Annual Report | 2019

Center for Quantum Spintronics

QuSpin

Norwegian Centre of Excellence
The Research Council of Norway

NTNU
Norwegian University of Science and Technology

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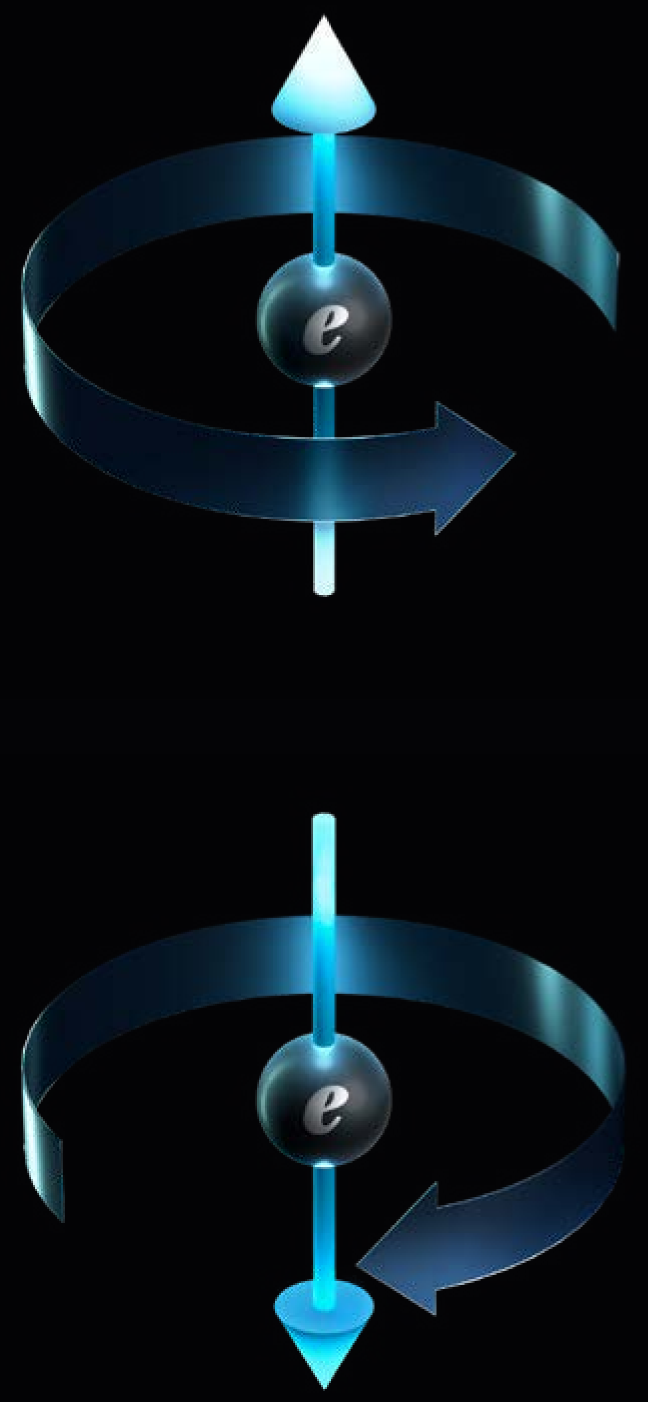


THE ELECTRON SPIN: *The electron spin, the electron's magnetic moment, is a prime example of a quantum entity. Classically, when the earth orbits around the sun, it has an orbital angular momentum. The spin is the electron's intrinsic angular momentum. It is as if something orbits around inside the electron.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

CENTER DIRECTOR ARNE BRATAAS

Foreword

Thanks to our outstanding researchers and their remarkable achievements, the Center for Quantum Spintronics has had another great year. Collaborations within QuSpin and with other environments and researchers are vital to us. We are blessed to have tremendous and continuous support from the Department of Physics, the Faculty of Natural Sciences, and the Rector at Norwegian University of Science and Technology. We appreciate the funding and advice from the Research Council of Norway and the recommendations from the International Advisory Board. We are grateful for all the constructive support we get from a wide range of people and institutions.

Our activity focuses on the electron spin. A simple image is that the electron rotates around its axis, but this is not the entire story. Spin is a prime example of a quantum variable. Spin in electron devices, spintronics, is the critical element in data-storage devices used by everyone. Although the spin is a quantum entity, most devices use it in classical ways, as a brand-new colour to the electron. QuSpin aims to utilize the quantum behaviour of the electron spin and other quantum variables in novel ways to open doors to new classes of low-dissipation electronics devices. In carrying out fundamental research, QuSpin will take the spin to the future.

Center for Quantum Spintronics is a center of excellence funded by the Research Council of Norway and the Norwegian University of Science and Technology. Our main task is to carry out high-quality research. Ultimately, our standing will be measured by our scientific impact in our field. We are proud that we in 2019 have published ten groundbreaking papers in the most celebrated non-profit journal in our area, Physical Review Letters. Other glossy for-profit journals may have higher impact numbers but are detrimental to the scientific enterprise at large. A reason for the latter is that many glossy magazines let young inexperienced editors have much more influence than external well-established reviewers; hype favours quality.

Our group stands on the shoulder of a great decades-long tradition of excellence in theoretical physics in Trondheim. An essential part of our vision is to increase collaborations between theory and experiments and to achieve more excellence in experimental condensed matter physics, generating a more substantial impact. We are pleased to announce that we have reached several milestones on this path. December 18, 2019, we installed our new spin-ARPES. With this new large-scale investment, we can measure the intriguing electronic and spintronic properties in new materials with a significant new level of details as compared to previously. Our MBE system is up and running, and we expect to produce high-quality magnetic, topological, and superconducting materials soon. Finally, our already very productive activity on functional topological materials received a further boost with the award of an ERC consolidater grant. We look forward to an exciting new year with these three laboratories now running at the full speed.

> *Our group stands on the shoulder of a great decades-long tradition of excellence in theoretical physics in Trondheim. An essential part of our vision is to increase collaborations between theory and experiments and to achieve more excellence in experimental condensed matter physics, generating a more substantial impact.*

In conclusion, two years into our project and with eight years to come, we have arrived at a good position out of the starting blocks. We have excellent human capital, funding, and state-of-the-art equipment. We look forward to the next year, which we are confident will bring new opportunities for QuSpin, our collaborators, and our supporters.

A Center of Excellence

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

To innovate in the field of Spintronics our research center will be receiving funding throughout it's duration of ten years. QuSpin will receive part of the total funding of 1.5 billion Norwegian Kroner for the Centers of Excellence.

By the end of 2019, the center developed into the more than sixty member strong team with members from twelve different countries. QuSpin now has ten permanent professors and associate professors, three researchers, six postdocs, twenty-seven Ph.D students, eleven master students, and one administrator.

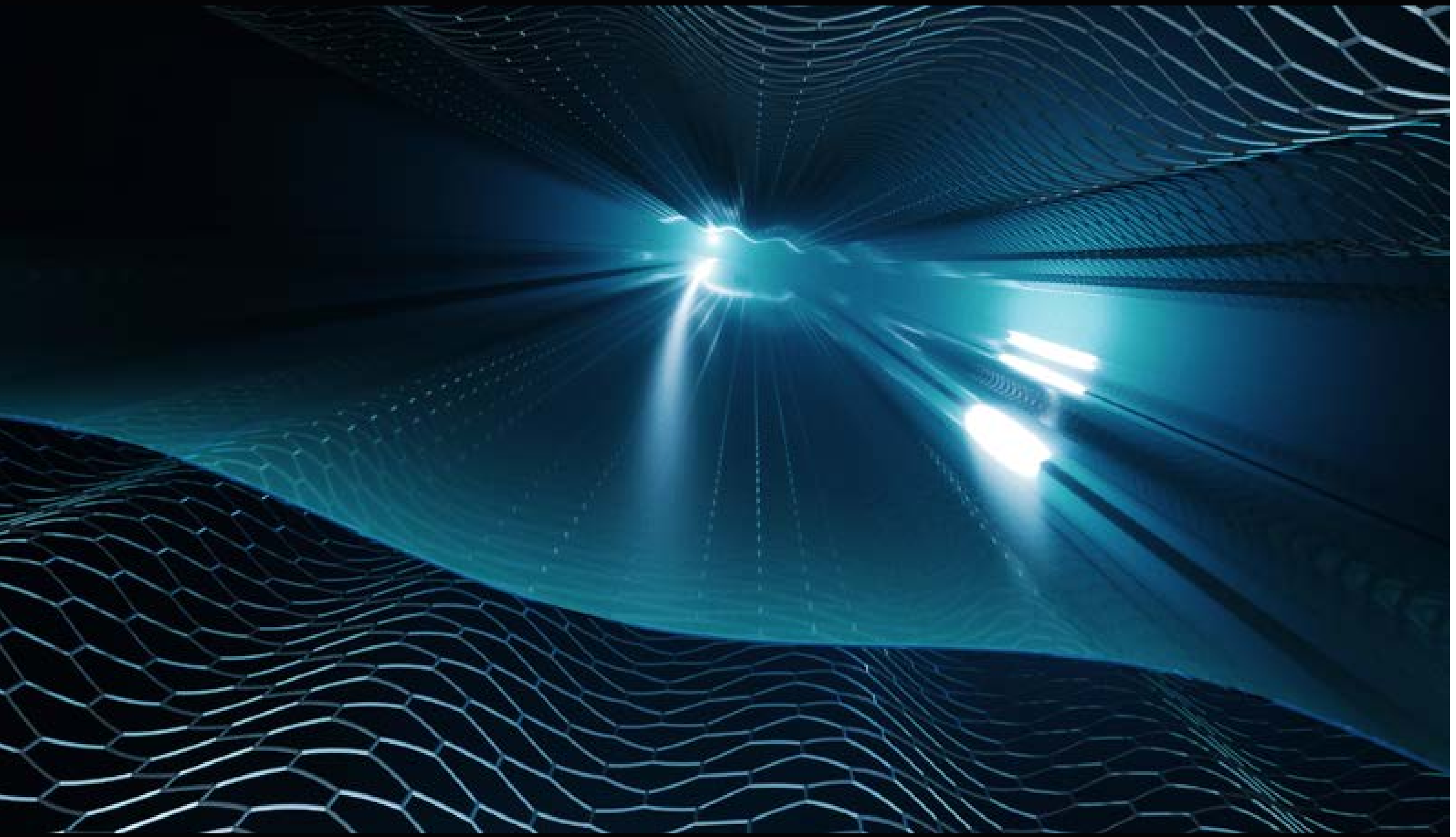
QuSpin being an international research center, values having a highly professional international advisory board of researchers, as well as an experienced board with senior researchers from NTNU.

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

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

Colleagues at QuSpin - Our research center at the Deparment of Physics at NTNU in Trondheim.

> *QuSpin has now entered a phase where a vivid exchange and collaboration among groups has kicked in. This is reflected in a positive, fruitful atmosphere leading to important publications of the consortium.*
>
> *– Milena Grifoni, Chair Advisory Board*



SUPERCONDUCTING ELECTRONS: *This is a 3D illustration that shows superconducting electrons (the blue wave) in a smart material. The electrons behave not like individual particles, but like a collective state. This enables them to move without resistance in a smart material. The smart material is illustrated by two layers of atoms (for example, carbon atoms) organised in a honeycomb pattern.*

Smart Materials can Reduce Power Consumption

A popular science article written for newspapers and for the broad public by Jacob Linder, Asle Sudbø and Karen-Elisabeth Sødahl.

Approximately 10 percent of the world's energy use today is for powering smart telephones, computers, and internet. That is going to continue to increase. About half of that energy is lost to heat due to electrical resistance.

Smart materials, with practical application properties that can be controlled by the environments in which they operate, have the potential to increase efficiency in an environmentally friendly way.

At the research center, QuSpin, at NTNU in Trondheim, researchers from 12 different countries are studying new physical properties found in smart materials that can reduce today's energy consumption.

Metals without electric resistance are called superconductors. When an electric current goes through a normal metal, it warms up and energy is lost. In a superconductor, there is no generation of heat and it can, therefore, transport an electric current completely without any loss, frictionless.

One analogy would be an ice hockey puck sliding on a very smooth surface of ice with nothing to stop it. In the same way, electrons in a superconducting material move with no resistance. (See information box).

Superconductors in the wind

Superconductors have made their entrance into renewable energy, more specifically, windpower. In 2018, there was 36 percent more energy produced by wind power in Norway than in 2017 (1). In windmills at sea or on land, a generator made from these more efficient materials will mean a reduction in weight and size. This will result in the production of energy at less cost.

Last year, this was realised in the EU project EcoSwing. Denmark is now the home to the world's first windmill with a superconductor-based generator (2).

THE FACT: THIS IS A SUPERCONDUCTOR

- A superconductor is a material that, under a specific temperature, transports electric current with no measurable resistance.
- Superconductors additionally have the property that they completely or partially shield magnetic fields around them.
- Many elements become superconductors at low temperatures. The phenomenon was discovered in 1911 using mercury.
- Superconductors are explained within the physics theory of quantum mechanics and is an active field of research.
- Superconductors are used technologically as highly accurate sensors and in medicine, among other things.

Smart materials, with practical application properties that can be controlled by the environments in which they operate, have the potential to increase efficiency in an environmentally friendly way.

Still achieving world records

Superconductivity requires low temperatures. This is a challenge for large-scale applications. The highest superconducting temperature measured at normal air pressure is currently -135 C, far below natural temperatures measured on Earth. By creating extremely high pressure, in 2014, German scientists (3) managed to get hydrogen sulfide (H_2S) to become superconducting at -70 C. It was also the first time superconductivity was detected at a temperature naturally occurring on Earth, corresponding to a very cold winter night in Siberia.

2018 was the setting for yet another new world record (4). The highest superconducting temperature measured is now -23 C, which corresponds to a moderately cold winter night in Kautokeino. Room temperature superconductivity had suddenly gone from a distant dream to within reach. Just 35 years ago, the world record was -250 C!

Supercomputers and communication

Both the US and China have recently launched major research projects aimed at creating the first superconducting supercomputer. It looks as though superconducting supercomputers can lead to a reduction in energy consumption to less than one hundredth of today's energy consumption, even taking into account the need for strong cooling (5). Such machines will be in a completely different league than those based on semiconductor technology in terms of energy efficiency.

One area where superconductivity has not yet been explored to any significant degree is the increasing electrification of transport. It is clearly seen in the automotive industry but is likely to become more relevant for boats and airplanes in the coming decades.

New smart materials

The advancements that have been achieved within superconducting the last five years have required high pressure. In order to achieve large-scale applications, we need to get superconductivity closer to room temperature and normal atmospheric pressure. Otherwise, the technology becomes too expensive and impractical to compete with the energy-efficient solutions we already have. This requires new smart materials.

The production of such new materials is progressing slowly but surely. These developments must be accelerated. The next generation has come to understand this. It is our experience that young students and researchers are wanting to contribute to this groundbreaking research work. A new generation of researchers, the future's key to solve the climate problems, stand ready to take on the big challenges that lay before us.

[1] https://energiogklima.no/nyhet/datakilder/status-for-vindkraft-i-norge/
[2] https://www.chemistryworld.com/news/world-first-as-wind-turbine-upgraded-with-high-temperature-superconductor/3009780.article
[3] https://www.nature.com/articles/nature14964
[4] https://www.nature.com/articles/s41586-019-1201-8
[5] https://cacm.acm.org/news/232327-the-outlook-for-superconducting-computers/fulltext

Science is a Random Walk, Utilizing the Opportunities

Article based on a group dialogue with Asle Sudbø, Vetle Kjær Risinggård, Arne Brataas, Øyvind Johansen and Jacob Linder facilitated by Karen-Elisabeth Sødahl.

QuSpin researchers published their paper "Current Control of Magnetism in Two Dimensional Fe3GeTe2" in the Physical Review Letter (PRL) in May 2019. The team sits around the table and shares their reflections about the two years of work put into the paper.

The motivation

The project was initiated by the center's director and principal investigator, Arne Brataas. There were several articles in high profile journals on two-dimensional magnets that had caught his interest. These discoveries opened up new and exciting doors in exploring magnetism in the flatland. Advancement in the field was happening fast. Arne realized that we could further exploit our knowledge of current-induced magnetization dynamics and spin-pumping to push the frontier of this rapidly progressing field. The questions were how QuSpin could contribute to research, which material to focus on, which direction to explore first, and who should be involved. These questions were also an excellent opportunity to enhance the collaborations within the center.

'There is usually a more clear goal at the beginning. However, we knew that the systems were important to investigate.' – Arne Brataas

The walk

Typically, in the hard sciences, professors assign a topic to study to a Ph.D. student or post-doc. In this case, instead of just having one Ph.D. candidate exploring the subject, Vetle Kjær Risinggård, and Øyvind Johansen, as well as primary investigator, Jacob Linder, joined to collaborate. The Ph.D. students had an initial path to follow but as far as to what material to work with, and other conclusions to draw from the study, it was up to them. They had many opportunities and challenges. Before the Ph.D students joined, in the early discussions, the investigating team included Sol Jacobsen, but due to the pressing nature and the timing of the work, they continued on themselves when she left for maternity leave.

'Normally, a research is to investigate or compute a particular quality and look for any interesting outcome. But this time we had the idea of finding an exciting material to study. We could look for any properties we could find that were of interest.' – Jacob Linder

> *If we had started out with a clearer, more defined goal, we may not have noted all of the results we saw or reflected on the implications of it as much. – Øyvind Johansen*

Vetle and Øyvind worked on analysis and modeling. Their starting point was an existing framework developed by Arne Brataas and a former post-doc, Kjetil Hals, who is now a professor at the University of Agder. Øyvind suggested considering the material Fe3GeTe2 because of its unique symmetrical properties. They believed it had the desired features required to change the magnetic state with currents. The material had to have the right crystal structure. The symmetry had to be low enough to be able to manipulate the direction of the 2D magnetic field in the material.

'Everything that is not forbidden, is compulsory.'
– Vetle Kjær Risingggård

They also learned, from recent research, that experiments with the Fe3GeTe2 material could take place in a warmer environment than earlier attempts. They concluded they could work at the temperature of -150 C; one hundred degrees warmer than earlier work by other researchers.

The informal meetings places

Informal meetings enable the exchange and development of new ideas. In a group of people with diverse backgrounds, our combined lunch and seminar room allows for spontaneous encounters and a more open line of communication. At QuSpin we are certainly seeing more collaboration and interaction than before, and its benefits. Scientific and interpersonal relationships benefit from informal meeting places and, at QuSpin, it played an essential role in the second part of their project.

Vetle and Øyvind were discussing their work with principal investigator, Asle Sudbø, over a cup of coffee in the lunchroom on the 5th floor. They had discovered that the direction of the 2D magnets could turn vertically or horizontally in the material while magnetic. But, the material was non-magnetic exactly between these positions. Asle pointed out that by using a precise current, one might see an interesting type of phase transition in the system between the vertical and horizontal magnetic states. With this, he widened the original scope of the study. The nature of this phase transition is usually very difficult to explore, except at ridiculously low temperatures. This material offered new revelations at temperatures that are routinely achieved in laboratories.

After explaining their observations of the current control, Asle commented, 'You have more here than you think!'

Øyvind and Vetle went back to their research and Asle joined the team. What Asle pointed out helped to widen the study and made the paper interesting to a broader scientific audience. The target publication moved from a Physical Review B (PRB), up to a Physical Review Letter (PRL).

After the article was published, we had an opportunity to discuss the work during an informal exchange at our internal collaboration workshop in Oppdal. Our German experimentalist colleague, Co-principal investigator, Mathias Kläui, had seen the article. Coincidentally, his team had some interest in the same material. The road is now laid open to test the conclusions in the experimental lab, if possible. The collaboration between our theoretical and experimental research is an opportunity and a possible next step to prove the findings in the article.

Strategic supervision, intuition and luck

When writing scientific papers, people have different roles. Varied input comes from putting more senior researchers together with the younger researchers. Often, Phd candidates carry out the technical work. In the regular project meetings, the main role of principal investigators is to mentor and supervise. They evaluate findings to ensure consistency and look for new possibilities. They help guide through the direction and steps to be taken next. With their years of experience, they have developed a sense of intuition and insight of what to look for and those skills can help make sense of the findings. There can be a lot of random events that follow, but, by coordinating efforts and persevering, understanding the results is made possible.

> *It is essential to have the skills and experience to explore all the opportunities as they emerge. – Arne Brataas*

This creativity and sensibility is something the Ph.D.s will develop over time. The supervisors have experience publishing papers in the scientific community. They understand what the referees look for in a successful paper. They are aware of what the potential critical points are in the study and how to solve or approach them. Because of their central role, supervisors are co-authors on papers in the hard sciences. It's a kind of quality assurance. 'Ultimately, it is the quality of the science that matters, not the number of papers.' adds Arne.

'There is no such thing as sheer luck, but at the same time, it is about luck, depending on the interest of the referee and other articles up for evaluation.' – Jacob Linder

Øyvind and Vetle found an open culture at QuSpin. Everyone is involved and the process is dynamic. They were able to generate and present their own ideas and their points were listened to. The principal investigators were approachable and collaborative. It is a generous learning environment. Some of the conclusions being drawn from the work ran contrary to conclusions published by Arne himself. He shrugs and smiles as he mentions this himself in the meeting. 'It's weird, but it happens. It's still weird.'

'A lot of time was spent thinking about how to sell the results. Why should people care about this?' – Arne Brataas

Experienced Ph.D. candidates

In such an open-ended project it was valuable to have two very experienced Ph.D. candidates in the project. Arne and Jacob were confident giving a more open ended brief to begin with.

'It was good we had two experienced Ph.D. students. Less experienced students with an unclear goal could have been more frustrated.... And it would have taken longer.'
– Arne Brataas and Jacob Linder

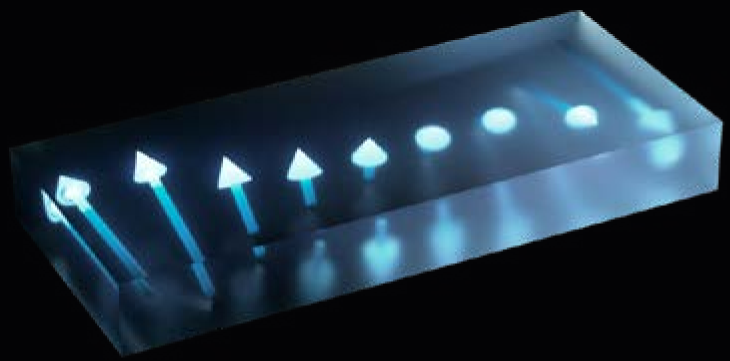
They may have been in a hurry to study the 2D magnetic properties, but they took their time to understand the results. 'For example', Øyvind adds, 'most of the results on the paper were discovered in the last quarter of the project.'

Insights for the future

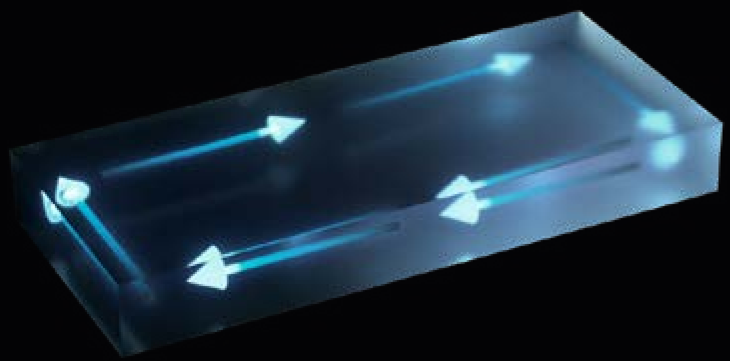
Through this type of research, we reveal information about a wide range of systems with similar physical phenomena that exhibit similar behavior. Our prime interest is knowledge. This is the key. Usefulness is also of interest, but secondary, and in the long run, most likely, for others to explore. It could take 10-30 years before it is realized.

Looking for new insights in physical phenomena can lead to new and interesting discoveries. That, in turn, can open up new horizons. We certainly feel that our findings, through the collaboration in this open-ended assignment, has the potential of being a valuable contribution to international research and possible future results. It was an exciting walk together with a rewarding destination!

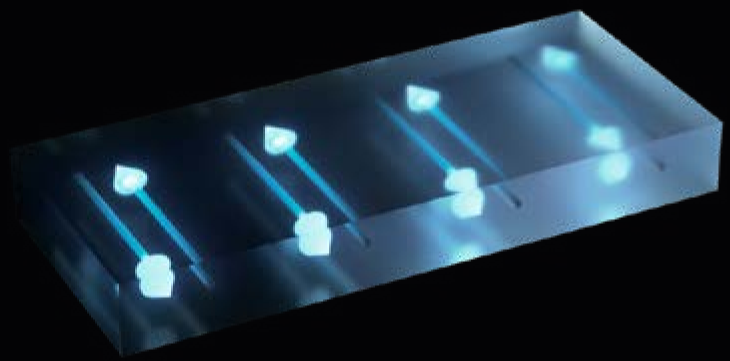
MAGNETIC INSULATORS



TOPOLOGICAL INSULATORS



SUPERCONDUCTORS



Main Research Themes, Goals and Activities

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

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

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

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

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

Illustration:

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

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

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

OUR PRINCIPAL INVESTIGATORS

Arne Brataas

Asle Sudbø

Jacob Linder

Justin Wells

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 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 to what extent 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 far and how spin propagates in insulators, how we can control correlations that cause new states of matter, and to detect signatures of these phenomena.

Activity in 2019

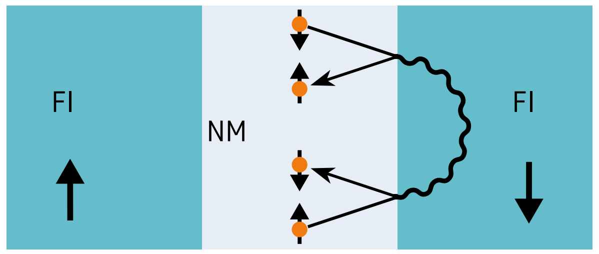
Magnetic insulators can enable new forms of matter in adjacent conductors. Two examples are superconductors and exciton condensates that can dissipationlessly charge transport.

We have recently demonstrated how ferromagnetic insulators can induce superconductivity in atomic-size thick metal layers. Superconductivity requires pairing of electrons via an attractive interaction. In our case, the underlying pairing mechanism arises from the spin excitations and is unconventional. The research paves the way for the controlled creation of new superconducting devices with unique properties.

In 2019, we generalized our previous studies to the case of antiferromagnetic insulators. Importantly, we find that the squeezed nature of the spin excitations in antiferromagnets can significantly enhance the spin-triplet pairing. The electron-magnon coupling across metal-antiferromagnetic insulator interfaces is considerably enhanced when it is uncompensated.

Electrons and holes residing on the opposing sides of an insulator can form an indirect exciton condensate. We have considered a trilayer system where the insulator is antiferromagnetic. We show that by employing magnetically uncompensated interfaces, we can design the magnon-mediated interaction to be attractive or repulsive by varying the thickness of the antiferromagnetic insulator by a single atomic layer. For realistic material parameters, we estimate Tc to be around 7 K. The magnon-mediated interaction is expected to cooperate with the Coulomb interaction for condensation of indirect excitons, considerably increasing the exciton condensation temperature range.

Additional activities are the developments of a theory of current-induced hopfion, a three-dimensional spin texture, and a theory of current control of the magnetic anisotropy in a particular class of recently discovered two-dimensional van der Waals magnets. The latter finding provides the possibility to study the Berezinskii-Kosterlitz-Thouless phase transition in the 2D XY model and its associated critical exponents.



ASLE SUDBØ

Topological Quantum Matter

Theme and goal

Topology is a branch of mathematics that investigates global geometric properties of objects. These objects could 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. Topological phase transitions are phase transition where the ordered state cannot be characterized by a standard simple local order parameter. Rather, the ordered state has a lack of topological defects, while the disordered states has proliferated large amounts of topological defects "ripping" the ordered state apart".

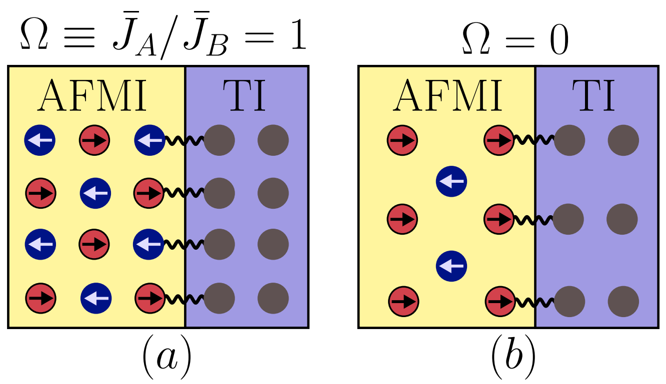
Superfluidity and superconductivity are the phenomena that fluids in the quantum regime may flow without any dissipation. Superconductivity, superfluidity, and magnetism are cooperative phenomena where enormous numbers of degrees of freedom spontaneously self-organize themselves into various ordered 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 2019

A major aspect of the research carried out in 2019, has been 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. A particularly novel and important result is that when exposing a metal/topological insulator to a sublattice of a bipartite antiferromagnet, one finds a large enhancement of the coupling between magnons in an antiferromagnet and the electrons in a metal or topological insulator. This comes about through a constructive interference of magnetic eigen-excitations originating on the exposed sublattice. The result is a major enhancement of the superconducting critical temperature of the superconductor induced in the layer between the quantum antiferromagnet and the metal/topological insulator. Our results open new perspectives on magnon-induced superconductivity in heterostructures involving a number of novel systems in proximity to antiferromagnets.



Exchange coupling between a quantum antiferromagnet (AFM) on a bipartite lattice and a topological insulator (TI). In a), both sublattices of the AFM are coupled to the TI. In b), only one sublattice is coupled to the TI. Case b) vastly enhances magnon-induced superconductivity in the TI compared to case a).

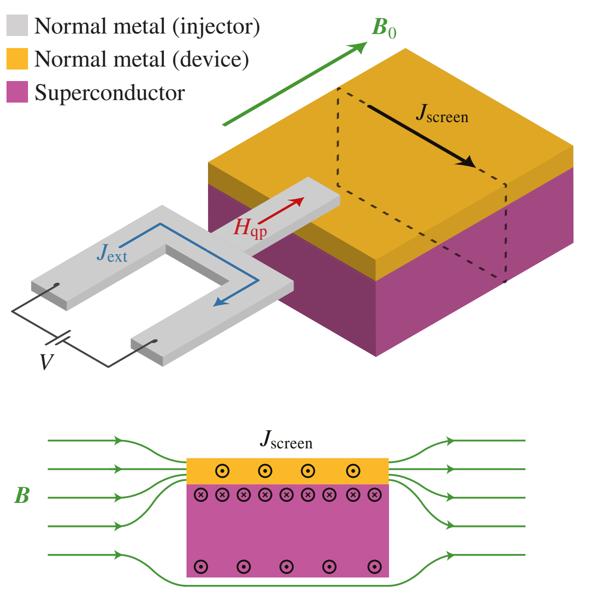
JACOB LINDER

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.



Inverse Meissner effect in non-equilibrium superconductors.

Two main goals guide our research. Firstly, 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 enhance 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 2019

One of our research highlights from the past year is the prediction of how driving a system through a superconducting transition can cause a magnetization reversal. Soon after this prediction, we were contacted by an experimental group who had done the experiment we proposed and found precisely the predicted results. We have also studied unconventional vortex matter that arises in extreme environments such as half-metallic ferromagnets, resulting in the prediction that superconducting vortices accompanied by spin supercurrents can be generated in half-metals. In a collaboration between the theory Principal Investigators at QuSpin, we have studied current-induced magnetization dynamics in 2D van der Waals ferromagnets and found that such systems can be used to study the Berezinskii-Kosterlitz-Thouless phase transition in a controllable way. Finally, we have managed to solve the challenging problem of how spin-orbit coupled interfaces can be described in non-equilibrium heavy metal/superconductor heterostructures.

JUSTIN WELLS

Electronic Structure

Theme and goal

The electronic band structure of a material contains information about all the electrons which are relevant for bonding 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 interest to try to directly measure the electronic band structure, and hence to gain access to this information. Over the last decade, the instrumentation available has improved dramatically. During 2019, we have been part of this revolution in instrumentation and have been developing ultra-high efficiency spin-resolved imaging with exceptional energy, moment and spatial resolutions.

The primary goals are to complete the construction of our home spin-resolved momentum microscope, and to demonstrate unparalleled efficiency in spin detection. We aim to make ourselves ideally positioned to support the theoretical activities within QuSpin, to continue to produce research contributions in important and topical fields, and at an internationally respected level. We also strive to bring interesting and up-to-date research work into the undergraduate classroom, to educate Master students, to contribute to the career development of young scientists and to enable the production of high-quality Ph.D. theses.

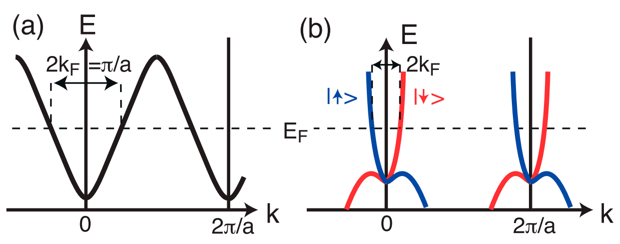
Key questions

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

Most of the methods we use come under the category of “photoelectron spectroscopy” and are based in Einstein’s photoelectric effect, for which he received the Nobel Prize in 1921. 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 two instruments at NTNU which are based on various refinements of this method. We also make significant use of similar instruments at international synchrotron radiation facilities. In 2020 we will complete the installation of our state-of-the-art spin-resolved photoelectron microscope to extend the range of possible measurements at NTNU.

Activity in 2019

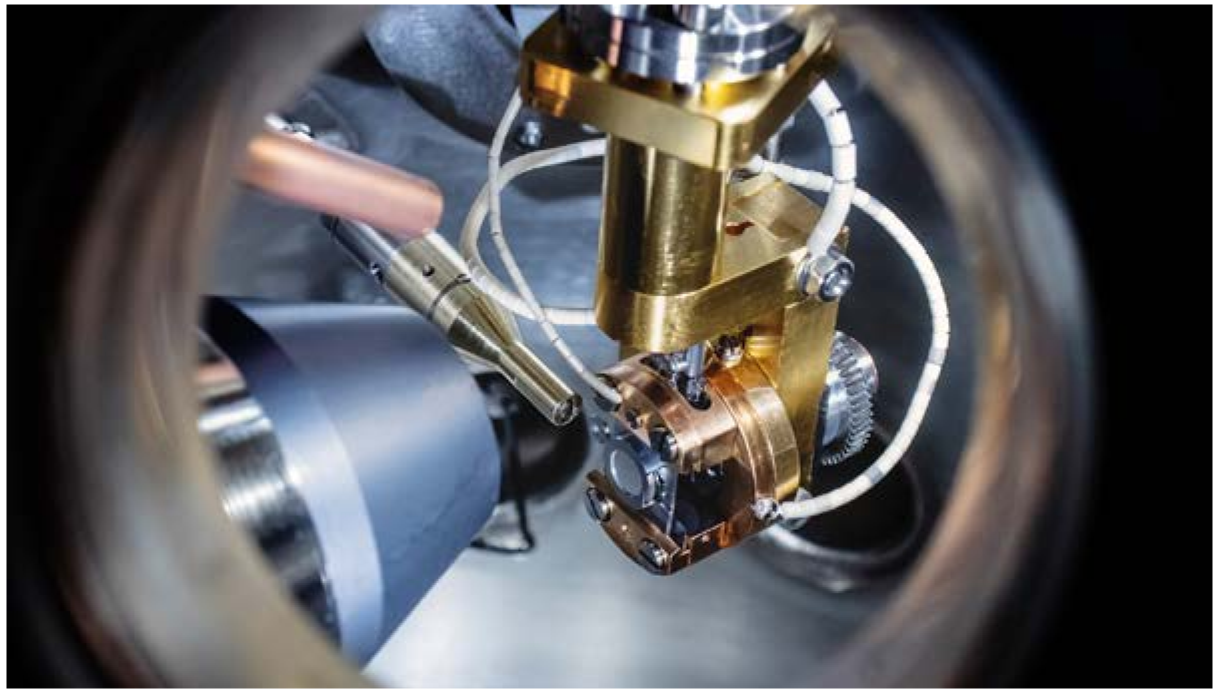
Highlights include studying charge density waves in 1-dimensional topological semi-metals, phonon-mediated superconductivity in 2D materials (with theoretical support from Sudbø’s group), novel on-surface growth of heavy group-V semimetal phthalocyanines for understanding Kondo physics in molecular systems, and developing 2D doped diamond superconductors and silicon delta layers for quantum computing applications. Strengthening our collaboration with the Chinese Academy of Sciences and the Shanghai Synchrotron, the Siam Photon Source, and the Center for Quantum Computation and Communication Technology in Sydney were also highlights of 2019, as is our co-development of our bespoke spin resolved momentum microscope.

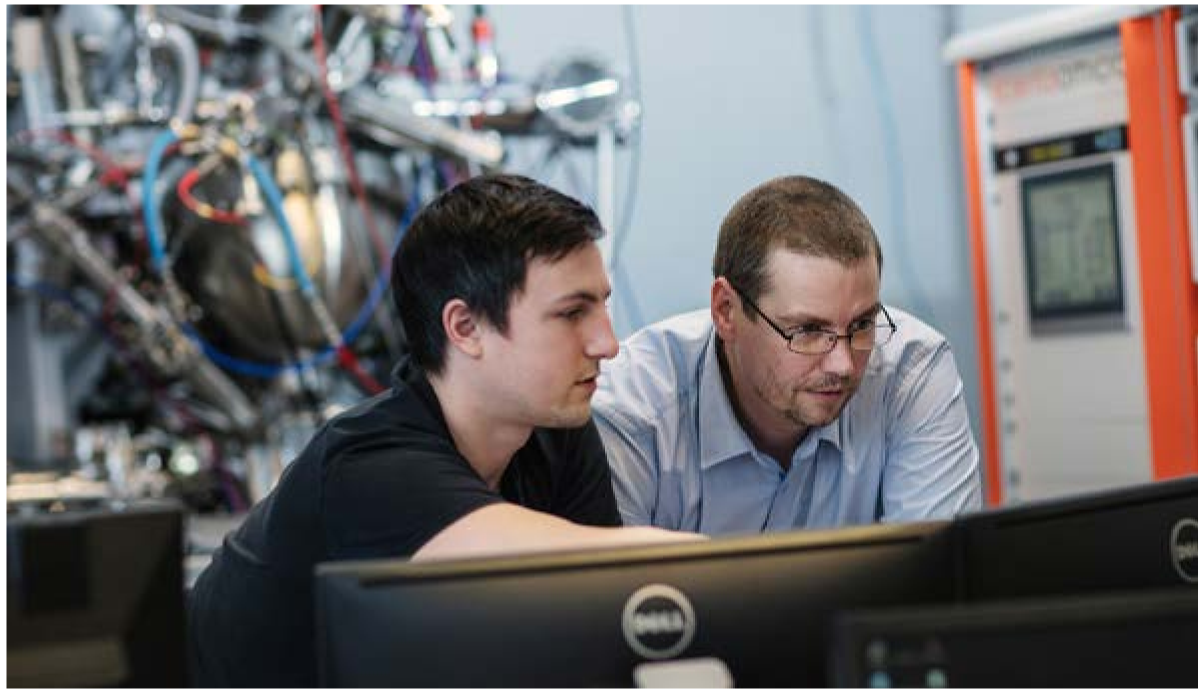


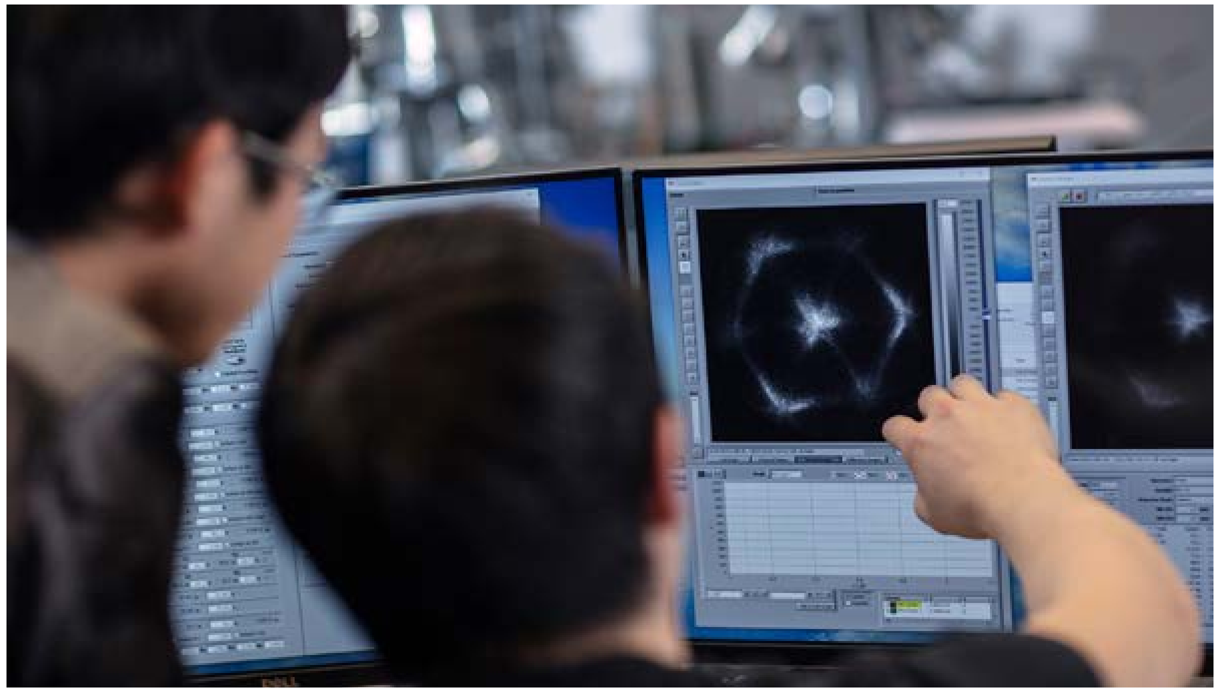
The role of spin texture in protecting against conventional charge density waves in 1-dimensional systems: (a) Conventional one-dimensional electronic state at half-filling. The black dispersion is spin degenerate. This system is sensitive to a Peierls-type instability due to the perfect nesting and the fact that the nesting vector’s length corresponds to a real space periodicity of 2a. (b) The situation when spin degeneracy of the bands is lifted. While perfect nesting is still present, it takes place for a very short nesting vector and between states of opposite spin (indicated by the colour of the bands and the arrows), thus protecting against a Peierls-type instability.

SPIN-ARPES LAB

Here we are installing and testing our new spin-ARPES instrument and multi-purpose preparation and characterisation chamber.







DENNIS MEIER

Topological Spin Textures

Theme and goal

Chiral magnets develop a wide variety of topological spin textures such as skyrmions, dislocations and disclinations, as well as completely new types of magnetic domain walls. These topological spin textures currently attract worldwide attention due to their unusual and intriguing physical properties. Skyrmions, for example, represent stable nano-sized whirls that give rise to emergent electrodynamics, and their position and motion can be controlled at ultra-low energy costs. Because of these outstanding properties, skyrmions hold great promise for future spintronic devices and neuromorphic computing.

With our research, we go beyond "classical" skyrmion-related studies, exploring the large zoo of topological spin textures available in chiral magnets. We are particularly interested in the physics of magnetic dislocations and disclinations, which naturally occur in the magnetic ground state, i.e, even without the external magnetic field usually needed to stabilize skyrmions. These instabilities share strong similarities with dislocations and disclinations formed by, e.g., crystalline solids, liquid crystals, convection patterns and swimming bacteria.

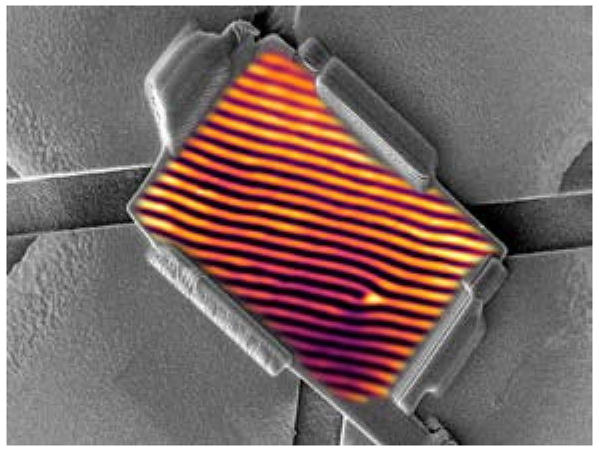
The goal of our research is to understand the nanoscale physics of such novel topological spin structures and demonstrate emergent functional properties, developing device paradigms into new realms of magnetism.

Key questions

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

Activity in 2019

In 2019 we made several breakthroughs in the characterization and understanding of the nano-scale physics of topological magnetic spin textures in chiral magnets, with a focus on their dynamical response. Working closely together with Alireza Qaiumzadeh, Arne Brataas and our international collaborators, we began to develop models to rationalize our novel experimental findings. In addition, in collaboration with Christoph Brüne's team, we identified different new systems of interest that are not available as thin films yet and successfully performed first test experiments on related single crystals. In the next step, we will synthesize such systems in the form of high-quality thin films and study their functional properties in device-relevant geometries, using the MBE and microscopy infrastructure available within QuSpin and in close collaboration with NTNU NanoLab.



Magnetic stripe pattern with dislocation, imaged by magnetic force microscopy.

CHRISTOPH BRÜNE

Molecular Beam Epitaxy of Antiferromagnets

Theme and goal

The QuSpin molecular beam epitaxy (MBE) group is a newly established group still in the build-up phase. Our goal is to develop the synthesis of high-quality materials with potential for spintronics research and application. To achieve this goal, we will rely on a technique 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 such 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 will be the group's second research area. These materials are very interesting due to their complex magnetic structures, based on a spiralling (helical) order of the spins in the material. This enables also so-called 'Skyrmions', stable magnetic whirls inside the material. These are promising due to their potential as nano-objects for future low-energy memory devices. We will develop the growth of materials that host helimagnetic or skyrmionic structures at room temperature for future applications.

These investigations are conducted in close collaboration with Dennis Meiers' group, with two PhD 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 2019

The central activity in 2019 was the start-up of our new MBE lab. We successfully refurbished an older system to enable the growth of magnetic materials. The new system can grow several highly interesting material systems: the antiferromagnetic semiconductor CuFeS2, the helimagnet and skyrmion system MnPtxPt1-xSn and the FeSn material system, helimagnets with a frustrated magnetic lattice.

Very recently, we succeeded in growing the first FeSn containing magnetic layers. The growth of further materials and the investigations of such magnetic thin films will be central in 2020.

We will also install a second growth chamber in 2020, which is dedicated to the growth of MnTe antiferromagnetic semiconductors.

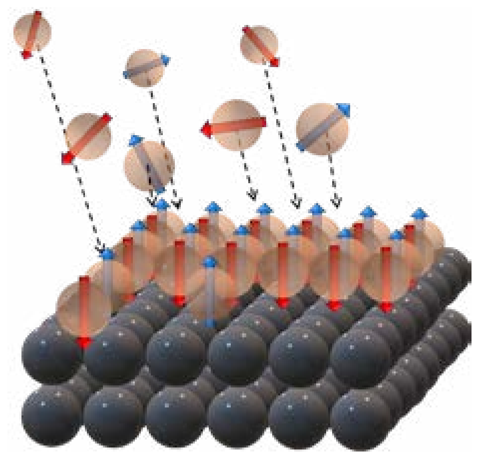
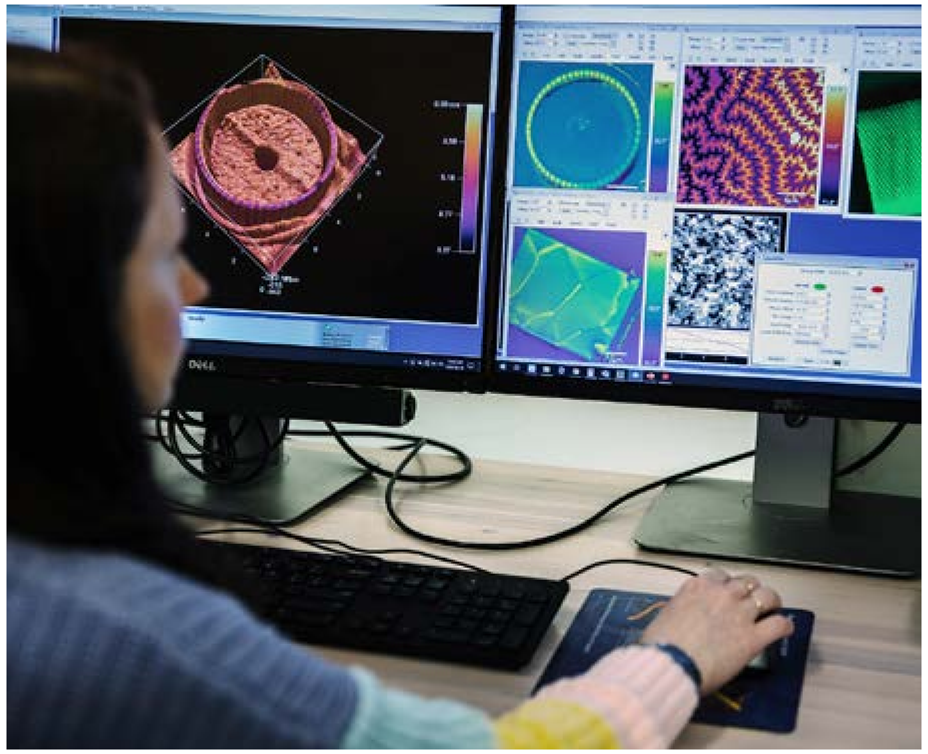


Illustration of molecular beam epitaxy growth of an antiferromagnetic layer on a non-magnetic substrate.

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.

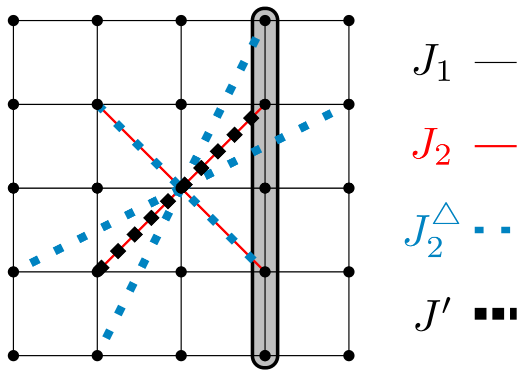
The overall goal is to get a better understanding of the "zoo of phases" that may arise in frustrated quantum antiferromagnets, and contribute towards their description and classification.

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 2019

Together with a PhD student and a master student, we have continued spin-wave studies of signatures of magnetic order in the entanglement/Renyi entropy in various models of two-dimensional quantum antiferromagnets. Research is also ongoing on a coherent-state path integral representation for spin systems. Finally, we have started collaboration with researchers at Chongqing University, China on trying to use bosonization to understand the nature of quantum phase transitions in some quantum spin chain models.



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 for this 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.

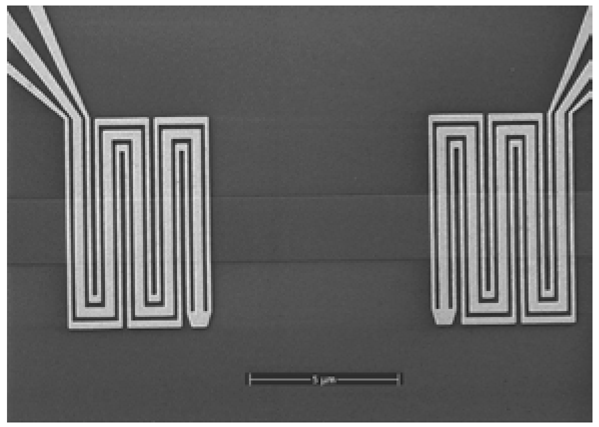
Key questions

Our key primary concern is understanding and probing 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 motif 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 2019

In 2019 the activity was somewhat limited due to my duties as department head. However, we have proceeded with our collaboration with Thomas Tybell in the electronics department, with the primary aim to map basic spin wave propagation properties in the perovskite magnetic oxide LSMO. We have published an investigation of interface modes at the substrate (STO) / film (LSMO) interface of the 111 oriented film, where we for the first time have been able to give evidence of the formation of magnetodynamic interface modes in a perovskite system. Here we have continued to set up and prepare for pulse propagation measurements. We have also continued to work on diamond oxygen vacancy based lateral mapping of magnetodynamic wave propagation with our collaborators in Japan, Toshu An (School of Materials Science, Japan Advanced Institute of Science and Technology (JAIST).



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

MBE LAB

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

JEROEN DANON

Quantum Computation with Multi-spin Qubits

Theme and goal

The quest for the optimal physical qubit (it should be stable, controllable, and scalable) is at full speed, and by now the research has been narrowed down to a handful of very promising approaches. My research is theoretical, but focuses on practical aspects of such qubit implementations, usually in close collaboration with experimentalists. Most problems my group is working on are related to questions such as: How 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?

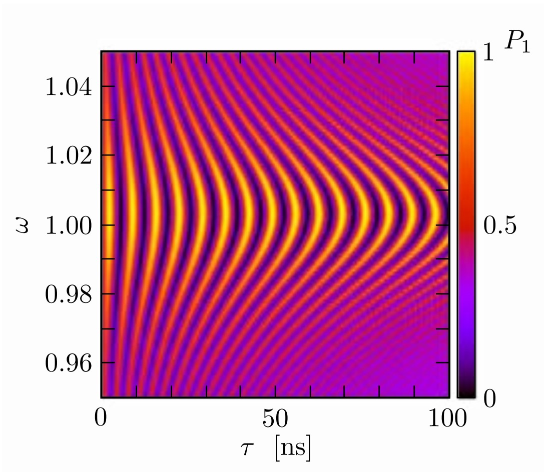
A large part of this work is in the field of spin qubits in semiconductor quantum dots (small potential traps inside a semiconductor), where the basic idea is to use the spin degree of freedom of the electron as a qubit basis. A recent and particularly interesting proposal is to create such qubits out 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 2019

My group has expanded significantly and counts now three Ph.D. students and one postdoc, which has resulted in a boost of research activity. Besides fruitful collaborations with the Center for Quantum Devices at the Niels Bohr Institute in Copenhagen, we have worked on an improved proposal for a multi-particle singlet-only spin qubit, which is intrinsically insensitive to the fluctuating nuclear spins, and we have discovered 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.



SOL H. JACOBSEN

Triplet Spintronics

Theme and goal

Superconducting spin-polarized triplets carry coherent quantum information. 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

Until now our research has focused on conversion mechanisms from superconducting singlets to triplets, and their experimentally accessible signatures in standard spintronic contexts using thin-films and nanowires. In the future, we would like to challenge the geometrical constraints required to make use of superconductivity in spintronics.

The first question builds on 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. Therefore, we will determine the potential and scope of curvature to generate and control triplet populations out of equilibrium.

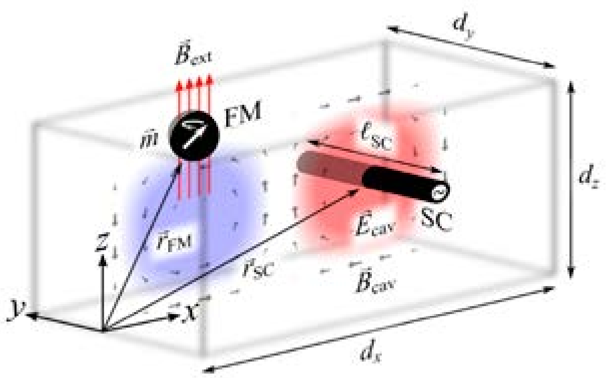
Our second question challenges a more central tenet of superconducting spintronics, which relies on the proximity effect for harnessing superconducting signatures. We will aim to show that triplet signatures can be manipulated non-locally via hybridization with spatially separated magnons in a resonant cavity. This may increase device operational range by several orders of magnitude.

Finally, we 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 2019

In 2019 I returned to full-time work after maternity leave, and subsequently a sizable portion of 2019 was spent devising new projects and preparing research proposals to fund them. This involved some preliminary investigations, as well as establishing new international collaborations. The first of these proposals has now been funded by the Research Council of Norway in the form of a Young Research Talents grant of 7.7MNOK/€780k. Consequently, a new Ph.D. student will join these projects in the autumn of 2020, and a PostDoc will join slightly later.

The groundwork for the super cavitronics project has been laid with Ph.D. students Andreas Janssønn and Haakon Simensen. Internal collaborators are Prof. Brataas and Dr. Kamra, and separately Prof. Linder on other aspects. Dr. Hans Huebl at the Walther Meissner Institute in Münich has agreed to be an experimental partner in further developing the cavitronics ideas. Dr. Paola Gentile of CNR-SPIN Salerno, Italy, will be our international partner for the curvature-related investigations.



Super Cavitronics: we aim to go beyond the proximity effect to show photonic mediation of superconductive signatures.

AKASHDEEP KAMRA

Quantum Magnonics

Theme and goal

We aim to explore and exploit macroscopic manifestations of quantum mechanics in spin systems. How do the laws operational at tiny lengths and for microscopic particles result in remarkable properties tangible to human eye and experience? Magnetism and spin provide the perfect playground for this as these two phenomena are fundamentally quantum in origin. Despite the roots, hallmarks of quantum mechanics, such as entanglement, have been elusive in macroscopic manifestations of magnetism. Understanding the reasons for reversion to a "classical" behavior and predicting systems capable of bringing out and exploiting the quantum nature is a key motivator in our research.

Key questions

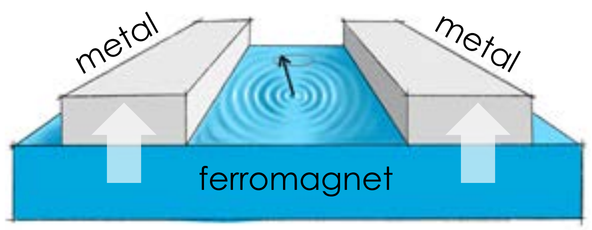
How should one reconcile the two descriptions – quantum and classical – of a magnet? The two ways of describing the same system result in remarkably different answers for various physical properties. A majority of the experiments seem to be consistent with the "classical" picture. Have the quantum effects been hiding under this classical facade? Have we simply been looking at the wrong physical quantities? Since magnetism in many materials is robust at room temperature, can we exploit this robustness for useful entanglement under ambient conditions, for example?

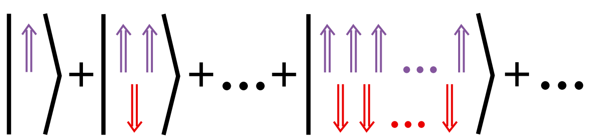
Activity in 2019

Our research this year epitomizes the collaborative spirit. Working together within QuSpin and with the Utrecht, Konstanz, Munich, and Dresden groups, we have made progress towards answering the above mentioned questions, both theoretically and experimentally.

Inspired by the field of quantum optics, we have theoretically demonstrated that magnonic spin current cross correlations show the magnon-bunching effect. This implies that magnons like to stick together – a quintessential feature of bosons. We have proposed an experimentally feasible method to detect these statistics of magnons in addition to quantifying the coherence of a magnonic condensate. The latter achievement is a crucial step towards realizing and exploiting spin superfluidity in magnetic insulators. Our corresponding article published in Physical Review Letters received widespread attention with it being highlighted as Editors' suggestion. It was also the subject of a viewpoint article in the periodical Physics (APS) and a popular science feature article at phys.org.

We have also shown that antiferromagnetic magnons are comprised by a quantum superposition involving a large number of spins. This allows it to interact strongly with other excitations. We have successfully employed this interaction enhancement in theoretically demonstrating magnon-mediated superconductivity and indirect exciton condensation at substantial temperatures in engineered heterostructures. The same physics has also been experimentally observed in the form of ultrastrong magnon-magnon coupling probed via magnetic resonance measurements in a compensated ferrimagnet. With these preliminary theoretical and experimental results demonstrated in multiple systems, the ball for exploiting quantum effects has been set in motion with yet bigger rewards aimed and expected in the future.





Schematic depiction of spin current cross correlation setup (left, image adapted from PRL 122, 187701) and the quantum superposition of states that makes one antiferromagnetic spin-up magnon (right, image adapted from PRB 100, 174407).

ALIREZA QAIUMZADEH

Quantum Magnetism and Ultrafast Phenomena

Theme and goal

Magnetism is one of the few purely quantum-relativistic phenomena that can be observed even in the macroscopic limit and under ambient conditions in daily life. The origin of magnetism is intrinsic spin angular momentum of electrons. The strongest interaction in magnetically ordered systems, that tends to align the spins of electrons, is called the Heisenberg exchange interaction whose sign determines parallel/antiparallel orientation of the spins leading to ferro-/antiferro-magnetism. The origin of this interaction is the Coulomb interaction between electrons and the Pauli's exclusion principle. Other important spin interactions in magnetic systems are anisotropic exchange and Dzyaloshinskii-Moriya (DM) interactions originated from relativistic dipolar and spin-orbit interactions. The competition between different spin interactions results in various exotic and emergent phases of magnetic systems. Therefore, direct manipulation of spin interactions enables control of magnetic states of quantum materials.

The major focus in our group is to study ultrafast phenomena (i.e., phenomena which occur on a time scale of picoseconds or less) and quantum dynamics in various magnetic systems far from equilibrium under different perturbations such as laser pulses, electric fields and temperature gradients. We are interested in phenomena such as ultrafast spin dynamics and two-magnon creation, Bose-Einstein condensation of magnons, generation of topological magnetic solitons and their dynamics.

The goal is to develop theories for understanding the mechanisms behind different nonequilibrium spin dynamics phenomena and consequently use them to design and control novel state-of-the-art quantum devices for future information technology.

Key questions

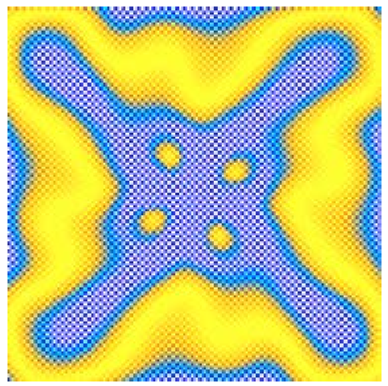
Effects of different interactions, such as electron-electron, magnon-magnon, magnon-phonon etc., on nonequilibrium systems are challenging problems which call for the development of sophisticated analytical and advanced numerical techniques. The development of theoretical frameworks for describing these phenomena on a microscopic level are the most important open questions in this research field.

Activity in 2019

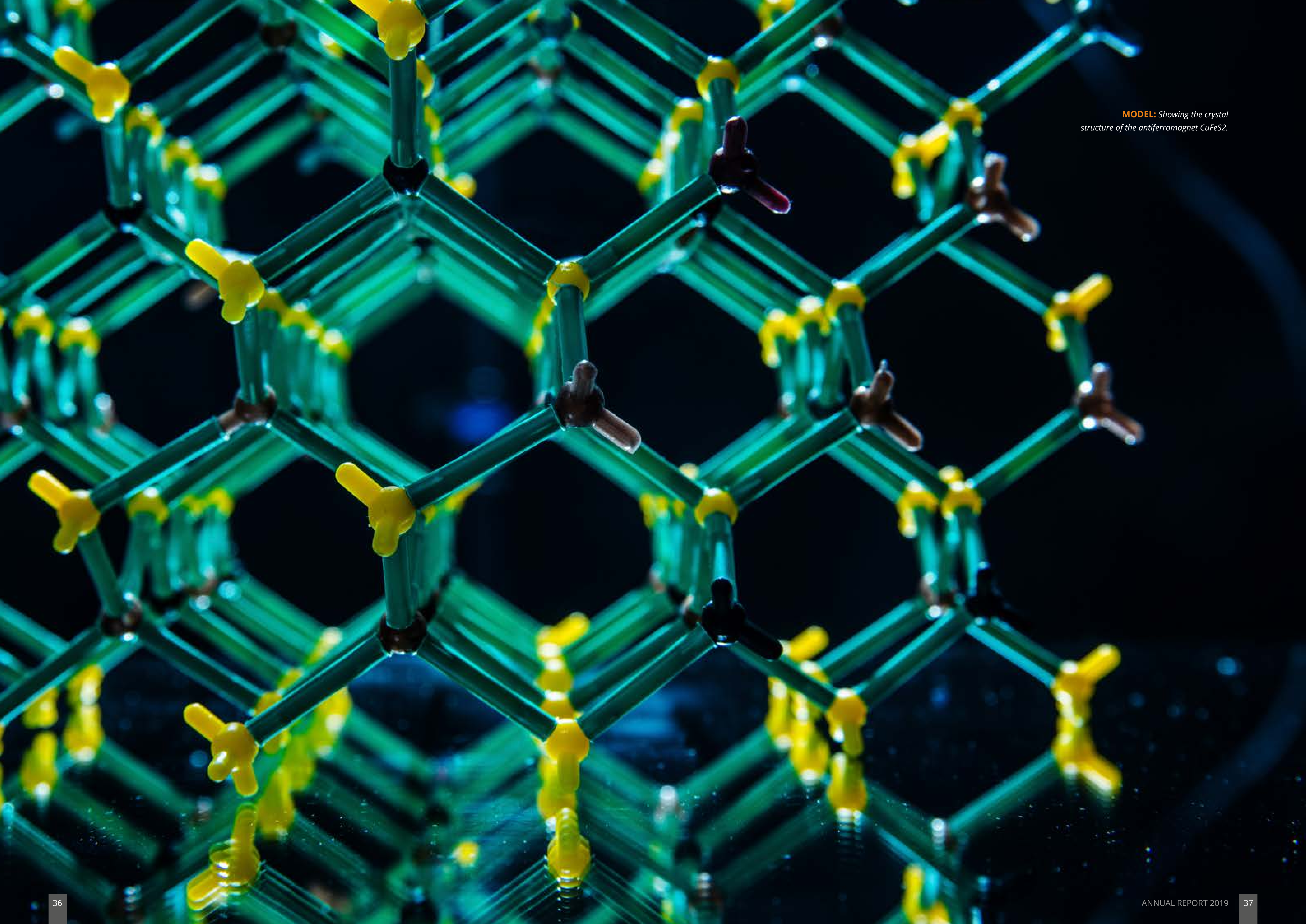
In 2019, we have mostly focused our research on ultrafast spin dynamics in 2D metallic and insulating antiferromagnets. Within the Floquet formalism, we have shown that in the strongly correlated regime of the extended Kane-Mele-Hubbard model, both Heisenberg exchange and DM interactions are dramatically renormalized in the presence of optical laser pulses. Also, we have developed a formalism to compute non-equilibrium DM interaction in the presence of ac electric fields in metallic antiferromagnets.

In another project, using atomistic spin dynamics simulations and microscopic calculations, we have shown that isolated topological skyrmions might be created in antiferromagnetic thin films as a metastable state using picosecond magnetic field pulses, see the following figure. The ultrafast dynamics of antiferromagnetic skyrmions shows a great advantage with respect to their ferromagnetic counterparts.

We have also started to explore the phase diagram of the extended Kane-Mele-Hubbard model in 2D hexagonal lattices. Another project that we have started in 2019 is the study of ultrafast two-magnon creation in antiferromagnets and entanglement of photoinduced magnon pairs. Our aim is to explore the effect of interactions on ultrafast two-magnon generation and dynamics.



The snap shot of skyrmion generation using a magnetic field pulse in a 2D antiferromagnetic film.



MODEL: *Showing the crystal structure of the antiferromagnet CuFeS2.*

Building the New Spin-ARPES Laboratory

Article based on a group dialogue with Justin Wells, Frode Strand and Håkon Røst facilitated by Karen-Elisabeth Sødahl.

Background and motivation

Over the last few years we have developed an ARPES laboratory at NTNU. We built a homemade preparation chamber, a detector upgrade and a 5-axis manipulator. This gave us good facilities for routine ARPES measurements, a wide range of preparation options, as well as supplementary techniques such as XPS, LEED and Auger analysis. Our existing instrumentation has mostly relied on established technological developments and has proven itself to be generally useful for a wide range of applications, from biophysics to photovoltaics, quantum computer architectures and more.

This year, we have constructed a new bespoke instrument. Unlike the existing equipment, which relied on well-established principles, we have jumped into the co-development of a new type of spin-resolved and spatial-resolved ARPES instrument. Using the combination of our existing knowledge and background, together with the utilization of the latest developments internationally, we have been able to design and build a state-of-the-art spin-ARPES instrument.

What is spin-ARPES?

ARPES (Angle Resolved Photo-Electron Spectroscopy) is a refinement of the photoelectric electric effect for which Einstein received the Nobel Prize. In fact, photoelectron spectroscopy was the topic of other Nobel Prizes since i.e. when Siegbahn demonstrated the application to material characterization.

By measuring the angle of a photoemitted electron, it is possible to extract the initial momentum vector of the electron before emission from a sample. Since we also measure the energy of the electron, this gives access to the spectral function.

Spin-ARPES goes one step further and also allows the spin non-degeneracy of the electronic band structure to be probed.

How did you know what was possible?

Justin was involved in some of the early developments in spin-ARPES and has kept in touch with developments in the field ever since. In the period 2006-2008, Justin was involved in the commissioning of the Swiss spin-ARPES beam line "COPHEE" and is responsible for one of the first paper from this facility [PRL 102:096802 (2019)]. Whilst the early instruments were extremely slow (a typical dataset taking ~24h to collect), and the spatial resolutions were poor, the technique proved its usefulness. This led to a number of interesting prototypes appearing in which the large improvements of the spin-detection efficiency are claimed.

In parallel, we have also been gaining experience with Photo-Emission Electron Microscopy (PEEM): a technique in which the spatial resolution of the method has been dramatically improved, but at the expense of energy, momentum and spin resolutions.

We therefore realized that the time was right to jump into the co-development of a spin-resolved instrument, in which we co-develop a state-of-the-art spin-filter and use it in conduction with the latest developments in ARPES and PEEM instrumentation, such that we can construct an energy, momentum, spin and spatially resolved instrument with unprecedented performance.

How did you get support for this investment?

The financial support for this investment was part of QuSpin's application to the Research Council of Norway to be granted as a Center of Excellence (SFF). Our strong background in this area was also an important prerequisite. Having worked with different research groups and companies internationally gave us the necessary positioning in the field.

The group

The underlying idea for a spin-resolved instrument, and the original research group was already established prior to the commencement of QuSpin. Associate Professor Simon Cooil played a central role in making the technical drawings and evaluation of the technical feasibility. An earlier version of our versatile preparation chamber, and our variable temperature 5-axis manipulator was designed and built by him during his postdoctoral period.

After the commencement of QuSpin, Ph.D. candidate Frode Strand was hired, and he took a central role in liaising with the external suppliers, figuring out what was technically possible, and dealing with the legalities of the procurement. Ph.D. candidate Håkon Ivarssøn Røst came onboard after these decisions were made and has been more involved in setting it up and using it.

More recently, the group has expanded and all of the group members have been involved in site preparations and the construction, installation and testing of the new equipment. Everyone has contributed a lot of hard work and effort.

> *People want to show their competence and share it. They want to see it work. It is not like a supplier and customer relationship, but more like a scientific collaboration. – Justin*

The procurement process and suppliers

The spin detector which is at the heart of the new instrument could only be constructed by one company; Focus GmbH in Hünstetten, Germany. Focus were also able to supply several other key components (i.e. suitable light sources, PEEM lenses and hemispherical electron analysers), but not able to meet all of our demands. The additional components (vacuum system, sample manipulator, liquid helium cryostat, water and gas manifolds, etc) were supplied in a partnership with Scienta-Omicron in Uppsala, Sweden. The sample transfer system, preparation chamber, sample characterization components were acquired from a wide range of suppliers (UHV-design, LewVac, OCI, Argon Services, and others), and we also utilized many refurbished components and in-house fabrication from NTNU's mechanical workshop. Co-ordinating this project with many suppliers and non-standard components has been challenging, but has ultimately worked extremely smoothly.

Contrary to the case of a standard purchase, this was a shared risk between us and the various suppliers. However, all parties also share an interest in seeing this instrument completed and performing to a high standard, and in it becoming a flagship of its generation. During the process, the relationship with the suppliers becomes deeper and ultimately they become friends as well as partners.

The timeline
The procurement paperwork took about 16 months to complete. Although this was longer than we originally anticipated, after signing the contracts, the project went much faster. It took under one year from signing the contract for the purchase of the main components until we had the equipment fully constructed, tested and up and running. Ultimately, the project was completed on time and on budget. This was only possible because of the detailed technical planning which we had done in advance.

Developing and sharing knowledge and competence
We believe this solution is in the forefront of the field and in the world. Furthermore, the research environment gains a lot from the competence of understanding, building and implementing this new equipment.

> *The best guys out there are the best because they learn from the best. – Håkon*

This competence is shared by having visitors from all around the world. We already have had visitors from Germany and China, and will soon have visitors from Denmark, UK and USA to collaborate on measurements which can be facilitated with our new instrument. This is typical within our field: the papers we publish are normally the result of a collaborations with others who are experts in complementary fields. You can't be the expert of everything.

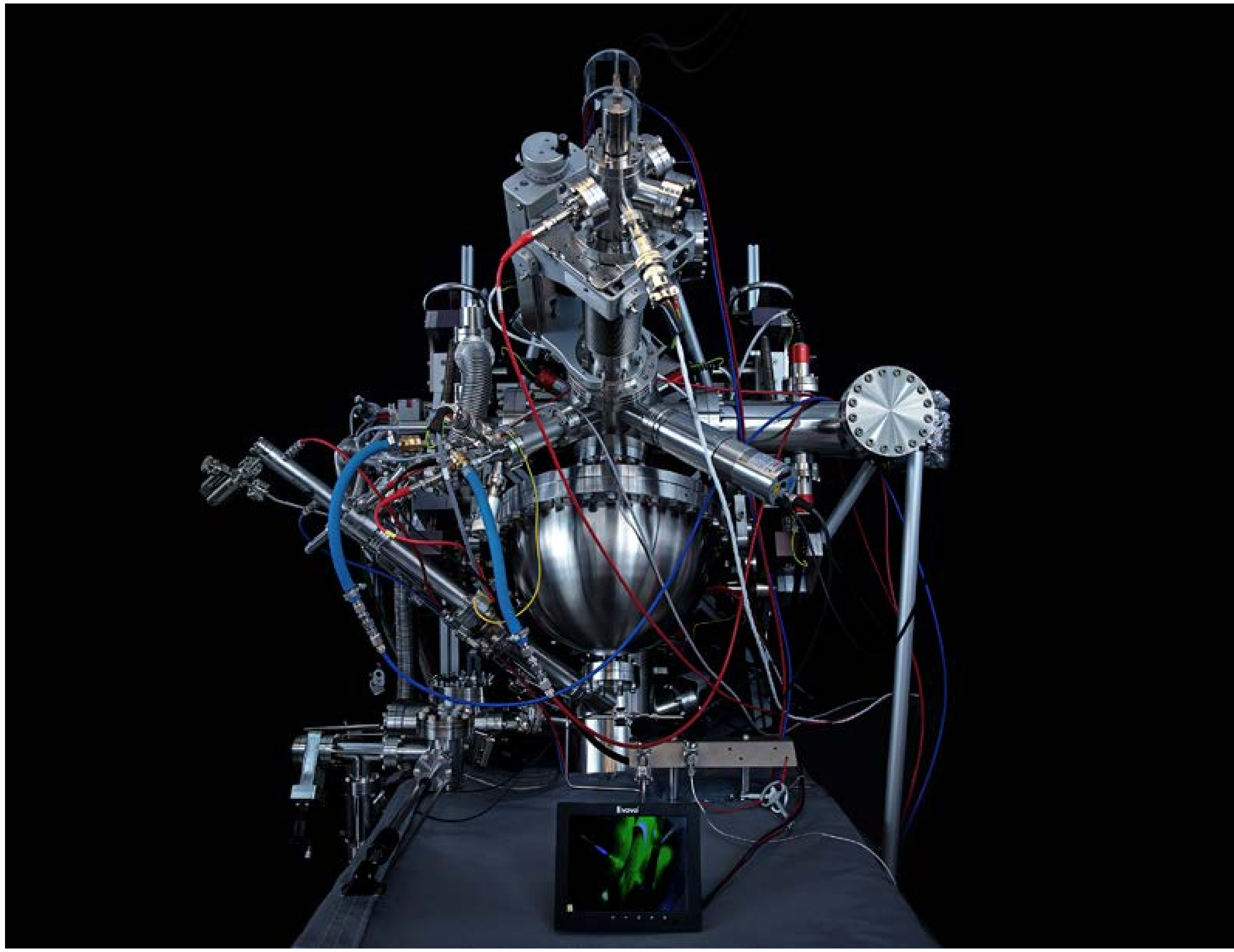
What can you do with this instrument?
We will measure electronic band-structure with very good spatial resolution, energy resolution, momentum resolution and spin resolution. This allows us to measure all kinds of new materials and structures that otherwise would not be possible. A lot of exciting new materials are coming, and we want to be able to measure their electronic structure even if they are very small or inhomogeneous. In addition, our conjoined custom-made preparation and characterization chamber allows us to grow, clean, dope and otherwise modify a wide range of materials and heterostructures.

Collaboration between theorists and experimentalists at QuSpin?
For example, one main topics within QuSpin is understanding the electrons' interactions with magnon and phonons. This is something that we are working on together with our theorists.

> *It took a long time to read, grasp and understand, but in that process you learn a lot more than you think. – Frode*

The individual learning experiences
All of us have put a lot of extra hours into tasks that is not in our job description. However, the bigger picture is that we all gained a lot from this. When something goes wrong with the equipment, we are in a stronger position to fix it because we have been involved in every step of the design, construction and testing. If you buy something "off the shelf" you generally rely on the manufacturer to come and fix it.

All these tasks and experiences leads to a much better base of competence. It is a transferable skill that goes in your tool set for later. It builds both competence and confidence. The willingness to learn and having a leader who is mentoring and letting people dive into the process and testing, are personal qualities crucial in this learning process!

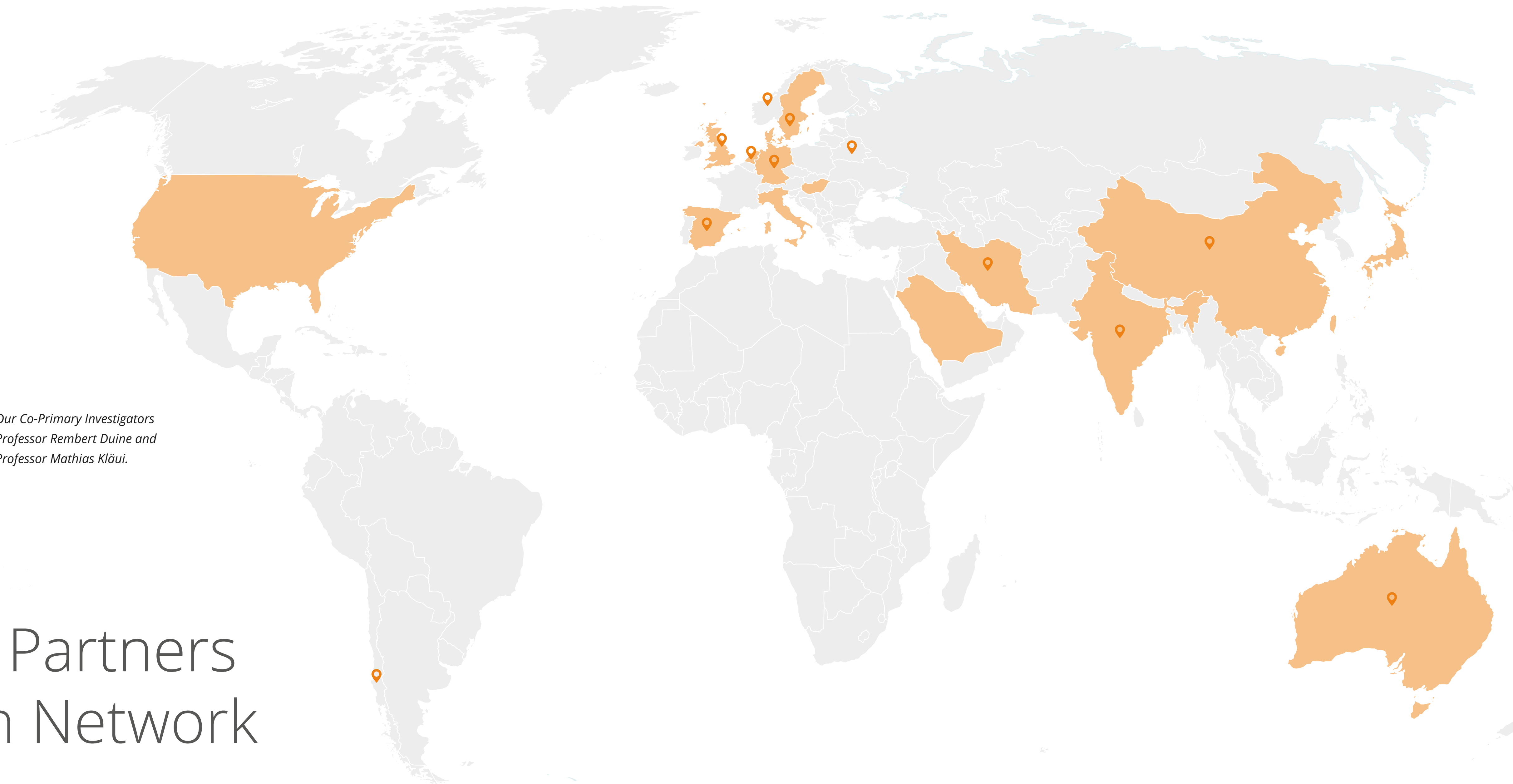


Our new Spin-ARPES intrument.

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

International Partners and Research Network

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



Countries our staff comes from

International collaborations

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

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

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

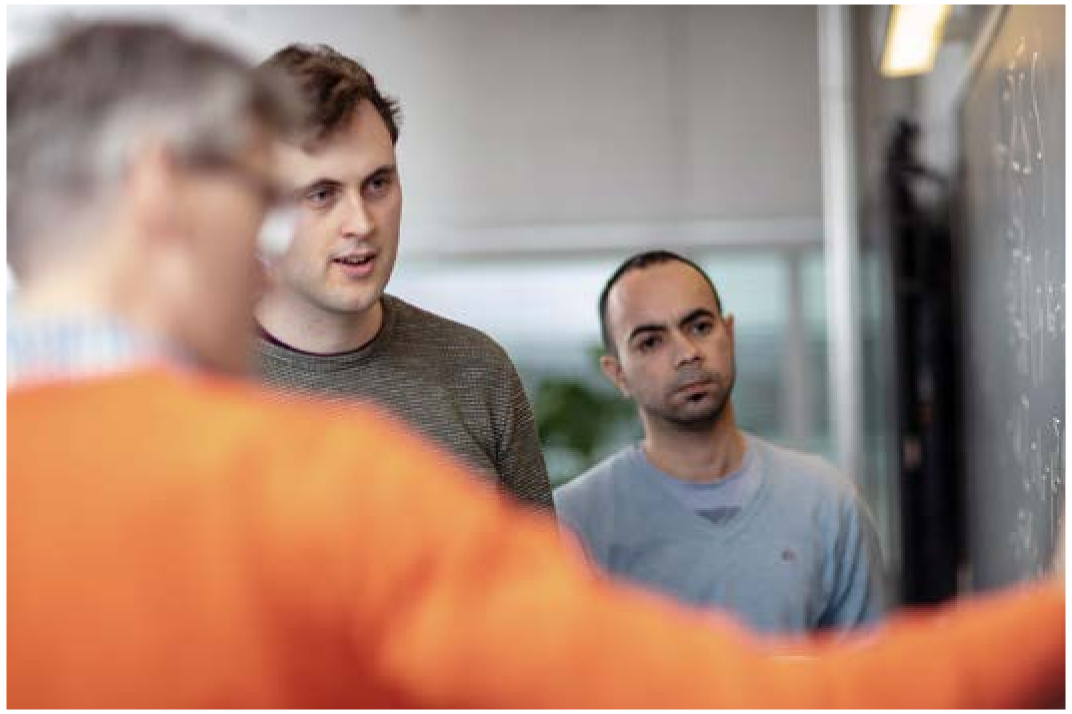
The QuSpin center is happy for the opportunities it has to host visiting researchers and has been host to thirty-six researchers in the recent year. These visits allow for interactions on a personal level that bolster the professional work and exposure, going both ways, to new, ongoing and past projects.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

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

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

Research Training of our PhD Candidates and PostDocs

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



Glimpses from various collaboration settings at our center.

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

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

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

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

Other arenas for training is also by giving popular scientific presentations to people outside of our center. Last year we had presentations on Researchers Night at NTNU, for visiting school classes, as well as presentations for female college students as a part of "Teknologiuka for jenter 2019" at NTNU.

QUANTUM SPINTRONICS 2019

Our Annual International Workshop

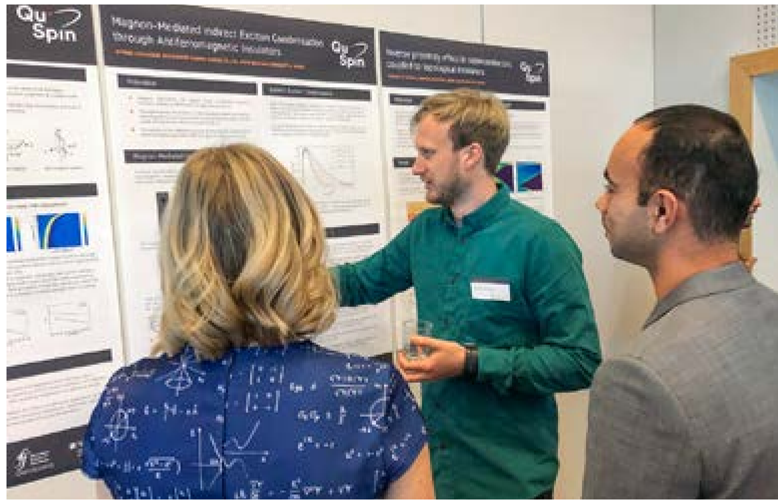
It is critical to gather with leading international professionals outside QuSpin. Targeted workshops allow for inspiration, discussions around current challenges and findings, and a strengthened environment for focused peer discussions.

The twelve speakers, representing both the theoretical and experimental areas, came to share their perspectives and work with our nearly seventy attendees. This year, we also included a poster session, presenting the work at our center, and to open up for deeper discussions and possible collaborations.

In moving forward, this state-of-the-art field needs hands-on and intensive workshops. This year, we focused on our close network. Over the next years, we plan to broaden our spectrum of participants as well.

Our workshop does not need to be all work and no play. Our city also hosted other types of connection and learning opportunities for attendants. The workshop was held at the Scandic Nidelven Conference Centre, a point where history meets modernity at the mouth of the river Nidelven. Through a walk in the historic city center and a visit to Rockheim, Norway's National Museum of Popular Music, our strong history of trade, culture, and cultivation of knowledge was introduced to our guests. At the workshop dinner at the Rockheim restaurant we were served delicious local food while overlooking the sunset and the fjord.

From upper left: Shahal Ilani, Matthias Eschrig, Norman Birge, Burkard Hillebrands, Ralph Claessen, Asle Sudbø, Gerrit Bauer, Kai Rossnagel and Justin Wells. From lower left: Jude Laverock, Anton Akhmerov, Hans Huebl, Arne Brataas, Jacob Linder and Oscar Tjernberg.



Glimpses from the city and the workshop.

We were hosted in the mountains of Oppdal, a two hours drive from Trondheim.

QUSPIN COLLABORATION WORKSHOP 2019

Internal Collaboration Workshop

We also focused on creating good meeting places for internal collaboration. Time and a good atmosphere for formal and informal interaction and dialogue is key.

For our first internal collaboration workshop, we chose Bjerkeløkka Conference Center at Oppdal, a two-hour drive from Trondheim. The place is rich in local food and architecture with its nine wooden houses, the oldest dating almost as far back as the year 1700.

Seventy participants from QuSpin, Trondheim, and our partners in Mainz and Delft presented plenatory talks on spin insulatronics, topological insulators, super spintronics, experimental facilities and possibilities in Mainz, and experimental facilities and possibilities in Trondheim. This was followed up by parallel workshops.

During in-depth discussions many new ideas for collaborative projects were born, and we exchanged ideas to identify exciting topics for future work. In addition to the intensive scientific work during the seminars, we had a great time with various winter sports activities.

Outreach

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

This year we used several opportunities to share our knowledge in physics and the research activity at our center to a broader audience.

Researchers Night
As last year, our PhD candidates reached out to more than two hundred collleges students at Researchers Night 2019 at NTNU, with the lecture on "Flying Super-conductors and the Quantum Revolution", followed by an experiment. A very attractive subject!

Teknologijenteuka
During the Teknologijenteuka 2019 at NTNU our MBE lab team presented a lecture to more than forty female students with the title "Magnetic materials for the future: Building up crystals one atomic layer at a time». The students were met on their curiosity by inviting them our MBE lab for further understanding of the experimental work in building new materials.

School visits
We also received visits from students from Greveskogen High School, Tønsberg, and Fagerlia High School, Ålesund. They were given presentations of our center, and our MBE lab activity. These students had teachers who were previous students from our faculty who wanted to show them the university and study possibilities.

Female recruitment
One of our female researchers gave the seminar on "Quantum Physics: Career and life", a motivational seminar organised by Maths and Physics student association "Delta".

Motivation and recruitment of female candidates is a focus area for QuSpin. We are participating in newly established student portal at NTNU, initiating a research project in of females in academia. We are looking for NTNU student candidates who wants to look into "How to increase the number of females in physics studies and research? ". This is a project for students to collaborate with the academic staff at our center, to improve the understanding on how to recruit more female candidates to the discipline of physics, and to our center. The key question is how to motivate female candidates into research.

Seniorakademiet
Finally our center director gave a lecture on "Nano-ingen liten sak" to about three hundred and fifty listeners at Seniorakademiet in Oppegård. This was a group of highly engaged senior listeners.

All in all, this has been a year we have reached out to a broad audience, ranging from teenagers to senior people, male and female. We hope this has created an increased interest for the field of physics and our research.

Glimpses from Our Center

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

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

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

We spend time and resources on developing a prosocial and robust culture. We need places and arenas where people can meet, create and exchange.

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

Gathering around scientific discussions, social happenings or celebrations helps build a strong social culture at our center.

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.

FELLOW OF THE AMERICAN PHYSICAL SOCIETY 2019

Principal Investigator, professor Asle Sudbø was selected as APS Fellow by the Division of Condensed Matter Physics, and the citation reads "For his pioneering contributions to the theory of vortex matter in strongly fluctuating superconductors, superfluids, and multicomponent condensates."

Each year, no more than one half of one percent of the Society membership is recognized by their peers for election to the status of Fellow in the American Physical Society. This is a prestigious recognition that also shows his important contributions to the research at our center, QuSpin, a center of excellence (SFF).

ERC CONSOLIDATOR GRANT

Professor Dennis Meier has received a ERC Consolidator Grant for his project on Atronics- creating building blocks for atomic-scale electronics.

With the project "ATRONICS", Dennis and his team aim to emulate the behavior of electronic components at the atomic scale. The research will provide new insight into the physics of functional oxide materials and potentially lead to major breakthroughs in electronics. If the team succeeds, their research will enable energy efficient and ultra-small circuitry and networks, playing a key role in the transition from nano- to atomic-scale electronics. The funding will enable five new members to join his team over five years.

FRITJOF NANSEN´S AWARD FOR YOUNG SCIENTISTS 2019

Professor Dennis Meier received the Fritjof Nansen award for young scientists 2019 from the Norwegian Academy of Science and Letters for his outstanding research within materials physics. The award is NOK 75.000.

YOUNG RESEARCHERS 2019

Professor Dennis G. Meier was awarded with Det Kongelige Norske Videnskabers Selskabs scientific award to young researchers 2019.

The awards goes to Dennis G. Meier and Dave Kush. The award is NOK 75.000 to each. The award goes to young researchers in Norway who has documented extraordinary talent, and work, and who has achieved exceptionally good results within one's scientific field.

FRIPRO YOUNG RESEARCH TALENTS 2019

Researcher Sol H. Jacobsen has received a FRIPRO Young Research Talents 2019 grant from the Research Council of Norway for her project on Superconducting Triplet Spintronics: Generation, control and application.

With the help of curvature, cavities and spin-orbit coupling, the project will go beyond rigid proximity-coupled systems to explore new directions for low-dissipation superconducting spintronics. The funding will enable one PhD candidate and one PostDoc to join her as the project leader.

DISTINGUISHED LECTURER FOR 2020

Co-PI, Professor Mathias Kläui, Mainz, has been selected as Distinguished Lecturer for 2020. Kläui will be doing a lecturing tour during 2020 to a range of universities, presenting his research field. The title of his lecture is "Antiferromagnetic Insulatronics: Spintronics without magnetic fields and moving electrons".

MEMBER OF HONOUR 2019

Principal Investigator, Professor Justin Wells has been elected Member of Honour 2019 by the Nano students at NTNU. For his long and deep interest and contributions to his students, scientifically and socially.

BEST STUDENT TALK AT NANO NETWORK 2019

PhD candidate Håkon Ivarssøn Røst was awarded for the Best student talk at the Nano Network 2019, Norwegian PhD Network on NanoTechnology for Microsystems, 10th annual workshop, in Tromsø, Norway. The commitee was headed by Olav Solgaard from Stanford University, USA.

Scientific Publications

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

1. Bender, Scott A.; Kamra, Akashdeep; Belzig, Wolfgang; Duine, Rembert.
Spin current cross-correlations as a probe of magnon coherence. ***Physical Review Letters*** 2019; Volume 122.

2. Johansen, Øyvind; Kamra, Akashdeep; Ulloa, Camilo; Brataas, Arne; Duine, Rembert.
Magnon-Mediated Indirect Exciton Condensation through Antiferromagnetic Insulators.
Physical Review Letters 2019; Volume 123. (16)

3. Johansen, Øyvind; Risinggård, Vetle Kjær; Sudbø, Asle; Linder, Jacob; Brataas, Arne.
Current Control of Magnetism in Two-Dimensional Fe3GeTe2. ***Physical Review Letters*** 2019 ;Volume 122. (21)

4. Kamra, Akashdeep; Polishchuk, Dmytro; Korenivski, Vladislav; Brataas, Arne.
Anisotropic and controllable Gilbert-Bloch dissipation in spin valves. ***Physical Review Letters*** 2019 ;Volume 122. (14)

5. Liensberger, Lukas; Kamra, Akashdeep; Maier-Flaig, Hannes; Gepraegs, Stephan; Erb, Andreas; Goennenwein, Sebastian; Gross, Rudolf; Belzig, Wolfgang; Huebl, Hans; Weiler, Mathias.
Exchange-enhanced ultrastrong magnon-magnon coupling in a compensated ferrimagnet.
Physical Review Letters 2019; Volume 123. (11)

6. Polishchuk, Dmytro; Kamra, Akashdeep; Polek, Taras; Brataas, Arne; Korenivski, Vladislav.
Angle Resolved Relaxation of Spin Currents by Antiferromagnets in Spin Valves. ***Physical Review Letters*** 2019; Volume 123. (24) p. 247201-1-247201-6

7. Thingstad, Even; Kamra, Akashdeep; Brataas, Arne; Sudbø, Asle.
Chiral Phonon Transport Induced by Topological Magnons. ***Physical Review Letters*** 2019; Volume 122. (10)

8. Wang, Xiansi; Qaiumzadeh, Alireza; Brataas, Arne.
Current-Driven Dynamics of Magnetic Hopfions***.*** ***Physical Review Letters*** 2019; Volume 123. (14)

9. Werner, Miklos Antal; Brataas, Arne; von Oppen, Felix; Zarand, Gergely.
Universal Scaling Theory of the Boundary Geometric Tensor in Disordered Metals. ***Physical Review Letters*** 2019; Volume 122. (10)

10. Linder, Jacob; Balatsky, Alexander.
Odd-frequency superconductivity. ***Reviews of Modern Physics*** 2019; Volume 91. (4)

11. Amundsen, Morten; Linder, Jacob.
Quasiclassical theory for interfaces with spin-orbit coupling. ***Physical review B*** (PRB) 2019; Volume 100.(6)

12. Danon, Jeroen; Balram, Ajit C.; Sánchez, Samuel; Rudner, Mark S.
Charge and spin textures of Ising quantum Hall ferromagnet domain walls. ***Physical review B*** (PRB) 2019; Volume 100.(23)

13. Ding, S.; Ross, A; Lebrun, R; Becker, S; Lee, K; Boventer, I; Das, S; Kurokawa, Y; Gupta, S; Yang, J; Jakob, Gerhard; Klaui, Mathias Michael.
Interfacial Dzyaloshinskii-Moriya interaction and chiral magnetic textures in a ferrimagnetic insulator.
Physical review B (PRB) 2019; Volume 100. (100406)

14. Erlandsen, Eirik; Kamra, Akashdeep; Brataas, Arne; Sudbø, Asle.
Enhancement of superconductivity mediated by antiferromagnetic squeezed magnons. ***Physical review B*** (PRB) 2019; Volume 100. (10)

15. Eskilt, Johannes Røsok; Amundsen, Morten; Banerjee, Niladri; Linder, Jacob.
Long-ranged triplet supercurrent in a single in-plane ferromagnet with spin-orbit coupled contacts to superconductors. ***Physical review B*** (PRB) 2019; Volume 100. (22)

16. Fjærbu, Eirik Løhaugen; Rohling, Niklas; Brataas, Arne.
Superconductivity at metal-antiferromagnetic insulator interfaces. ***Physical review B*** (PRB) 2019; Volume 100. (12)

17. Fyhn, Eirik Holm; Linder, Jacob.
Controllable vortex loops in superconducting proximity systems. ***Physical review B*** (PRB) 2019; Volume 100. (21)

18. Fyhn, Eirik Holm; Linder, Jacob.
Superconducting vortices in half-metals. ***Physical review B*** (PRB) 2019; Volume 100. (22)

19. Hofmann, Philip; Ugeda, Miguel; Tamtogl, Anton; Ruckhofer, Adrian; Ernst, Wolfgang E; Benedek, Giorgio; Martınez-Galera, Antonio; Strozecka, Anna; Gomez-Rodrıguez, Jose; Rienks, Emile; Jensen, Maria; Pascual, Jose; Wells, Justin.
Strong-coupling charge density wave in a one-dimensional topological metal. ***Physical review B*** (PRB) 2019; Volume 99. (3)

20. Hugdal, Henning Goa; Amundsen, Morten; Linder, Jacob; Sudbø, Asle.
Inverse proximity effect in s-wave and d-wave superconductors coupled to topological insulators.
Physical review B (PRB) 2019; Volume 99. (9)

21. Jakobsen, Martin Fonnum; Qaiumzadeh, Alireza; Brataas, Arne.
Scattering theory of transport through disordered magnets. ***Physical review B*** (PRB) 2019; Volume 100. (13)

22. Johnsen, Lina G.; Banerjee, Niladri; Linder, Jacob.
Magnetization reorientation due to the superconducting transition in heavy-metal heterostructures.
Physical review B (PRB) 2019; Volume 99. (13)

23. Kamra, Akashdeep; Thingstad, Even; Rastelli, Gianluca; Duine, Rembert; Brataas, Arne; Belzig, Wolfgang; Sudbø, Asle.
Antiferromagnetic magnons as highly squeezed Fock states underlying quantum correlations.
Physical review B (PRB) 2019 ;Volume 100.(17) p. 174407-1-174407-9

24. Khoshlahni, Rohollah; Qaiumzadeh, Alireza; Bergman, Anders; Brataas, Arne.
Ultrafast generation and dynamics of isolated skyrmions in antiferromagnetic insulators.
Physical review B (PRB) 2019; Volume 99. (5)

25. Losada, Juan Manuel; Brataas, Arne; Qaiumzadeh, Alireza.
Ultrafast control of spin interactions in honeycomb antiferromagnetic insulators.
Physical review B (PRB) 2019; Volume 100. (6)

26. Ouassou, Jabir Ali; Linder, Jacob.
Voltage control of superconducting exchange interaction and anomalous Josephson effect.
Physical review B (PRB) 2019; Volume 99. (21)

27. Risinggård, Vetle Kjær; Linder, Jacob.
Direct and inverse superspin Hall effect in two-dimensional systems: Electrical detection of spin supercurrents.
Physical review B (PRB) 2019; Volume 99. (17)

28. Salimath, A; Abbout, A; Brataas, Arne; Manchon, A.
Current-driven skyrmion depinning in magnetic granular films. ***Physical review B*** (PRB) 2019; Volume 99. (10)

29. Simensen, Haakon Thømt; Troncoso, Roberto; Kamra, Akashdeep; Brataas, Arne.
Magnon-polarons in cubic collinear antiferromagnets. ***Physical review B*** (PRB) 2019; Volume 99. (6)

30. Singh, Suraj Kumar; Bolstad, Torstein; Hallsteinsen, Ingrid; Tybell, Per Thomas Martin; Wahlström, Erik.
Magneto-dynamic properties of complex oxide—La0.7Sr0.3MnO3/SrTiO3— heterostructure interface.
Applied Physics Letters 2019; Volume 114. (22)

31. Abdelsalam, Hazem; Saroka, Vasil; Younis, Waleed Othman.
Edge functionalization of finite graphene nanoribbon superlattices.
Superlattices and Microstructures 2019; Volume 129. p. 54-61

32. Håkonsen, Verner; Singh, Gurvinder; Normile, Peter S; De Toro, Jose Angel; Wahlström, Erik; He, Jianying; Zhang, Zhiliang.
Magnetically Enhanced Mechanical Stability and Super-Size Effects in Self-Assembled Superstructures of Nanocubes.
Advanced Functional Materials 2019; Volume 29. (46)

33. Ivanova-Rohling, Violeta N.; Rohling, Niklas.
Optimal choice of state tomography quorum formed by projection operators. ***Physical Review A*** (PRA) 2019; Volume 100. (3)

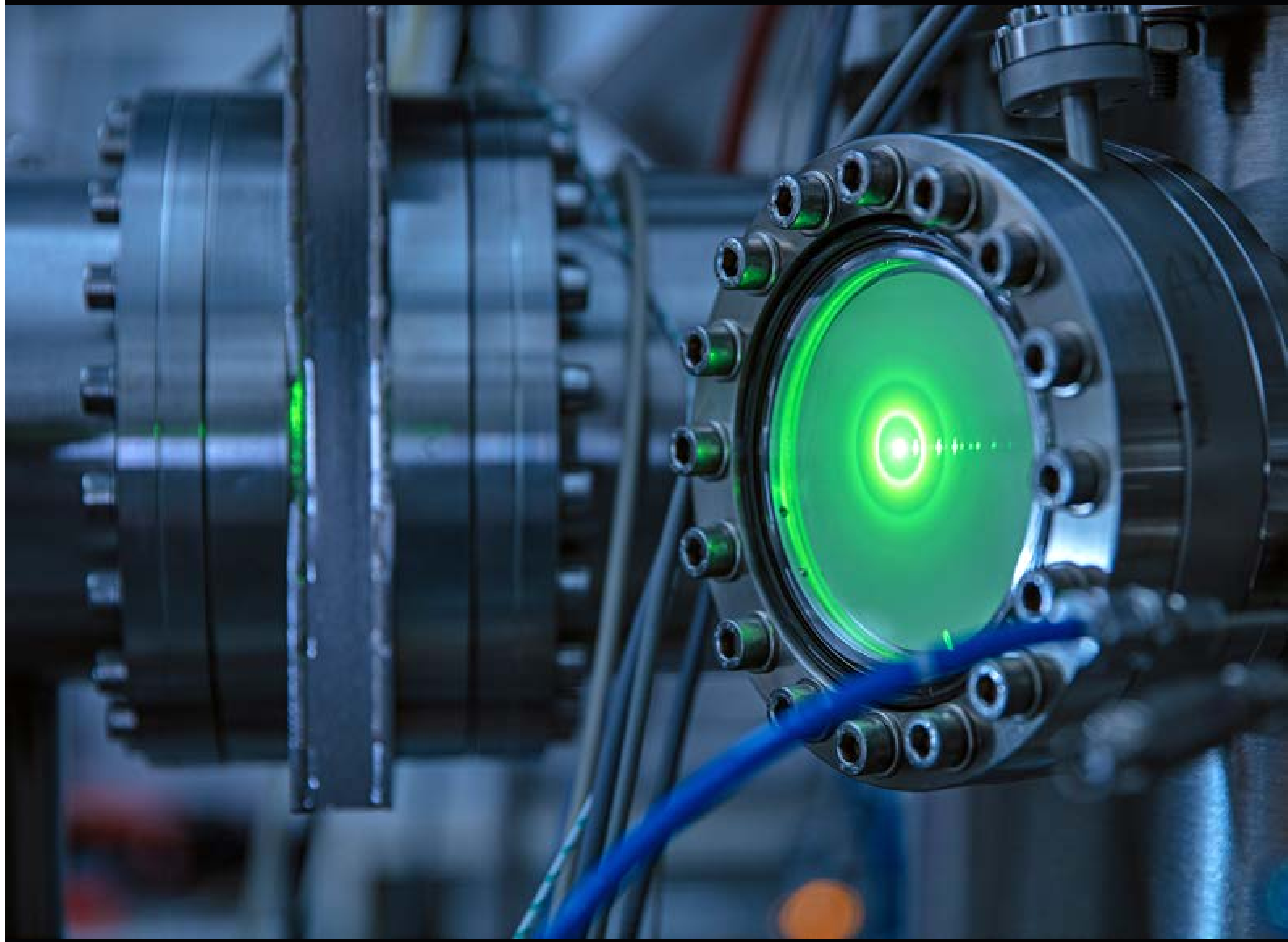
34. Nogueira, Flavio S.; van den Brink, Jeroen; Sudbø, Asle.
Conformality loss and quantum criticality in topological Higgs electrodynamics in 2+1 dimensions.
Physical Review D 2019; Volume 100.

35. Lebrun, Romain; Ross, Andrew; Gomonay, Olena; Bender, Scott A.; Baldrati, Lorenzo; Kronast, Florian; Qaiumzadeh, Alireza; Sinova, Jairo; Brataas, Arne; Duine, Rembert; Klaui, Mathias Michael.
Anisotropies and magnetic phase transitions in insulating antiferromagnets determined by a Spin-Hall magnetoresistance probe. ***Communications Physics*** 2019; Volum 2.(1) p. 1-7.

36. Ouassou, Jabir Ali; Robinson, Jason W.A.; Linder, Jacob.
Controlling spin supercurrents via nonequilibrium spin injection. ***Scientific Reports*** 2019; Volume 9.

37. Payod, Renebeth B.; Saroka, Vasil.
Ab Initio Study of Absorption Resonance Correlations between Nanotubes and Nanoribbons of Graphene and Hexagonal Boron Nitride. ***Semiconductors (Woodbury, N.Y.)*** 2019; Volume 53. (14) p. 1929-1934

38. 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; Duine, Rembert; Brataas, Arne; Rothschild, Avner; Klaui, Mathias Michael.
Propagation Length of Antiferromagnetic Magnons Governed by Domain Configurations. ***Nano letters (Print)*** 2019; Volume 20. (1) p. 306-313



Highlights

MARCH

PhD Defense
Jabir Ali Ouassou

DKVS Grant
Dennis Meier

QuSpin Internal
Collaboration Workshop

MAY

Fritjof Nansen´s Award
Dennis Meier

AUGUST

PhD Defense
Vetle KJær Risinggård

SEPTEMBER

Fellow of the American
Physical Society (APS)
Asle Sudbø

Quantum Spintronics 2019

DECEMBER

PhD Defense
Øyvind Johansen

ERC Consolidator
Grant Dennis Meier

RCN/FRIPRO Grant
Sol H. Jacobsen

Spin-ARPES components
delivered and building
started

First MBE chamber
installed

Facts

Per 2019.12.31.

10 PROF/ASSOC.PROF

3 RESEARCHERS

6 POSTDOCS

27 PHD STUDENTS

11 MASTER STUDENTS

1 ADMINISTRATOR

12 DIFFERENT NATIONALITES

36 VISITING RESEARCHERS

38 PUBLICATIONS

*Note: In addition we have a 25 % Finance Officer position, and Head Engineer from the Department of Physics/NTNU.

Funding

FUNDING 2019 (NOK)

The Research Council of Norway, Center of Excellence	14 895 000
Norwegian University of Science and Technology	9 525 000
SUM	**24 420 000**
The Research Council of Norway, Center of Excellence	10 080 000
International Funding	6 100 000
Other Public	717 000
SUM	**16 897 000**
TOTAL FUNDING	**41 317 000**

People Overview

Colleagues who left QuSpin before 2019.12.31 are marked with an *

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Asle Sudbø

Professor/Primary Investigator
Jacob Linder

Professor/Principal Investigator
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Associate Professor
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Associate Professor
John Ove Fjærestad

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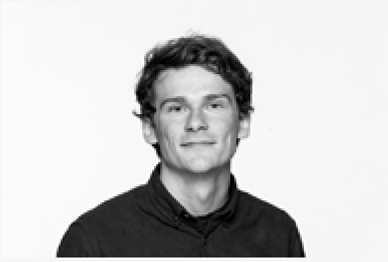

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Frode Sneve Strand

Even Thingstad

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Bjørnulf Brekke
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Trond H. Haug
Karl Kristian Ladegård Lockert
Andreas Halkjelsvik Mjøs
Kristian Mæland
Jonas Halse Rygh
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Ivan Ushakov

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Professor
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Simon Phillip Cooil (NTNU)

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

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