneve; Nyborg, Thomas; Curcio, Davide; Schenk, Alex Kevin; Cooil, Simon; Bianchi, Marco; Wells, Justin W; Hofmann, Philip; Miwa, Jill A..
Observation and origin of the [delta] manifold in Si:P [delta] layers. ***Physical Review B*** (PRB) 2020 ;Volume 101.(12)

21. Hugdal, Henning Goa; Sudbø, Asle.
Possible odd-frequency Amperean magnon-mediated superconductivity in topological insulator–ferromagnetic insulator bilayer. ***Physical Review B*** (PRB) 2020 ;Volume 102.(12)

22. Jakobsen, Martin Fonnum; Næss, Kristian B; Dutta, Paramita; Brataas, Arne; Qaiumzadeh, Alireza.
Electrical and thermal transport in antiferromagnet-superconductor junctions. ***Physical Review B*** (PRB) 2020 ;Volume 102.(14)

23. Janssønn, Andreas; Simensen, Haakon Thømt; Kamra, Akashdeep; Brataas, Arne; Jacobsen, Sol.
Macroscale nonlocal transfer of superconducting signatures to a ferromagnet in a cavity. ***Physical Review B*** (PRB) 2020 ;Volume 102.(18)

24. Kamra, Akashdeep; Wimmer, Tobias; Huebl, Hans; Althammer, Matthias.
Antiferromagnetic magnon pseudospin: Dynamics and diffusive transport. ***Physical Review B*** (PRB) 2020 ;Volume 102.(17)

25. Li, Yang; Amado, Mario; Hyart, Timo; Mazur, Grzegorz P; Risinggård, Vetle Kjær; Wagner, Thomas; McKenzie-Sell, Lauren; Kimbell, Graham; Wunderlich, Joerg; Linder, Jacob; Robinson, Jason W.A..
Transition between canted antiferromagnetic and spin-polarized ferromagnetic quantum Hall states in graphene on a ferrimagnetic insulator. ***Physical Review B*** (PRB) 2020 ;Volume 101.(24)

26. Panas, Jaromir; Irsigler, Bernhard; Zheng, Junhui; Hofstetter, Walter.
Bulk topological proximity effect in multilayer systems. ***Physical Review B*** (PRB) 2020 ;Volume 102.(7)

27. Simensen, Haakon Thømt; Kamra, Akashdeep; Troncoso, Roberto; Brataas, Arne.
Magnon decay theory of Gilbert damping in metallic antiferromagnets. ***Physical Review B*** (PRB) 2020 ;Volume 101.(020403)

28. Thingstad, Even; Kamra, Akashdeep; Wells, Justin; Sudbø, Asle.
Phonon-mediated superconductivity in doped monolayer materials. ***Physical Review B*** (PRB) 2020 ;Volume 101.(21)

29. Troncoso, Roberto; Bender, Scott; Brataas, Arne; Duine, Rembert.
Spin transport in thick insulating antiferromagnetic films. ***Physical Review B*** (PRB) 2020 ;Volume 101.(5)

30. Ross, Andrew; Lebrun, Romain; Ulloa, Camilo; Grave, Daniel A.; Kay, Asaf; Baldrati, Lorenzo; Kronast, Florian; Valencia, Sergio; Rothschild, Avner; Klaui, Mathias Michael.
Structural sensitivity of the spin Hall magnetoresistance in antiferromagnetic thin films. ***Physical Review B*** (PRB) 2020 ;Volume 102.(9) p. -

31. Zheng, Jun-Hui; Brataas, Arne; Klaui, Mathias Michael; Qaiumzadeh, Alireza.
Theory of domain-wall magnetoresistance in metallic antiferromagnets. ***Physical Review B*** (PRB) 2020 ;Volume 102.(18) p. -

32. Ross, Andrew; Lebrun, Romain; Gomonay, Olena; Grave, Daniel A.; Kay, Asaf; Baldrati, Lorenzo; Becker, Sven; Qaiumzadeh, Alireza; Ulloa, Camilo; Jakob, Gerhard; Kronast, Florian; Sinova, Jairo; Rembert, Duine; Brataas, Arne; Rothschild, Avner; Klaui, Mathias Michael.
Propagation Length of Antiferromagnetic Magnons Governed by Domain Configurations. ***Nano Letters*** 2020 ;Volume 20.(1) p. 306-313

33. Abdelsalam, H.; Younis, W.O.; Saroka, Vasil; Teleb, N.; Yunoki, S.; Zhang, Q..
Interaction of hydrated metals with chemically modified hexagonal boron nitride quantum dots: wastewater treatment and water splitting. ***Physical Chemistry, Chemical Physics*** - PCCP 2020 ;Volume 22. p. 2566-2579

34. Becker, Sven; Heinz, Sven; Vafaee, Mehran; Klaui, Mathias Michael; Jakob, Gerhard.
The challenge in realizing an exchange coupled BiFeO3-double perovskite bilayer. ***Journal of Magnetism and Magnetic Materials*** 2020 ;Volume 506.

35. Brataas, Arne; van Wees, Bart; Klein, Olivier; de Loubens, Grégoire; Viret, Michel.
Spin insulatronics. ***Physics Reports*** 2020 ;Volume 885. p. 1-27

36. Demin, V.A.; Artyukh, A. A.; Saroka, Vasil; Chernozatonskii, L.A..
Study of a New Type of Crimped-Shape Nanotubes Cut from Bilayer Graphene with the Moiré Angle Θ = 27.8°. ***JETP Letters*** 2020 ;Volume 111.(7) p. 397-402

37. Hu, Jinbang; Hu, JinPing; Zhang, Zhengde; Shen, Kongchao; Liang, Zhaofeng; Zhang, Huan; Tian, Qiwei; Wang, Peng; Jiang, Zheng; Huang, Han; Wells, Justin W; Song, Fei.
Ullmann coupling of 2,7-dibromopyrene on Au (1 1 1) assisted by surface adatoms. ***Applied Surface Science*** 2020 ;Volume 513.

38. Hu, Jinbang; Strand, Frode Sneve; Chellappan, Rajesh Kumar; Zhang, Zhengde; Shen, Kongchao; Hu, JinPing; Ji, Gengwu; Huai, Ping; Huang, Han; Li, Zheshen; Jiang, Zheng; Wells, Justin W; Song, Fei.
Direct Synthesis of Semimetal Phthalocyanines on a Surface with Insights into Interfacial Properties. ***The Journal of Physical Chemistry Letters*** 2020 ;Volume 124.(15) p. 8247-8256

39. Irsigler, Bernhard; Zheng, Jun-Hui; Grusdt, Fabian; Hofstetter, Walter.
Z2 characterization for three-dimensional multiband Hubbard models. ***Physical Review Research*** (PRResearch) 2020 ;Volume 2.(1)

40. Izadi Vishkayi, Sahar; Torbatian, Zahra; Qaiumzadeh, Alireza; Asgari, Reza.
Strain and electric-field control of spin-spin interactions in monolayer CrI3. ***PHYSICAL REVIEW MATERIALS*** 2020 ;Volume 4.

41. Kamra, Akashdeep; Belzig, Wolfgang; Brataas, Arne.
Magnon-squeezing as a niche of quantum magnonics. ***Applied Physics Letters*** 2020 ;Volume 117.(9)

42. Klaui, Mathias Michael.
Freezing and melting skyrmions in 2D. ***Nature Nanotechnology*** 2020 ;Volume 15. p. 726-727

43. Lebrun, Romain; Ross, Andrew; Gomonay, Olena; Baltz, V.; Ebels, U; Barra, Anne Laure; Qaiumzadeh, Alireza; Brataas, Arne; Sinova, Jairo; Klaui, Mathias Michael.
Long-distance spin-transport across the Morin phase transition up to room temperature in ultra-low damping single crystals of the antiferromagnet α-Fe2O3. ***Nature Communications*** 2020 ;Volume 11.

44. Lidal, Jonas; Danon, Jeroen.
Generation of Schrödinger-cat states through photon-assisted Landau-Zener-Stückelberg interferometry. ***Physical Review A*** (PRA) 2020 ;Volume 102.(4)

45. Mazzola, Federico; Chen, Chin-Yi; Rahman, Rajib; Zhu, Xie-Gang; Polley, Craig; Balasubramanian, Thiagarajan; King, Philip D.C.; Hofmann, Philip; Miwa, Jill; Wells, Justin W.
The sub-band structure of atomically sharp dopant profiles in silicon. ***npj Quantum Materials*** 2020 ;Volume 5.(1)

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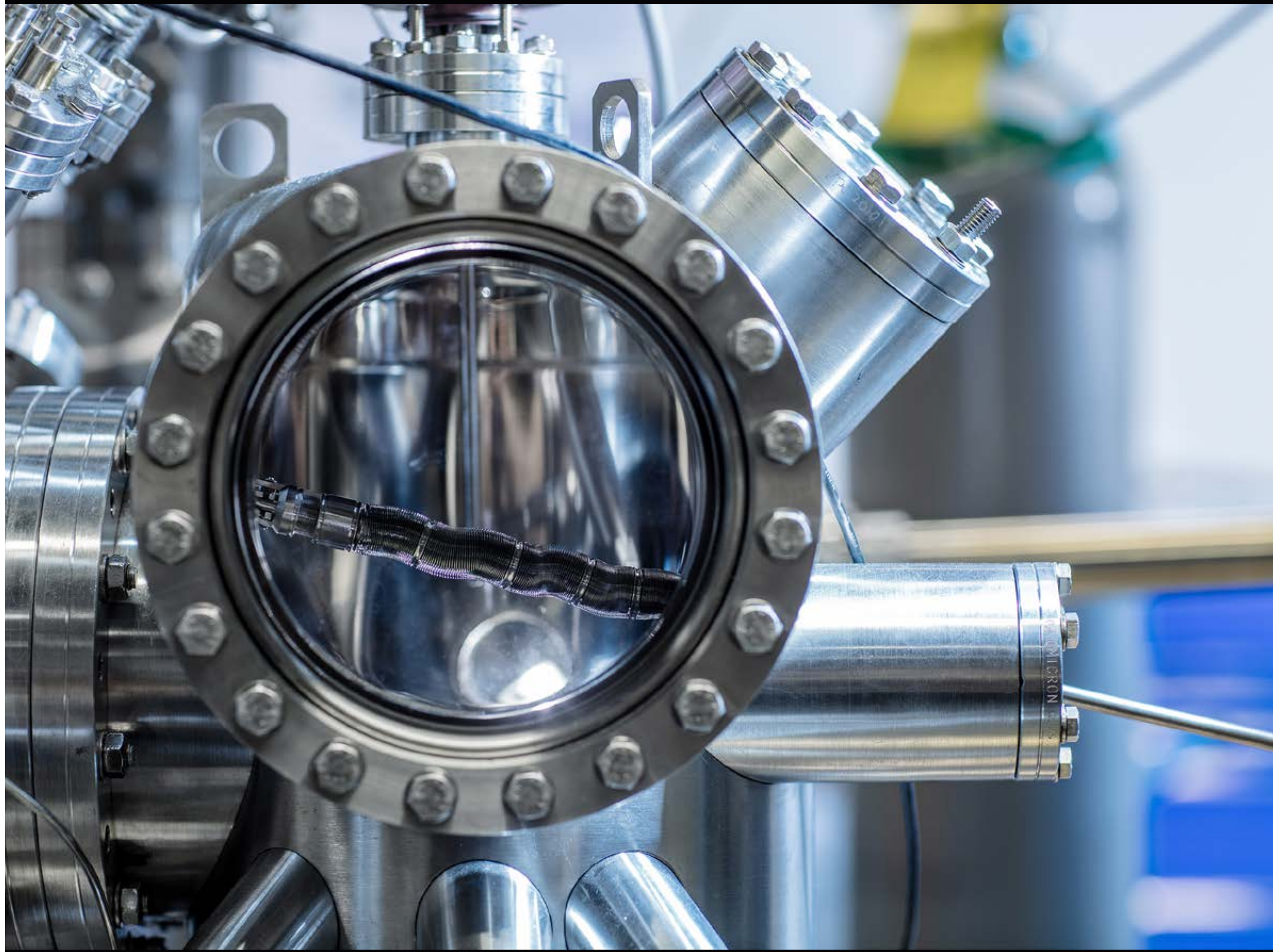

Facts

Per 2020.12.31.

9 PROF/ASSOC.PROF

4 RESEARCHERS

7 POSTDOCS

27 PHD STUDENTS

12 MASTER STUDENTS

1 ADMINISTRATOR

13 DIFFERENT NATIONALITES

7 VISITING RESEARCHERS

53 PUBLICATIONS

* Note: In addition we have a 25 % Finance Officer position, Head Engineer from the Department of Physics/NTNU, two Co-Principal Investigators in 20% positions, and one of our researchers holding a 20% position as associated professor II.

Funding

FUNDING 2020 (NOK)

The Research Council of Norway, Center of Excellence	13 880 000
Norwegian University of Science and Technology	7 534 000
SUM	**21 414 000**
The Research Council of Norway (Center of Excellence)	5 978 000
International Funding	5 292 000
Other Public	1 721 000
SUM	**12 991 000**
TOTAL FUNDING	**34 405 000**

People Overview

Colleagues who left QuSpin before 2020.12.31 are marked with an *

QUSPIN LEADER GROUP

Center Director Professor/ Principal Investigator
Arne Brataas

Professor/Principal Investigator
Asle Sudbø

Professor/Principal Investigator
Jacob Linder

Professor/Principal Investigator
Justin Wells

Center Coordinator
Karen-Elisabeth Sødahl

ASSOCIATED MEMBERS

Associate Professor
Christoph Brüne

Associate Professor
Jeroen Danon

Associate Professor
John Ove Fjærestad

Professor (Onsager Fellow)
Dennis Gerhard Meier

Professor/Head of Department of Physics
Erik Wahlström

RESEARCHERS

Sol H. Jacobsen (also holding an associated professor II position)

Akashdeep Kamra

Alireza Qaiumzadeh

Nina Bjørk Arnfinnsdottir *

POSTDOCS


Vasil Saroka


Mariia Stepanova


Roberto Troncoso


Junhui Zheng


Xiansi Wang *


Rui Wu *


Marion Barbeau


Jinbang Hu

PHD CANDIDATES


Markus Altthaler


Dag-Vidar Krogstad Bauer


Kristian Mæland


Atousa Ghanbari Birgani


Payel Chatterjee


Eirik Erlandsen


Therese Frostad


Eirik Holm Fyhn


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Lina Grøvan Johnsen


Fredrik Nicolai Krohg


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Håkon Ivarssøn Røst


Jonas Lidal


Haakon Thømt Simensen


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Marius Kalleberg Hope
Herman Lileng Ottersen
Ida Cathrine Skogvoll
Mariell Breivik
Mathias Svendsen

CO-PRINCIPAL INVESTIGATORS

Professor
Rembert Duine, University of Utrecht
The Netherlands

Professor
Mathias Kläui, University of Mainz
Germany

ADJUNCT INVESTIGATOR

Associate Professor II
Simon Phillip Cooil (NTNU) *

HEAD ENGINEER

Senior Engineer
Rajesh Kumar Chellapan (Department of Physics/NTNU). From 2019.10.4.

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University of Cambridge, United Kingdom

QuSpin Alumni

Here are the members of our QuSpin Alumni. They are previous researchers at our Center, who are now in new positions within academia, research institutions, and industry.

Dr. Rui Wu
PostDoc 2019-2020
Next position: Associate professor in colleague of physics at University of Electronic Science and Technology of China (UESTC).

Dr. Arnau Sala
PhD 2017-2020
Next position: PostDoc at Interuniversity Microelectronics Centre (IMEC), Leuven, Belgium.

Dr. Xiansi Wang
PostDoc 2018-2020
Next position: Professor at Hunan University, Changsa, China.

Dr. Morten Amundsen
PhD 2017-2020
Next position: Postdoctoral Fellow at NORDITA, Stockholm, Sweden.

Dr. Sverre Aamodt Gulbrandsen
PhD 2017-2020
Next position: Researcher, Optonor AS, Trondheim, Norway.

Dr. Suraj Kumar Singh
PhD 2017-2020
Next position: Postdoc at the University of Liège, Belgium.

Dr. Øyvind Johansen
PhD 2016-2020
Next position: Service Consultant at Matrix Technology AG, Munich, Germany.

Dr. Jabir Ali Ouassou
PhD 2015-2019
Next position: Researcher Scientist at SINTEF Energy Research, Trondheim, Norway.

Dr. Vetle Kjære Risinggård
PhD 2015-2019
Next position: Researcher at Norwegian Research Centre (NORCE), Kr.sand, Norway.

Dr. Maximillian Kessel
PostDoc 2018-2019
Next position: Scientist at Fraunhofer-Institute for Applied Solid State Physics in Freiburg, Germany.

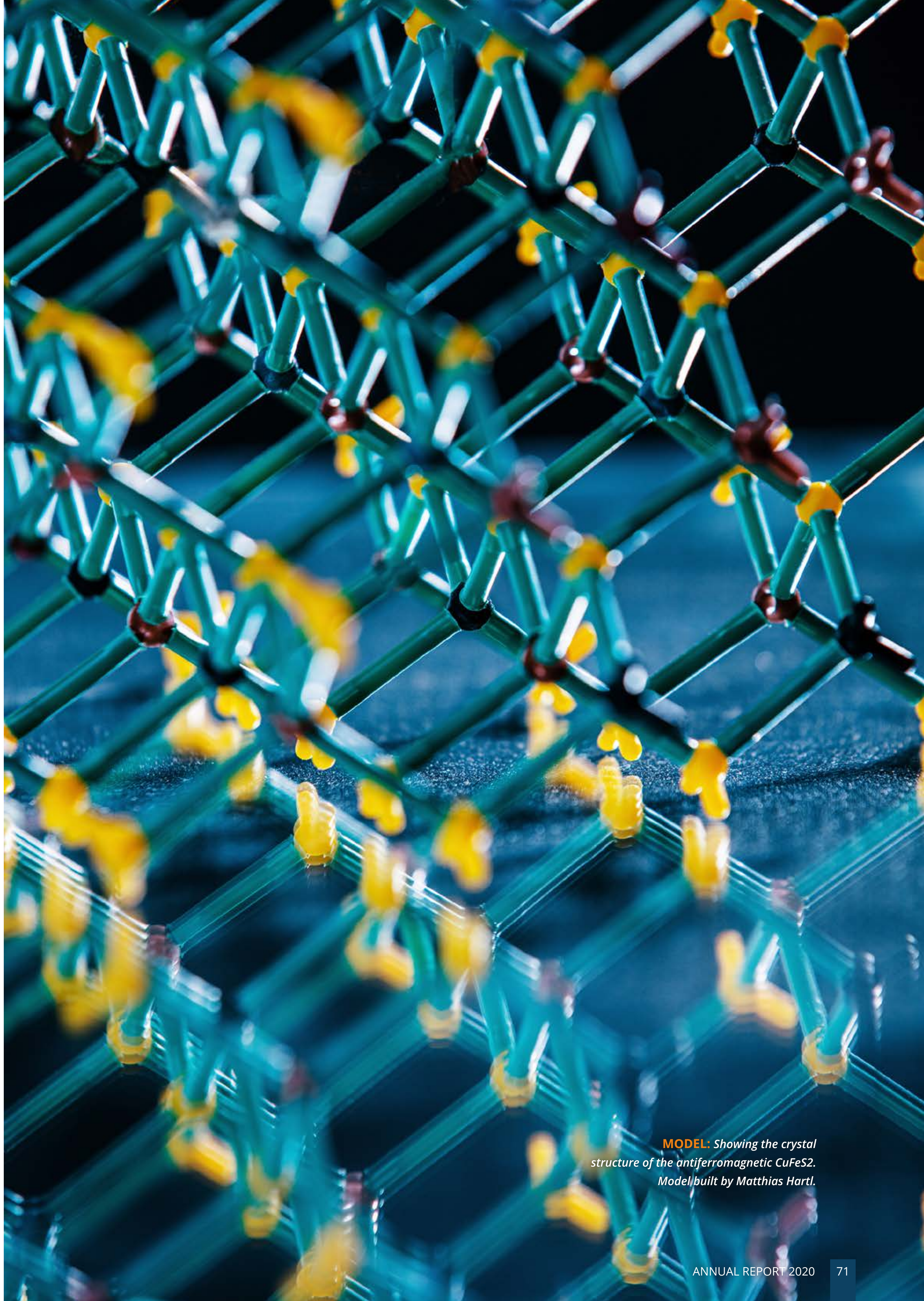
Dr. Rajesh Kumar Chellappan
PostDoc 2019
Next position: Chief engineer, Department of Physics, NTNU, Trondheim, Norway.

Dr. Alex Schenk
PostDoc 2018-2019
Next position: La Trobe University, Melbourne, Australia.

Dr. Niklas Rohling
Researcher 2017-2019
Next position: PostDoc at Universität Konstanz, Konstanz, Germany.

Dr. Eirik Løhaugen Fjærbu
PhD 2014-2018
Next position: Researcher at Norwegian Defense Research Establishment (FFI), Kjeller, Norway.

Dr. Camilla Espedal
PhD 2013-2017
Next position: Research Scientist at SINTEF Energy Research, Trondheim, Norway.



MODEL: *Showing the crystal structure of the antiferromagnetic CuFeS2. Model built by Matthias Hartl.*

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