Annual Report | 2024

Center for Quantum Spintronics

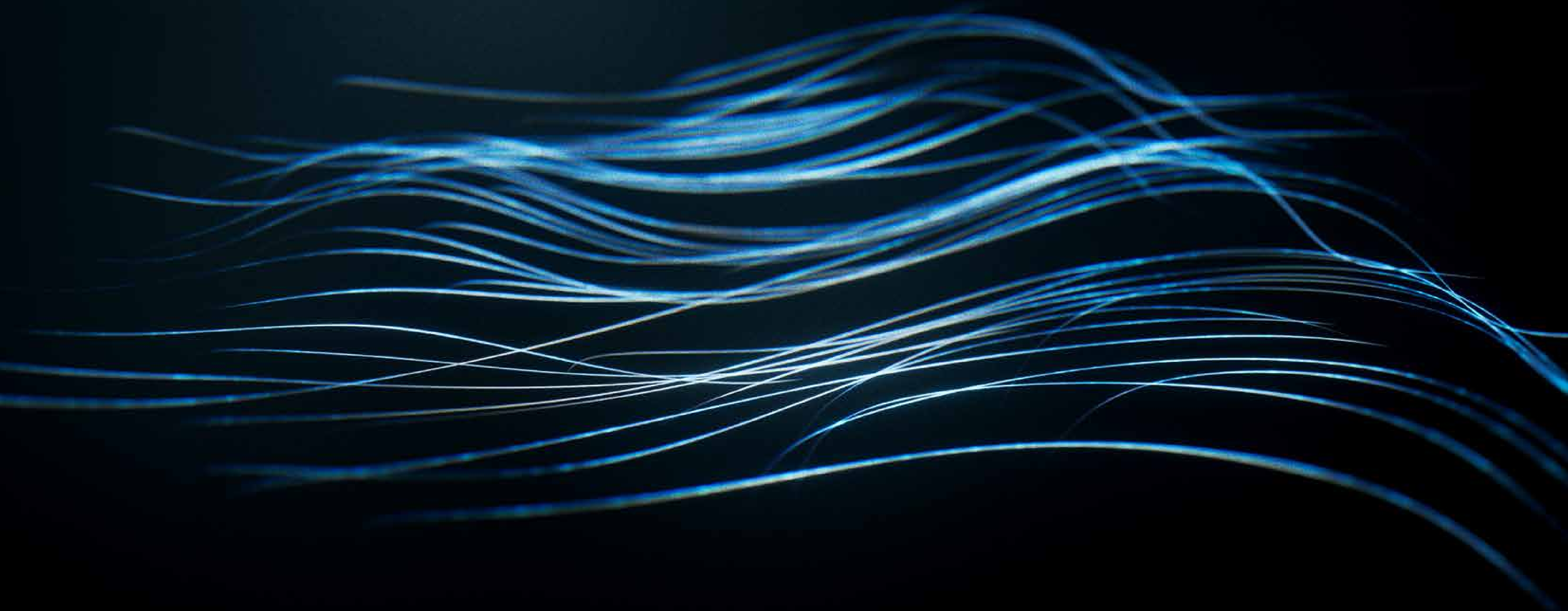
QuSpin

Norwegian Centre of Excellence
The Research Council of Norway

NTNU
Norwegian University of Science and Technology

Our Vision

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



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

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

CENTER DIRECTOR PROFESSOR ASLE SUDBØ

QuSpin entering its final three years of exploration and discovery

Quantum spintronics is a multidisciplinary domain that investigates the quantum mechanical properties of electron spin to facilitate advanced technological paradigms. By harnessing fundamental quantum phenomena—including spin coherence, spin-orbit interaction, and quantum entanglement—this field enables precise control and manipulation of spin states, thereby underpinning innovations in quantum information processing, ultra-low-power electronic architectures, and high-bandwidth data storage. Integrating theoretical and experimental frameworks from quantum mechanics, condensed matter physics, materials science, and nanoscale engineering, quantum spintronics is poised to drive transformative breakthroughs in quantum computation and the development of next-generation spintronic devices.

In 2024, QuSpin has been able to keep up the excellent publication rate in the world's premier research journals in the field of condensed matter physics, and continues to consistently educate PhD candidates and postdocs for the benefit of the global science community. Despite the fact that the announced midterm evaluation did not take place, QuSpin had planned the activity for the final 4 years thoroughly, and will continue to produce high-quality high-impact science.

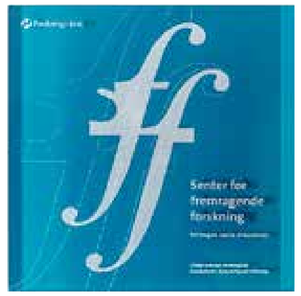
In June 2024, QuSpin organized its fifth international conference involving all members of the Center, including associate PI's and members of their groups both at the University of Mainz and Utrecht University, as well as a number of other internationally recognized researchers. The tradition of organizing these successful international conferences will be upheld throughout the duration of the Center.

As we advance into the final phase of exploration and discovery within QuSpin, we remain resolute in addressing the complex challenges and seizing the transformative opportunities that lie ahead. United by a shared vision, we are poised to navigate a trajectory where the fundamental principles of quantum spin drive groundbreaking advancements in both technological innovation and scientific inquiry. QuSpin stands at the forefront of this endeavor, guided by an unwavering commitment to research excellence, interdisciplinary collaboration, and the relentless pursuit of knowledge.

In this regard, 2024 has been a particularly distinguished year. Notably, no fewer than four members of the Center have secured highly competitive grants from the Norwegian Research Council. Furthermore, a significant initiative is currently underway to establish a new research Center, set to commence operations in 2027, building upon the strong foundation and achievements realized within QuSpin.

> QuSpin is guided by an unwavering commitment to research excellence, interdisciplinary collaboration and the relentless pursuit of knowledge.

Center of Excellence



QuSpin, recognized in 2017 as one of ten new Centers of Excellence by the Research Council of Norway, carries the responsibility to provide the resources and space for international researchers, to delve into and unravel the beautiful complexities of condensed matter physics to further our understanding and control of quantum physics in the pursuit of innovations. We are now a good seven years into our project and we look forward to the next three years.

SFF QuSpin's Principal Investigators (from left): Asle Sudbø, Arne Brataas, Hendrik Bentmann and Jacob Linder.

By the end of 2024, our Center had developed into a sixty-people strong team with members from twelve different countries. QuSpin has now nine permanent professors and associate professors, two senior researchers, two postdocs, twenty PhD candidates, eleven master's students, and one administrator. In addition, we have one 25%-position for a finance controller, two 20%-positions for Co-Principal Investigators, one professor II, and two lab engineers. For the period 2025-2027, Professor Chiara Ciccarelli from Cambridge University, UK will strengthen our team with yet another professor II.,

In addition to performing excellent basic research presenting scientific results in leading international journals, we are searching for closer collaboration with industry partners. We are seeking collaborations in developing competence within the main areas of data analysis, smart materials, sensing, and communication – areas in which we foresee the potential of contributing to great societal impact.

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

In bringing together Norwegian experts with their international counterparts, the Center puts Norway at the forefront of quantum spintronics research. In turn, our research will enable innovative applications.

Some of the researchers at QuSpin in Trondheim.

Site visit by QuSpin Advisory Board. From left: Asle Sudbø, Hendrik Bentmann, Milena Grifoni, Jacob Linder, Jason Robinson, Daniela Pfannkuche and Arne Brataas.

Site visit by the Research Council, Norway. From bottom left: Åshild Vik, Kaja Kvaale, Petter Helgesen, Jacob Linder, Liv Furuberg and Kathrine Røe Redalen. From upper left: Øyvind Gregersen, Kjell Emil Naas, Asle Sudbø and Arne Brataas.

Fundamental Quantum Physics Research: A Basis for Quantum Technologies

Written by Professor Asle Sudbø

Quantum physics, the study of the behavior of matter and energy at the smallest scales, has profoundly transformed our understanding of the universe. At its core, it challenges classical intuitions, revealing phenomena such as superposition, entanglement, and wave-particle duality. While initially perceived as an abstract theoretical framework, quantum physics has become the foundation for groundbreaking technological advancements. Fundamental quantum research is not merely a pursuit of knowledge; it is a wellspring of innovations that underpin emerging quantum technologies, including quantum computing, quantum communication, and quantum sensing.

The Core Principles of Quantum Physics
The unique principles of quantum physics distinguish it from classical physics and form the backbone of quantum technologies:

1. ***Superposition:*** A quantum system can exist in multiple states simultaneously until it is measured. This principle enables quantum computers to process vast amounts of information in parallel, far surpassing classical systems.

2. ***Entanglement:*** When particles become entangled, the state of one particle is instantaneously correlated with the state of another, regardless of the distance separating them. This phenomenon is critical for quantum communication protocols and secure cryptographic systems.

3. ***Wave-Particle Duality:*** Particles, such as electrons and photons, exhibit both wave-like and particle-like behavior depending on the experimental context. This duality underlies many quantum devices, such as electron microscopes and interferometers.

4. ***Quantization:*** Energy levels in quantum systems are discrete, leading to phenomena like the photoelectric effect, which has paved the way for technologies such as lasers and semiconductors.

Historical Milestones and Foundational Research
The journey of quantum physics began in the early 20th century with pioneers like Max Planck, Albert Einstein, Niels Bohr, and Werner Heisenberg. Planck's quantization of energy and Einstein's explanation of the photoelectric effect introduced the quantum nature of light and matter. Bohr's atomic model and Heisenberg's uncertainty principle further solidified the foundations of quantum mechanics.

The mid-20th century witnessed the development of quantum electrodynamics (QED) and other quantum field theories, providing a unified framework for understanding interactions between particles and forces. Fundamental experiments, such as the Stern-Gerlach experiment, the double-slit experiment, and Bell's inequality tests, validated quantum theory's predictions and showcased its non-intuitive nature.

Quantum Physics as a Catalyst for Technologies
Advances in fundamental quantum research have continually inspired technological innovations. For example:

1. ***Semiconductors and Transistors:*** Quantum mechanics explains the behavior of electrons in materials, leading to the development of semiconductors and transistors–the building blocks of modern electronics.

2. ***Lasers:*** The stimulated emission of radiation, a quantum phenomenon, forms the basis of lasers, which are indispensable in fields ranging from medicine to telecommunications.

3. ***Magnetic Resonance Imaging (MRI):*** Quantum spin properties underpin MRI technology, revolutionizing medical diagnostics.

Quantum Computing: Harnessing Superposition and Entanglement
Quantum computing represents one of the most promising applications of quantum physics. Unlike classical computers, which encode information in binary bits (0 or 1), quantum computers use quantum bits, or qubits, which can exist in superpositions of states. This allows quantum systems to perform certain computations exponentially faster than classical counterparts.

The development of quantum algorithms, such as Shor's algorithm for factoring large numbers and Grover's algorithm for database search, highlights the transformative potential of quantum computing. These algorithms promise to solve problems in cryptography, optimization, and materials science that are currently intractable for classical computers.

Quantum Communication: Secure and Efficient Information Transfer
Quantum entanglement and the no-cloning theorem–a principle stating that quantum information cannot be copied–form the basis of quantum communication. Quantum key distribution (QKD) protocols, such as BB84, leverage these principles to ensure secure transmission of information. Unlike classical encryption methods, QKD is theoretically immune to eavesdropping, as any interception alters the quantum states and alerts the communicating parties.

Recent advances include satellite-based quantum communication networks and efforts to integrate quantum communication systems with existing fiber-optic infrastructure. These developments aim to establish a global quantum internet, enabling secure communication and distributed quantum computing.

Quantum Sensing: Precision Beyond Classical Limits
Quantum sensors exploit quantum phenomena to achieve unprecedented precision in measuring physical quantities such as time, magnetic fields, and gravitational waves. Atomic clocks, which rely on the quantized energy transitions of atoms, are a prime example. They form the backbone of global positioning systems (GPS) and enable synchronization in telecommunications and scientific experiments.

Other emerging quantum sensors include magnetometers for brain imaging, accelerometers for navigation, and interferometers for detecting gravitational waves. These devices promise to revolutionize industries ranging from healthcare to geology.

In medicine, SQUIDs enable high-resolution brain imaging through magnetoencephalography (MEG), aiding in the diagnosis of neurological disorders.

For mineral exploration, SQUIDs help locate underground ore deposits by mapping subtle magnetic anomalies. Their extreme sensitivity makes them invaluable for detecting weak signals, advancing scientific research and technological innovation across multiple fields.

In navigation, their ability to detect minute magnetic field variations improves submarine and spacecraft positioning in GPS-denied environments.

A Superconducting Quantum Interference Device (SQUID), an ultra-sensitive magnetometer, highlighting its applications in medicine, navigation, and mineral exploration.

Challenges and Future Directions

While the potential of quantum technologies is immense, significant challenges remain:

1. ***Scalability:*** Building large-scale quantum systems requires overcoming issues such as qubit coherence, error rates, and hardware scalability.

2. ***Integration:*** Bridging the gap between quantum systems and classical infrastructure is essential for practical applications.

3. ***Resource Demands:*** Quantum technologies often require extreme conditions, such as ultra-low temperatures and high-vacuum environments, posing practical and economic constraints.

To address these challenges, interdisciplinary research combining physics, engineering, computer science, and materials science is crucial. Advances in quantum error correction, novel materials for qubit implementation, and hybrid quantum-classical architectures are paving the way for scalable and robust quantum technologies.

The Role of Fundamental Research

Fundamental quantum research continues to drive technological innovation by uncovering new phenomena and deepening our understanding of quantum systems. Breakthroughs in areas like topological quantum computing, quantum thermodynamics, and many-body quantum systems hold the potential to unlock new applications and capabilities.

Moreover, fundamental research fosters the development of a skilled workforce and the creation of collaborative networks among academia, industry, and government. Initiatives such as national quantum programs and international collaborations are accelerating progress and ensuring that quantum technologies contribute to societal and economic growth.

Conclusion

Fundamental quantum physics research serves as the cornerstone for the rapidly evolving field of quantum technologies. By exploring the principles of superposition, entanglement, and quantization, researchers have laid the groundwork for transformative innovations in computing, communication, and sensing. As we advance into the quantum era, continued investment in fundamental research and interdisciplinary collaboration will be essential to harness the full potential of quantum technologies, addressing global challenges and shaping the future of science and industry.

Main Research Themes, Goals and Activities

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

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

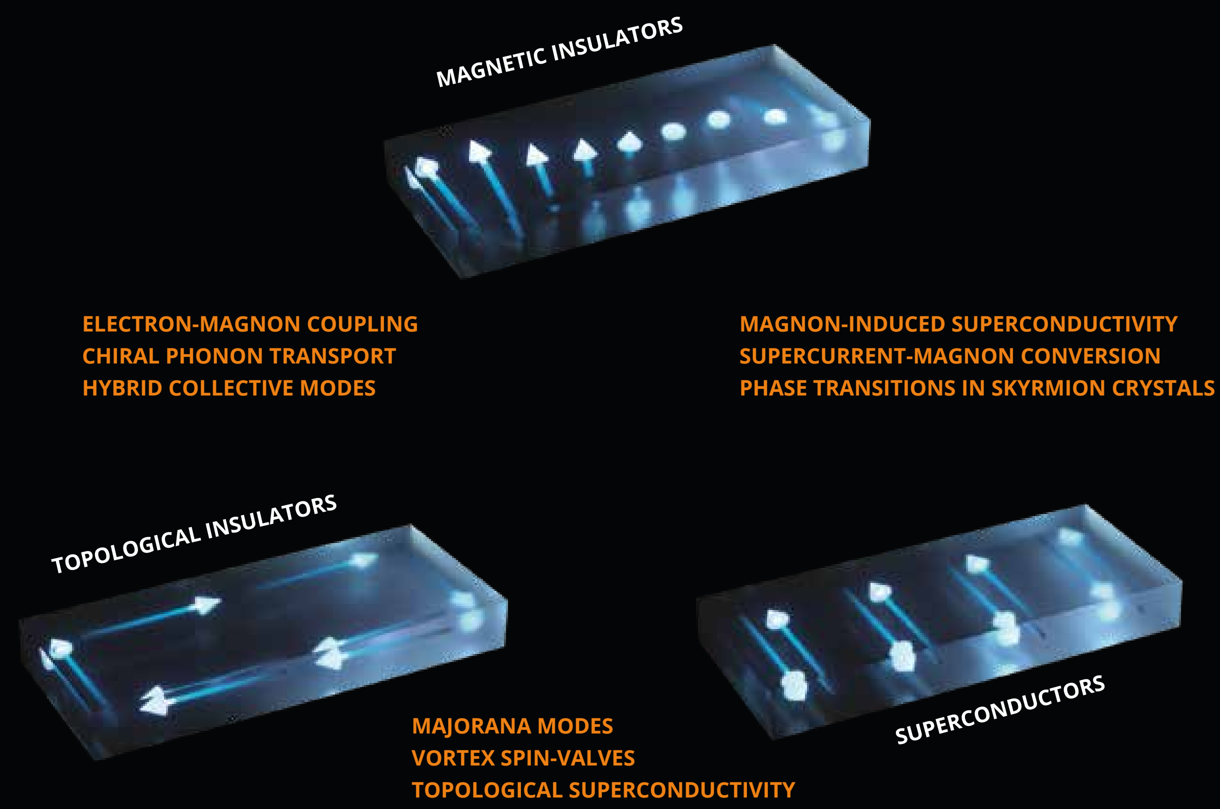
Our unique competitive edge is addressing the ultra-low power innovations by uniting expertise from insulator spintronics, topological matter, and super spintronics. Although these themes are individually exciting, we combine them to generate significant added value.

Electrons can move in free air. In materials, their motion can differ significantly. In metals, the collective flow of the electrons resembles that of particles, but with dramatically altered properties. Their mass, charge, and even spin can be modified. This dressed behavior resembles new particles, so-called quasi-particles, that require new models and new concepts.

We address how such quasi-particles can convey spin information with exceptional tiny energy losses. Also, we 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 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.

Overlapping research themes within the different research areas



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 exceptionally 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.*

ASLE SUDBØ

Topological Quantum Matter

Theme and goal

Topological quantum matter represents a profound domain at the confluence of quantum mechanics and topology, investigating the emergent electronic phenomena in materials that harbor intrinsically nontrivial quantum states. A particularly compelling aspect is the manifestation of nontrivial topological order in the electronic band structure, leading to the emergence of symmetry-protected surface or edge states. These topologically protected states, analogous to quantum anomalies, exhibit resilience against local perturbations and disorder, rendering them promising candidates for fault-tolerant quantum computing and advanced quantum information processing architectures.

In superconductors, electrons form pairs and move without resistance, enabling the efficient transmission of electrical currents. This phenomenon holds immense potential for revolutionizing power transmission and creating advanced electronic devices. Superfluids exhibit zero viscosity, allowing them to flow without any energy loss, and is observed in certain quantum fluids and even in ultra-cold gases. Superconductivity and superfluidity both highlight the extraordinary capabilities of matter when subjected to extreme conditions, offering a glimpse into the quantum world's remarkable and counterintuitive nature.

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 2024

A principal research focus in 2024 has been the exploration of novel quantum computing platforms leveraging quantum spin fluctuations within topological magnetic ground states. Building upon prior investigations from 2022 and 2023 into quantum skyrmion crystals and helical magnetic phases, our work extends to the domain of topologically protected quantum spin liquids. Specifically, we have analyzed and predicted superconducting instabilities in hybrid quantum systems composed of topological quantum spin liquids, such as Kitaev spin liquids, coupled to normal metallic states. Our results establish a more fundamental and less intricate framework for realizing topological superconductivity, in contrast to previous approaches relying on the interplay between skyrmions or helical states and superconducting phases. Notably, our methodology obviates the prerequisite of preexisting superconductivity within the hybrid quantum system, thereby simplifying the conditions necessary for the emergence of topological superconducting states.

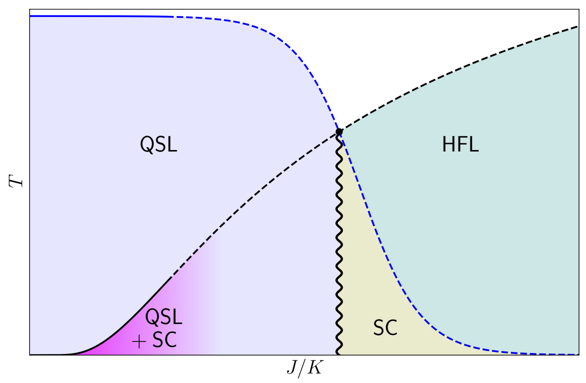


Figure caption: Schematic phase diagram of the system. The quantum spin liquid phase is denoted by QSL and the superconducting state where superconductivity of conduction electrons coexists with the spin liquid phase is denoted by QSL+SC. Beyond the perturbative regime of J/K one finds a heavy Fermiliquid (HFL) and a superconducting phase (SC), both due to the Kondo effect. The wiggly line represents a first-order transition separating the fractionalized Fermi-liquid phase from the nonfractionalized one, due to competing order parameters.

ARNE BRATAAS

Spin Transport and Spin Dynamics

Theme and goal

An electron has a spin in addition to its charge. The mobile charge carriers are the basis of conventional electronics and spintronics. In metals and semiconductors, electric fields induce currents. In magnets, a spin current occurs as well. In superconductors in contact with magnetic materials, charge and spin can flow without dissipation. In insulators, there are no moving charges. Spin information can, nevertheless, propagate. While electrons are immobile in insulators, another entity conveys information. At equilibrium, the electron spins become ordered. In response to external forces, the ordered pattern of the spins can be disturbed. The disturbance can take forms like spin waves or other dynamical spin textures.

We aim to determine how spins in magnetic materials connect to mobile electrons in adjacent semiconductors, metals, or superconductors. One aspect is to replace moving charges with magnetic insulators´ dissipation coherent and incoherent spin excitations. Another is to utilize superconductors in contact with magnetic materials to enable new ways of dissipationless flow of spin and charge. Additionally, coupling THz spin dynamics in antiferromagnets with conductors can facilitate new ways of creating THz electronics. In these systems, we can also enable unprecedented control of electron-electron, electron-magnon, and magnon-magnon interactions. These features can open doors toward creating new paths for magnon and exciton condensation, superfluidity, and superconductivity. Furthermore, since spin signals in these systems 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 even quantum information processing.

Key questions

We focus on the fundamental challenges facing quantum spintronics. Key questions are how spin can transfer from magnetic materials to conductors and superconductors, how far and how spin propagates in insulators, conductors, and superconductors, how we can control electron and magnon correlations that cause new states of matter, and how to detect these phenomena.

Activity in 2024

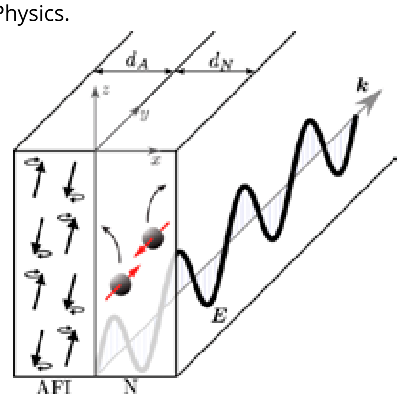
We have revised the Kubo formula for the electric conductivity in the presence of spin-orbit coupling. As a result, the widely used Rashba model provides a finite anomalous Hall conductivity if spin-orbit coupling corrections to the velocity and position operators are correctly considered. These findings have broad implications since other theories of spin-orbit coupling-related effects should be modified similarly.

We theoretically demonstrate that an easy-axis magnetic anisotropy facilitates magnon condensation in thin yttrium iron garnet (YIG) films. Our results may explain the recent experiment on Bi-doped YIG and open a pathway toward applying current-driven magnon condensation in quantum spintronics.

We have also studied how magnons and plasmons interact in antiferromagnet-semiconductor bilayers.

Finally, we have also participated in other developments with partners at QuSpin, such as currents and super-currents in altermagnets and p-wave ferromagnets.

We have published nine papers: one in Physical Review Letters, four in Physical Review B, two in Physical Review Research, one in the New Journal of Physics, and one in SciPost Physics.



An antiferromagnetic insulator in contact with a semiconductor. The spins in the antiferromagnet and the electrons in the semiconductor interact with each other and the electromagnetic field, determining the behavior of the polariton.

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 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 super-conductors. 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, new physics can emerge that is more than just the sum of properties of the materials. This is one of the motivations behind the field of superconducting spintronics where one studies spin-dependent quantum effects in superconductors.

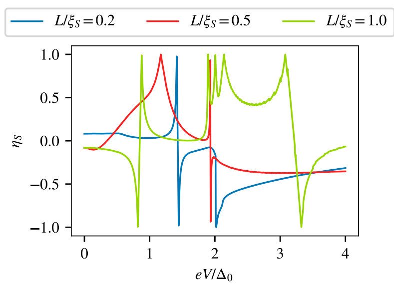
Two main goals guide our research. The first one is to discover new quantum phenomena that transpire when combining superconductors with materials that have fundamentally different properties, such as magnetic ones. Secondly, we focus on discovering phenomena that are relevant to the development of cryogenic information transfer, generation, and storage based on super-conductors. This is closely related to the transport of charge, spin, and heat in hybrid structures. 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 research problems we are focusing on solving are related to the functional properties of materials and how they can be controlled and altered by combining several materials or by applying external stimuli. For instance, is it possible to use magnetic materials to control when superconductivity appears and even enhance its properties? How can one use superconductors to generate and detect transport of not only charge, but also other degrees of freedom such as spin and heat, with minimal energy loss? Finally, we are interested in understanding the quantum dynamics of various types of long-range order in solid-state systems when quenches are applied in interaction parameters, to see if novel meta-stable quantum phases can be accessed.

Activity in 2024

Our research this year had altermagnets and p-wave magnets as a major focus. For instance, we predict that altermagnets develop a finite magnetization near interfaces and that when combined with superconductors they provide dissipationless spin-splitter and spin-filtering effects. We also studied triplet superconductors and revealed unique signatures in how their critical temperature can be magnetically controlled as well as the inverse phenomenon: such superconductors can be used to tune spin-spin interactions. Moreover, we continued our collaboration with experimentalists on cryogenic thermoelectrics and found that superconducting spin-valves can yield tunable Seebeck-coefficients with a large change in magnitude upon magnetic switching. We published 20 papers in 2024, including two papers in Physical Review Letters and one in Reviews of Modern Physics.



We predict that it is possible to generate an electrically tunable spin-diode effect with ideal efficiency by using superconductor/ ferromagnet multilayers.

HENDRIK BENTMANN

Spectroscopy of Quantum Materials

Theme and goal

The recent decades have seen the rise of modern information and communication technologies, largely based on the use of semiconductors in transistors and integrated electronic circuits. This era is sometimes referred to as the „silicon age", highlighting the importance of the material silicon in this context. The properties of silicon are well understood on fundamental grounds. However, there are classes of materials whose physical behaviour is vastly more complex and less understood, including superconductors, magnets, and topological systems. In these „quantum materials" the quantum-mechanical nature of the electrons and their mutual interactions come to the forefront and remain manifest over a wider range of energy and length scales. Researchers envision that proper control of these quantum effects and resolving some of their puzzles could enable new technologies beyond the silicon age. Understanding the physics of quantum materials is challenging, however, and involves the development and application of sophisticated experimental and theoretical techniques.

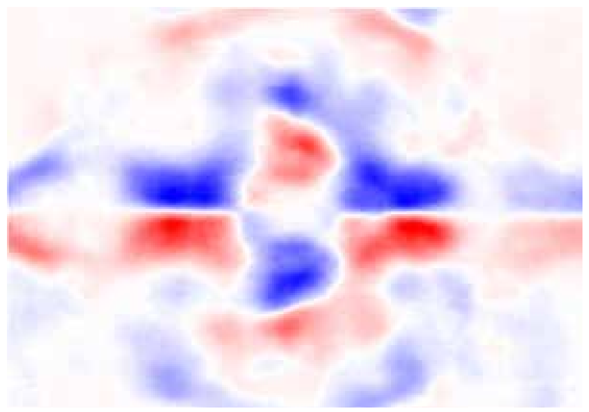
We use a method called spin- and angle-resolved photoelectron spectroscopy (spin-ARPES) to investigate magnetic and topological materials. Spin-ARPES is based on the photoelectric effect, i.e. the excitation of photoelectrons at a material surface upon irradiation with monochromatic light. The effect has long been known and constitutes one of the key observations that paved the way from classical electrodynamics to quantum mechanics. Use of modern spectrometers and light sources allows us to study the spatial, angular and spin distributions of photoemitted electrons as well as their dependence on energy and polarization of the exciting light, providing detailed information about electronic and magnetic properties. With this, our goal is to contribute to the discovery and to a refined microscopic understanding of quantum states in new and complex materials.

Key questions

Our primary focus lies on the investigation of electronic states with so-called topological properties which give rise to unusual spin textures in momentum space. We are interested in how topological properties and spin textures are related to or modified by ferromagnetic or antiferromagnetic order, specific crystalline symmetries, quantum confinement in atomically thin crystals and proximity coupling in heterostructures. Spin-ARPES allow us to directly address these points experimentally. Our experiments are performed in the laboratory at NTNU and at international synchrotron radiation facilities, such as PETRA III at DESY (Hamburg).

Activity in 2024

We have expanded the experimental activities and published the group`s first article, reporting on circular dichroism and orbital physics in chiral crystals. After long downtime, our momentum microscope is operational, and our focus is on commissioning, testing and optimizing the imaging spin filter. We are also in the early steps of commissioning a UV laser as a new light source at our momentum microscope. In addition to our work in the laboratory, we carried out successful experiments on superconducting topological semimetals and magnetic oxides at the synchrotron facilities PETRA III (Hamburg, Germany) and HiSOR (Hiroshima, Japan).



Circular dichroism in the angular distribution (CDAD) of photoemitted electrons for a topological semimetal, probing the chirality of Weyl nodes in the band structure.

CHRISTOPH BRÜNE

Molecular Beam Epitaxy of Antiferromagnets

Theme and goal

In the MBE lab we investigate the growth of new materials with promising magnetic and topological properties. The use of molecular beam epitaxy as our main growth technique allows us to synthesize high-quality crystalline thin films of these materials as the basis for further studies. Access to such high-quality materials is vital for future research and applications.

Key questions

Currently we are focusing our work on the growth and investigation of antiferromagnetic materials. We are mainly working with two material classes: antiferromagnetic semiconductors and antiferromagnetic kagome materials.

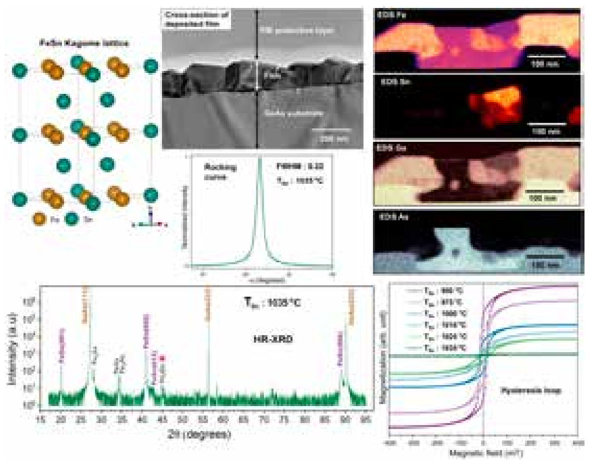
Antiferromagnetic semiconductors combine the potential for new spintronics applications with the possibility to manipulate the material properties using electric fields – similar to today's semiconductor technology. This will enable the integration of established semiconductor techniques and spintronics applications. Our material of choice is $CuFeS_2$, an antiferromagnetic semiconductor with a very high Néel temperature of 823 K. This work is done in collaboration with Arne Brataas' and Mathias Kläuis' group in QuSpin. We are also collaborating with Morten Kildemo and Magnus Nord for optical and structural studies of our thin films.

The kagome materials are very interesting because of their complex electronic bandstructure as well as their fascinating magnetic structure due to the frustrated magnetism that is an inherent property of kagome lattices. The complex band structure in these materials supports Weyl and topological surface states together with flat band and Van Hove singularity type features. Thus these materials potentially combine topological properties and correlated electron transport. In addition to this part, the magnetic structure supports skyrmions and helimagnetic phases. The combination of these physical features makes these materials highly interesting for research. However, the synthesis of (especially antiferromagnetic) kagome materials is difficult and the growth of high-quality, single crystalline thin films has been challenging so far. Synthesizing such high-quality thin films is therefore one of our key goals. We are developing the growth of both FeSn and Mn_3Sn in thin film form. These are both antiferromagnetic metals in which Fe or Mn crystallize in a kagome lattice. These investigations are conducted in close collaboration with Dennis Meiers' group, with two PhD candidates shared between the two groups.

Activity in 2024

In 2024 we mainly focused on the growth of kagome thin films. We explored substrate choice, fine-tuning of the growth parameters (particularly fine control of flux of constituent materials during growth) and in-situ annealing. This has rendered us the growth of single crystalline thin films of both FeSn and Mn_3Sn. These are two major achievements and we are currently working with the publication of several papers on these subjects.

As for the $CuFeS_2$ thin films, we have concentrated on growth start investigations, increase of maximum layer thickness and further optimization of the films. We are hoping to reach very high thin-film quality and enable lithography and device fabrication based on our thin films. Ultimately, we would like to study transport and bandstructure properties using lithographically structured devices.



Growth of FeSn on GaAs substrates: interaction with the substrate and suppression of unwanted ferromagnetic phases (P. Chatterjee et al. https://doi.org/10.1116/6.0004238)

JEROEN DANON

Semiconductor-based Quantum Technologies

Theme and goal

We do theoretical research on solid-state quantum devices, including semiconductor spin qubits, certain types of superconducting qubits, topologically protected qubits, gate-tunable Josephson junctions, and superconducting diodes. The long-term goal in this field is the realization of disruptive quantum technologies such as fault-tolerant quantum computing and more accurate quantum sensing.

In many solid-state quantum devices, an important role is played by semiconducting components. The precise control over the carrier density that most semiconductors offer, combined with the often strong and tunable spin-orbit coupling they induce, makes them versatile building blocks for a plethora of applications: In the ultra-low-density regime, single electrons or holes can be isolated for the purpose of using their spins as qubits; in this context the presence of strong spin-orbit coupling provides efficient ways of electrical qubit control. In combination with superconducting elements, semiconductors can be used to create highly tunable Josephson junctions, where the spin-orbit coupling can yield an unconventional current-phase relationship (potentially useful for creating protected superconducting qubits and superconducting diodes), or to realize effective topological superconductivity, which should host non-Abelian anyonic excitations that could be used to encode topologically protected quantum information.

Our goal is to understand the complex dynamics of cutting-edge semiconductor-based quantum devices, often in collaboration with world-leading experimental groups, and try to use that understanding to predict, design, and develop new functionalities in the next generation of devices. In parallel, we started investigating machine-learning techniques for tuning and control of more complex quantum devices as well as for quantum sensing applications.

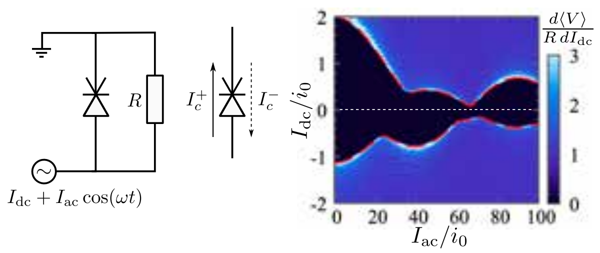
Key questions

The questions my group is currently working on are quite diverse, a few examples are the following: How can we improve quantum coherence properties of spin qubits or superconducting qubits, by smart choice of material platform, advanced device design, or machine-learning-assisted operation methods? How could we scale up so-called "artificial Kitaev chains" to a size that yields topologically protected zero-energy end modes? What kind of new quantum-device functionalities could result from using hybrid structures including superconductors and lower-dimensional hole gases?

Activity in 2024

The most important contributions from my group in the past year are (i) a detailed roadmap for the further theoretical and experimental development of the artificial Kitaev chain, which could potentially enable topological quantum computation, (ii) the realization of highly tunable Josephson junctions in germanium-based hole gases, (iii) a demonstration of real-time estimation of fluctuating Hamiltonian parameters in a spin qubit, and (iv) an understanding of the role of AC current driving for the manifestation of the superconducting diode effect in Josephson junctions.

We published 9 papers in 2024, including two in Nature Communications, one in PRX Quantum, and one in Physical Review Letters.



The IV-characteristics of a harmonically driven superconducting diode reveal a strong tunability of the diode efficiency through the driving strength.

EXPERIMENTALISTS AT WORK

The team in action in the ARPES lab.

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 2024
In collaboration with Huan-Qiang Zhou at Chongqing University and others, the activities included studies of the entanglement entropy of the 1D ferromagnetic Tasaki model and an entanglement perspective on fractals in various models with spontaneous symmetry breaking with type-B Goldstone modes. Other activities, in collaboration with master students, included a group-theoretical description of the ground-state order in the toric-code and double-semion models and an ongoing investigation of the entanglement entropy in Kitaev models.

ERIK WAHLSTRÖM

Probing Local and Global Magnetodynamic Properties

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

Our short-term goal is to explore the magnetoelectronics and magnonics of oxide ferromagnets and antiferro-magnets. 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 long-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
We primarily study the excitations and coupling between magnons, phonons and charge carriers at an energy scale that ranges from sub-thermal energies to electron volts. In the spin domain, the prime motive is to understand magnons, and the expression in the form of 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 seeking collaboration with groups on the material synthesis side to address our key questions.

Activity in 2024
We have continued our project on phonon-magnon coupling in oxide heterostructures. Travis Gustafsson was the first to join our team as PhD candidate. He has worked hard within the project with a main focus on establishing a versatile platform for electric measurements on combined surface acoustic wave and magneto dynamic wave mixing. The staffing up of the project has continued with the hiring íf Payel Chatterjee during 2024, to increase the activity within film-growth and our planned collaboration around optical characterisation with Professor Chiara Ciccarelli in Cambridge. During the autumn the activity was considerably enhanced with the start-up of Shubankar Mishra and Oleg Kurnosikov finalising the design of point-contact/RF/STM dip-stick STM for our PPMS system. Work that has been done jointly with Associate Professor Toshu An in JAIST, Japan. The progress has been good and we expect the system to produce results on 2D and metal-oxide based systems during 2025.

DENNIS MEIER

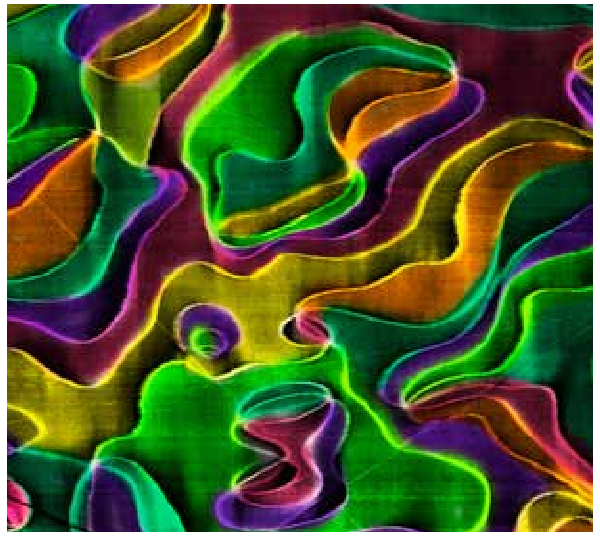
Topological Spin Textures

Theme and goal

Topological spin textures, such as domain walls, magnetic dislocations and skyrmions, exhibit emergent physical phenomena and hold great promise as functional nanoscale systems for low-energy information processing and data storage. Application opportunities range from logic gates and memory devices to innovative concepts for unconventional computing. Our research studies the fundamental physics that give rise to the unique properties and dynamical responses of topological spin textures in ferroic materials. We are particularly interested in the unusual local responses of these special magnetic entities, and how they can be utilized in future devices.

Key questions

Many developments in the field have occurred only recently, and it has become clear they only scratched the surface regarding topological textures that form in magnetically ordered materials. Specifically, controlling such textures remains a major challenge. We investigate new magnetic materials that host topological spin textures at the nanoscale, with a focus on spin-spiral systems. For this purpose, we apply micromagnetic simulations in combination with different microscopy and nanostructuring methods, such as magnetic force microscopy (MFM) and focused ion beam (FIB), working towards first proof-of-concept devices. For example, we use FIB to shape materials of interest into device-relevant structures. Based on these structures, we study, e.g., the impact of reduced physical dimensions on the magnetic order and how electrical currents and magnetic fields control the position and movement of individual spin textures. Ultimately, we want to understand the new degrees of flexibility topological spin textures can offer and demonstrate new opportunities that arise for future applications, including Green-IT (i.e. low-power technologies) and modern concepts for unconventional computing.



Network of topological defects in multiferroic hexagonal manganites.

Activity in 2024

Highlights in 2024 were the activities related to our Marie Skłodowska-Curie Actions Doctoral Network "TOPOCOM" (Topological Solitons in Ferroics for Unconventional Computing), which is funded via the European Union's Horizon 2020 research and innovation programme. The programme is now up and running with 11 international doctoral candidates from seven countries. We organized and hosted one workshop for the TOPOCOM members in Trondheim in June 2024 and co-organized a second one in Messina, Italy, in December 2024, combined with the PETASPIN 2024 School. Together with our academic and industrial partners, we offered various lectures, educating our students about modern materials- and computing-related questions. The scientific part *(Training through Research)* was complemented by advanced transferable business and cultural skills training *(Training for Life)*, providing a unique training programme at the forefront in unconventional computing based on electric and magnetic solitons. TOPOCOM was featured in GEMINI ("Smart samarbeid for framtidas teknologi") and we also wrote a perspective article on the topic, entitled "Topological magnetic and ferroelectric systems for reservoir computing", which has been published in Nature Reviews Physics.

SOL H. JACOBSEN

Triplet Spintronics

Theme and goal

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

Key questions

Our research considers atypical geometries and model setups for examining the conversion mechanisms, manipulation and detection of superconducting singlets and triplets in spintronic devices, including magnets. We primarily consider the effect of curvature and/or strain, as well as cavity-mediated effects, which may enable new superconducting spintronic device design and control.

Activity in 2024

This year, we consolidated our investigations into superconducting spin transport along geometrically curved wires [1-3], and began to expand the theoretical framework to curvilinear thin films [4]. Using wires that have both curvature and torsion, we found that differential conductance measurements can indicate the quality of a buried, uncompensated antiferromagnetic edge [1]. We also suggested a design for an electrically controlled superconducting spin valve, where torsion is controlled by a piezoelectric substrate (see figure) [2]. The video abstract of our study of mixed-chirality junctions [3] was featured on several social media platforms, as part of the Journal of Condensed Matter's Emerging Leaders of 2023 collection. We also featured in the European Magnetism Association's online campaign for the International Day of Women and Girls in Science.

Our article showing that circularly polarized light gives a dichroic response when the cavity contains a spin-split material was published as a Letter in PRB [5]. This provides a mechanism for non-invasive cavity engineering, as well as a novel way to estimate a material's exchange splitting in equilibrium. We are also excited to announce that we find strong photon coupling to antiferromagnetic magnons via topological insulator surface states [6].

2024 also featured a whirlwind European tour of invited talks on both cavity and curvature systems, from the ICM in Bologna, New Avenues in Quantum Materials in Gothenburg, Magnons on an Island in the Netherlands, the Chalmers and Tübingen seminar series, and of course the QuSpin international conference. The increasing visibility has been extremely useful in finding researchers with aligned goals, and in 2024 several of us got together to plan (and apply) to start a European Doctoral Network on spintronic effects of geometric curvature and strain.

I am delighted that all three of last year's Master students from our group (Henrik Kaarbø, Maxim Tjøtta & Kjell Heinrich) are now going on to pursue a Ph.D., and wish them all the very best. Our wonderful postdoctoral researcher Henning Hugdal left the group in 2024 to pursue other opportunities, and we thank him for a decade of fascinating discussions, collaborations and friendship.

Finally, I am very happy to announce my successful application to the Norwegian Research Council, who awarded 12 million NOK to the SUPERFLEX project, starting late 2025. It means we will be hiring two researchers, and it will allow us to explore many exciting opportunities over the next few years.

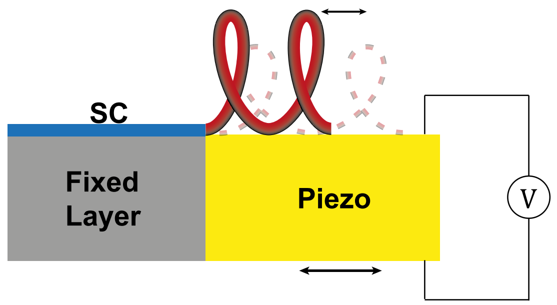


Illustration: Electrically controlled superconducting spin valve, using a ferromagnetic wire helix [2]. Fig. by T. Salamone.

[1] Phys. Rev. B 109 (9), 094508 (2024). [2] Appl. Phys. Lett. 125, 062602 (2024). [3] J. Phys.: Condens. Matter 36 235302 (2024). [4] arXiv preprint: 2412.07529. [5] Phys. Rev. B (Letter) 110, L161102 (2024). [6] arXiv preprint: 2410.14780.

Website: sites.google.com/view/soljacobsen
Social Media: @SpintronicMum

ALIREZA QAIUMZADEH

Emergent Phenomena in Quantum Matters

Theme and goal

Our group conducts basic research over a wide swath of *theoretical* and *computational* condensed matter physics, including *quantum spintronics and magnetism* (topological magnetic textures, superconducting spintronics, and neuromorphic spintronics); *quantum transport phenomena; topological phases of matter and quantum matter; ultrafast and nonequilibrium phenomena; and quantum field-theory of many-body systems.* Our goal is to understand and engineer emergent and exotic phenomena in novel quantum materials, such as 2D magnetic materials and topological materials. We are also interested to investigate potential application of these phenomena in quantum technology. Novel quantum materials have exotic and interesting behaviours. For example, in 2D systems, quantum fluctuations and interactions are usually strong and cannot be neglected. On the other hand, in novel 3D topological materials, such as Weyl and Dirac semimetals, emergent low-energy massless quasiparticles provide a testbed for investigation of new phenomena beyond conventional relativistic quantum field theory and the Landau Fermi liquid paradigm. Developing theories to predict and explain exotic equilibrium and nonequilibrium states of novel quantum materials with an ultimate application beyond the state-of-the-art quantum devices are among our goals.

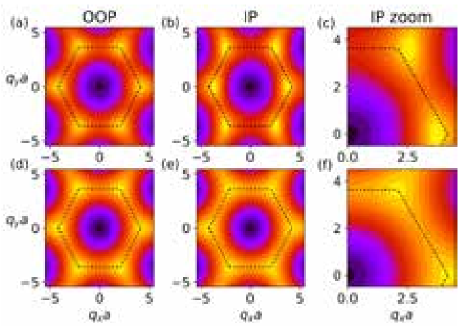
Key questions

The interplay between charge, spin, orbital, and lattice degrees of freedom, along with hybridization and scattering among quasiparticles and collective excitations—such as magnons, spinons, phonons, and plasmons—drives a wide range of emergent phenomena in quantum materials. Understanding these phenomena at the microscopic level is a fundamental challenge in theoretical physics, requiring advanced analytical and computational techniques. Our research aims to uncover the role of quantum and thermal fluctuations in stabilizing nontrivial magnetic phases, exploring exotic transport properties, and discovering novel functional intelligent materials and exotic phases of matter.

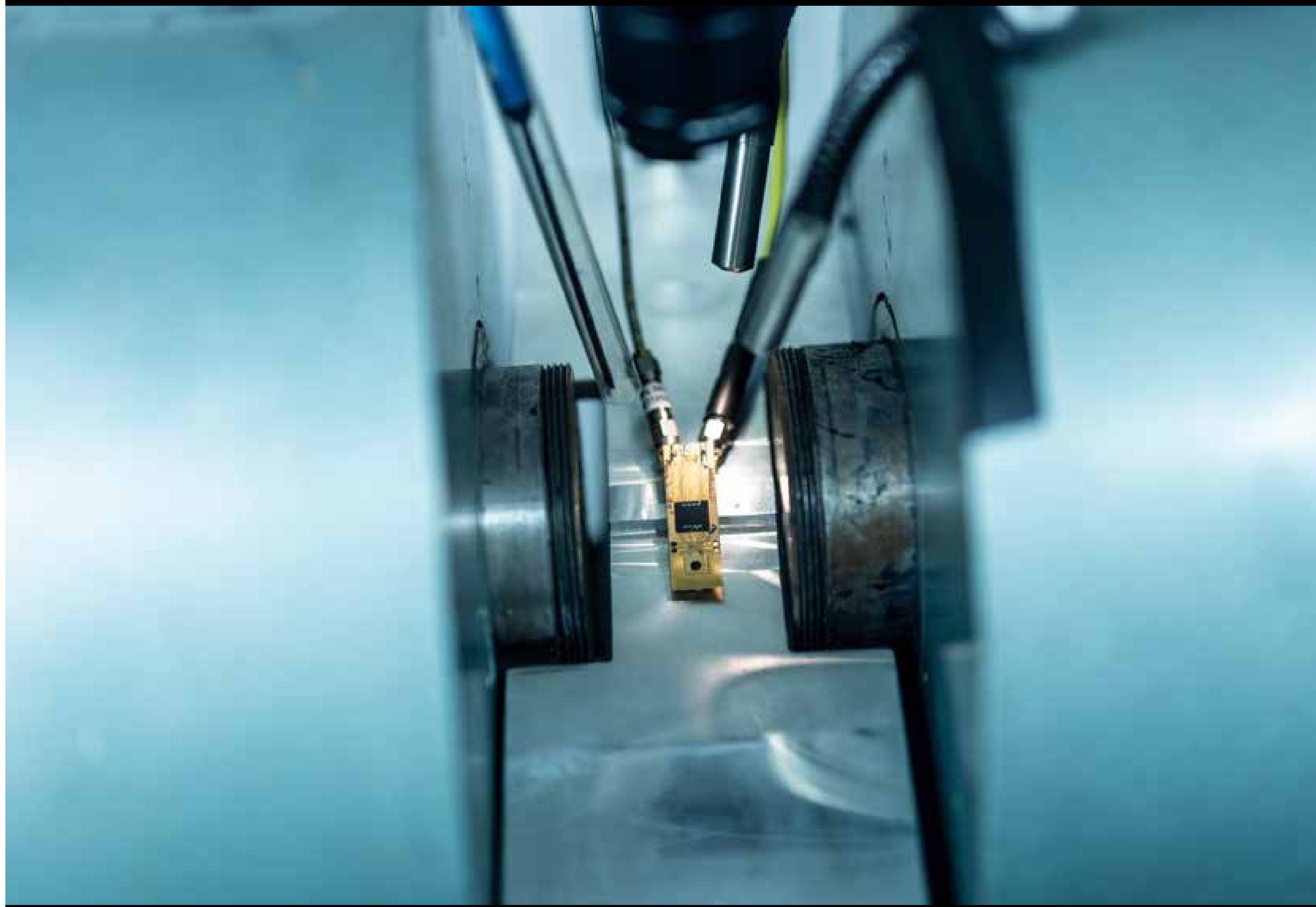
Activity in 2024

In 2024, our group published seven papers and presented the results in more than 10 international conferences, as either invited or contributed talks. Furthermore, our 12 MNOK (€1.02 million) research proposal, titled *"Unconventional Thermoelectric Quantum Transport in Novel 2D Magnetic Heterostructures,"* has been successfully funded by RCN for the period 2025–2029. In December, we were invited by Professor Tenghua Gao of Wuhan University of Technology in China to start a new collaboration with his recently established experimental group, focusing on 2D magnetic materials and orbitronics phenomena. In this year, we continued our collaboration with Professor Arne Brataas as our main internal collaborator and several other world-leading experimental and theoretical groups. Our group submitted four master's theses in June and one specialization project in December.

In collaboration with our PhD candidate, Verena Brehm, and our colleagues from the UK and Poland, we published two papers, in which we proposed a method to engineer topological magnons in 2D magnetic systems and we studied magnon transport in these systems. In two other articles, in collaboration with our Polish partners, we studied skyrmion-induced topological spin and charge currents in both compensated and canted antiferromagnets. In another collaboration with our colleague in Iran, we examined the effect of order parameter orientation on optical conductivity and magnetic dichroism of 2D antiferromagnetic Dirac semimetals. In collaboration with our colleagues from Germany, we uncovered the role of the magnetic anisotropy on magnon BEC. Finally, in another research direction, we studied magnon-plasmon polaritons in antiferromagnetic—semiconductor heterostructures.



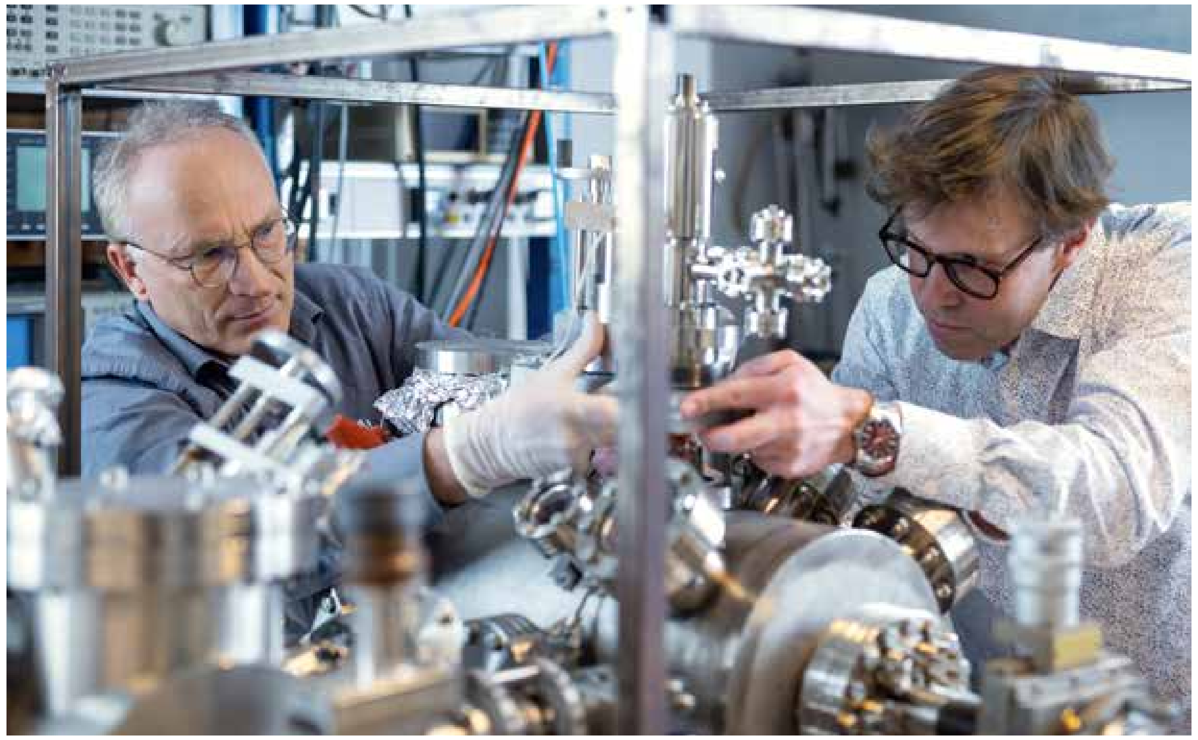
[Phys. Rev. B 109, 174425 (2024)]



General radiofrequency set-up for base characterization mixed spin-wave/acoustic wave transport and magneto-dynamic properties of samples.

EXPERIMENTALISTS AT WORK

The team in action in the Local and Global Transport and Excitation Spectroscopy lab.



International Partners and Research Network

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

Professor Mathias Kläui

Professor Mathias Kläui is a leading experimental scientist, and a Professor II at QuSpin. A central theme of the collaboration has been spin transport in antiferromagnetic insulators, where we have established fruitful synergies between experimental and theoretical developments. Combining the work of young and dynamic experimentalists in Trondheim and Mainz, with the support of our excellent theory activity, QuSpin is taking its experimental activity to the next level. In particular, the collaboration with JGU Mainz gives QuSpin access to state-of-the-art materials growth, characterization and transport measurements. Recently, exciting predictions on magnetic 2D materials have been corroborated in joint activities between Mainz and Trondheim. To strengthen our collaboration, joint PhD work where students from Mainz spend some time in Trondheim has recently started further support from a joint EU project between QuSpin members in Trondheim and Mainz.

Professor Rembert Duine

Professor Rembert Duine is a leading theoretician scientist in the quantum many-body physics of spin transport and spin excitations, and a Professor II at QuSpin. Landmark publications by Rembert Duine and his collaborators have led to the opening of new subfields 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. Most of the collaboration over the past year have focused on orbital magnetization.

The QuSpin Center is grateful for its opportunities to host visiting researchers that allow for interactions on a personal level, bolstering the professional work and exposure to new, ongoing, and past projects. In addition, we collaborate with internationally leading theoretical and experimental groups in many places around the world (See map next page).

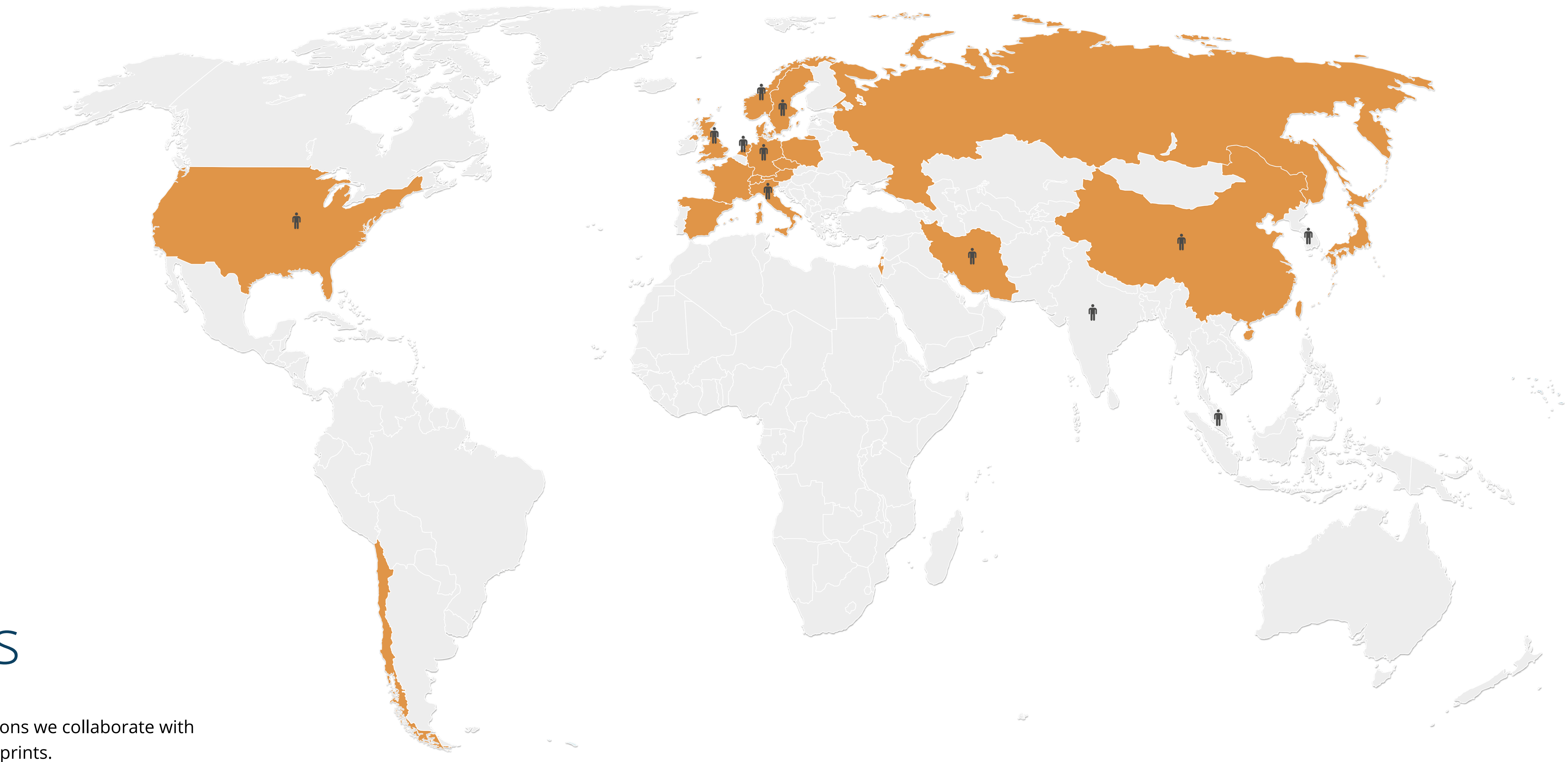
THE RESEARCH TEAM OF PROFESSOR MATHIAS KLÄUI *is part of the Institute of Physics at Johannes Gutenberg-Universität Mainz with more than 50 faculty members and more than 300 members in total. The Kläui lab has 10 permanent staff and about 50 members including junior researchers and staff in total.*

THE GROUP OF PROFESSOR REMBERT DUINE *at the Institute for Theoretical Physics (ITP) is part of the Department of Physics, at the Science Faculty at the Utrecht University. The ITP hosts over 10 faculty members and 70 members including junior researchers in total. Professor Duine's group has one permanent staff, one Postdoc and 4 PhD candidates, as well as master and bachelor students.*

Countries with collaborators

Nationality of our staff members

China	Norway
Germany	South-Korea
India	Sweden
Iran	The Netherlands
Italy	United Kingdom
Malaysia	USA



Collaborators

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

AUSTRIA
Graz University of Technology, Graz

CHILE
Universidad Adolfo Ibáñez, Santiago

CHINA
Beijing University of Technology, Beijing
Central South University, Changsha
China Academy of Engineering Physics, Beijing
Chinese Academy of Sciences, Beijing
Chongqing University, Chongqing
National Tsing Hua University, Hsinchu
Shenzhen University, Shenzhen
Southern University of Science and Technology, Shenzhen
University of Chinese Academy of Sciences, Beijing
Wuhan University of Technology, Wuhan

CZECH REPUBLIC
Czech Academy of Sciences, Prague
Wuhan University of Technology, Wuhan

DENMARK
University of Copenhagen, Copenhagen

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

GERMANY
Deutsches Elektronen-Synchrotron (DESY), Hamburg
Fritz-Haber-Institute of the Max-Planck Society, Berlin
Johannes Gutenberg University Mainz, Mainz
Karlsruhe Institute of Technology, Karlsruhe
Leibnitz Institute, Dresden
TU Kaiserslautern, Kaiserslautern
Technical University of Munich, Munich
University of Augsburg, Augsburg
University of Cologne, Cologne
University of Kiel (Germany)
University of Konstanz, Konstanz
University of Regensburg, Regensburg
University of Würzburg, Würzburg
Walther Meissner Institute for Low Temperature Research, Munich

HONG KONG
The Hong Kong Polytechnic University, Hung Hom, Kowloon

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

ISRAEL
Hebrew University of Jerusalem, Jerusalem

ITALY
Università di Milano-Bicocca, Milan
University of Bologna, Bologna
University of Genova, Genova
University of Salerno, Fisciano

JAPAN
Keio University, Tokyo
RIKEN Center for Emergent Matter Science, Saitama

NORWAY
University of Oslo, Oslo

POLAND
Adam Mickiewicz University, Poznań
Institute of Nuclear Physics, Polish Academy of Sciences, Krakow

ROMANIA
Technical University of Cluj-Napoca, Cluj-Napoca

RUSSIA
Russian Academy of Sciences, Moscow
Skolkovo Institute of Science and Technology, Moscow

SINGAPORE
Department of Physics, National University of Singapore

SPAIN
Donostia International Physics Center, Donostia-San-Sebastian
Instituto de Ciencia de Materiales de Madrid (CSIC)
Institute de Física Fundamental, Madrid
Universidad Autónoma de Madrid, Madrid

SWEDEN
KTH Royal Institute of Technology, Stockholm
Uppsala University, Uppsala

SWITZERLAND
ETH Zürich, Zürich

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

UK
Cambridge Graphene Centre, Cambrigde
Hitatchi Cambridge Laboratory, Cambrigde
Loughborough University, Loughborough
Swansea University, Swansea
University of Cambridge, Cambridge
University of Central Lancashire
University of Edinburgh
University of York, York

USA
Cubic Carbon Ceramics, Huntingtown
Department of Physics and Astronomy, University of Missouri
Harvard University, Cambridge, MA
Massachusetts Institute of Technology, Cambridge
National High Magnetic Field Laboratory, Tallahassee
University at Buffalo, State University of New York
University of California, Berkeley
University of California, Riverside
University of Central Florida, Orlando
University of Chicago, Chicago

Research Training of our PhD candidates and Postdocs

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

Glimpses from various collaboration settings at our center.

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

We organize a range of workshops and seminars at the Center where the speakers present their work, share ideas and discuss the challenges they face. Our regular Journal Club provides training in presenting a scientific article and its essence for discussion. These are valuable experiences in the process of their work and in writing articles for publication as well as giving talks at international conferences and workshops.

In addition, interesting talks by guest researchers give us an opportunity to extend our understanding of ongoing work by colleagues, and opportunities for fruitful collaborations.

In the self-organized Idea Forum, younger researchers share projects, ideas, and research challenges, stimulating collaboration across the theoretical and experimental fields, as well as between PhD candidates, Postdocs and researchers.

Excellent research deserves excellent communication. Scientific presentations should be understandable, engaging and memorable. In 2024, we offered all levels of staff at QuSpin, from professors to PhD candidates, intensive workshops where they trained on all aspects of public speaking and practised giving constructive feedback to each other. The goal was to strengthen their creative confidence and to encourage them to develop their own unique, personal presentation style – always with the memorability factor in mind.

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

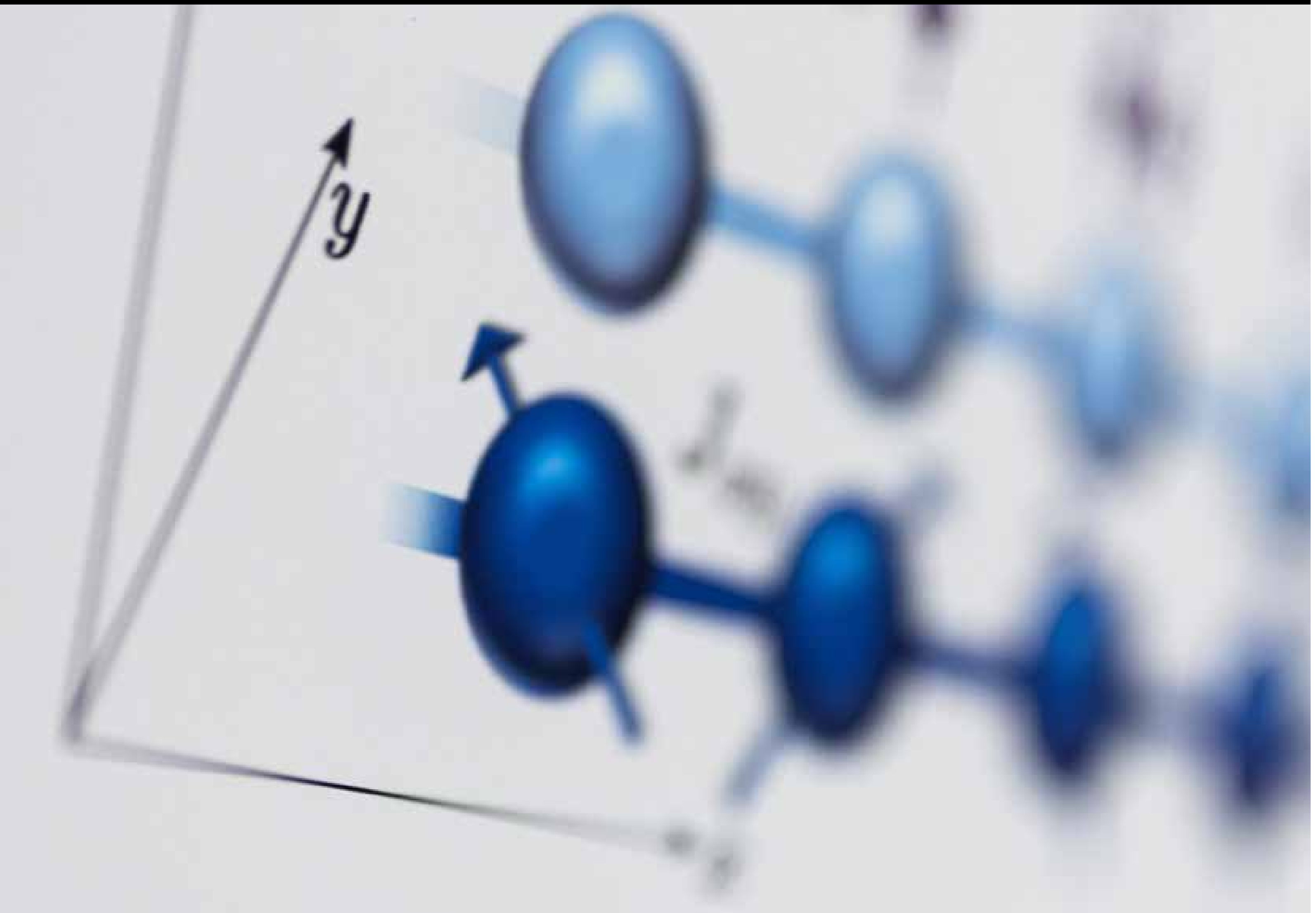


Photo from an illustration by PhD candidate Niels Henrik Aase from one of our scientific articles. The illustration shows superconducting instabilities, in coupled one-dimensional electron systems that now can be realized in the laboratory, are studied theoretically at QuSpin.

The QuSpin Mobility Grant

Encouraging our PhD candidates to seek international research experience, broaden their cultural outlook and extend their network.

In 2022 we established the QuSpin Mobility Grant which our PhD candidates can apply for in connection with research stays abroad if their application provides a clear explanation on how the research stay will benefit their current project and QuSpin.

The purpose of this grant is to learn and transfer research methods or techniques relevant to the project and QuSpin as a whole. We emphasize that these research stays should create stronger professional relationships between the host, the PhD candidate and QuSpin, and that it should result in a joint publication.

The grant will typically cover travel and accommodation costs. Candidates can apply for financial support for up to three months for a research stay. After the completion of the research term the applicant is required to present findings and experiences during the annual research conference. In addition, a presentation will be required at the Center and on our webpage.

Two PhD candidates applied and received the QuSpin Mobility Grant for 2024, namely PhD candidate Stefanie Brinkman travelling to Japan and PhD candidate Jacob Benestad travelling to Denmark and the Netherlands.

PhD Candidate
Stefanie Brinkman off to Japan.

PhD Candidate
Jacob Benestad off to Denmark and the Netherlands.

Stefanie's Journey to Japan

My motivation
My motivation for applying for this grant was my wish for a longer stay in a new country, to explore a different research environment in a different culture, and to visit laboratories where we could perform experiments that are complementary to the ones we do in our ARPES lab in Trondheim or the synchrotron lab in Hamburg.

The process from idea to action
My supervisor Hendrik Bentmann pointed me towards Japan, which is the place to be for photoemission experiments. He opened doors by contacting researchers in his network to make arrangements for me to visit as a guest researcher. Our applications for beam times, which was the main point of the stay, were approved.

I had the opportunity to see different labs, which also allowed me to travel around quite a bit. In September I visited Professor Kazuyuki Sakamoto in the Surface Physics research group at Osaka University, in October Professor Kenya Shimada at HiSOR (Research Institute for Synchrotron Radiation Science) in Hiroshima, and finally Professor Fumihiko Matsui at the Institute for Molecular Science at UVSOR (Ultraviolet Synchrotron Orbital Radiation Facility) in Okazaki.

Experiencing new research culture, collaboration and supervision
Apart from my Malaysian QuSpin colleague Xin Liang Tan, I mostly worked together with Japanese researchers. We had beam time with long stretches in the lab, and nice lunch breaks on campus. I found it easy to approach scientists and professors. People were eager to help, and they were very structured and meticulous.

The communication was a bit difficult at times because of the language. So sometimes I just talked via the Google Translate app on my phone and they were doing the same. The working culture seemed different from the work-life balance in Norway. Japanese PhD students told me they have few holidays and it is sometimes even frowned upon to actually take them.

Experiences from a different country, society and social life
I was fascinated by many things in Japan. With many people gathered in the cities it sometimes felt too crowded for me. But as a woman travelling alone, I always felt safe. I really liked the transport system, and everything is very clean. The society is very developed but not as digital in daily life as I would have expected: they still use paper train tickets, for example . I visited old temples and the Peace Memorial Park in Hiroshima, and the beautiful islands with lots of nature and wild deer were a nice way to escape the crowds. The hotsprings were a fantastic treat. Xin and I had many dinners and lunches together with people from the various research groups. Everyone was also helpful in giving us recommendations for activities.

Challenges and joys
Being a vegetarian proved to be a challenge since almost every dish contained meat. To get enough nutrition I just ate like a non-vegetarian. We also struggled with some technical difficulties in one of the labs at HiSOR. The best thing was meeting people and experiencing different ways of doing things, and building an international network. The stay has contributed to multiple running projects that will hopefully lead to publications.

My advice to other PhD candidates
Don't hesitate, grab the opportunity a Mobility Grant can give you. It can seem a bit scary to be alone in a new country, but that is very overcomable as long as you are open to new experiences. I was very happy I got the chance to do this!

Jacob's Journey to Denmark and the Netherlands

My motivation
Being able to go abroad was a significant motivation when I chose to pursue a PhD, which I have been lucky enough to do often as part of an international collaborative project. For me it was therefore completely natural to apply for the QuSpin Mobility Grant to get some more extended visits to my collaborators.

The process from idea to action
As I would be staying with groups that I had already worked with and visited previously, planning my visits was quite easy and mostly involved figuring out when would be a suitable time. In the end, I decided to split my time into one month with Evert van Nieuwenburg's group in Leiden, and one month with Ferdinand Kuemmeth's group in Copenhagen. While maybe not as exotic as other destinations chosen by previous recipients of the Mobility Grant, there is a perk of staying in Europe: no need for a visa!

Experiencing a new research culture, collaboration, and supervision
It is quite interesting to get to see what it is like to be part of other research groups and how they all differ slightly from one another. For instance, Evert's group was still quite newly formed when I visited, and for me that made group meetings feel quite exciting. The group was staking out the route ahead, choosing what the group name should be, etc.; and just being a witness to this sort of took me back to a similar feeling I might have gotten at the start of assembling a Lego set as a child. It was also nice to be able to spend entire days brainstorming possible projects with my colleague Jan, who is a postdoc in Evert's group.

In the land of Lego, at Ferdinand's group in the Danish capital, I got to experience being part of a big, established experimental group, which was also fun. I find that work that involves close collaboration with experimentalists is very satisfying, as it requires practical thinking, the workflow is quite dynamical, and best of all: you get to see your ideas applied in the real world.

Experiences from a different country, society and social life
Other than being significantly more urban, neither the Netherlands nor Denmark are that culturally dissimilar from Norway, although the groups hosting me did of course feature slightly more cultural diversity. It was also nice that people were happy to hang out together outside of work and would for instance invite me along to pub quizzes or their group outing.

Challenges and joys
Being away from home for one or two months, you do now and then feel like you're missing out on your social life back home. However, you get to gain new experiences and meet new people!

My advice to other PhD students
I would recommend anyone to take such an opportunity to stay abroad for a bit, it can be quite fun, it provides some new perspectives, and professionally it may help build your network or inspire new ideas for projects.

Conference participants at "Blomsterbrua" (the Bridge of Flowers) by the river Nidelven.

QUANTUM SPINTRONICS 2024

Our Annual International Conference

It is vital for our researchers to gather with leading international professionals outside QuSpin. Targeted conferences spark inspiring dialogues around current challenges and findings and are the ideal breeding ground for a creative environment for focused peer discussions.

In 2024 we had the pleasure of inviting to our annual three-day conference from 5-7 June at hotel Scandic Nidelven, nicely located by the river Nidelven and in walking distance from the city center and the Trondheim fjord.

The fifteen speakers, representing the theoretical and the experimental areas alike, shared their perspectives and work with around sixty participants physically present at the conference center. The various talks on state-of-the-art research were very inspiring to us all. The size of this conference, with its open and rather informal atmosphere, invited to interaction on many levels.

It is important for QuSpin to offer a stage not only to senior researchers but to also give younger researchers in the early phase of their careers the opportunity to gain presentation training and get feedback and have discussions on their scientific work.

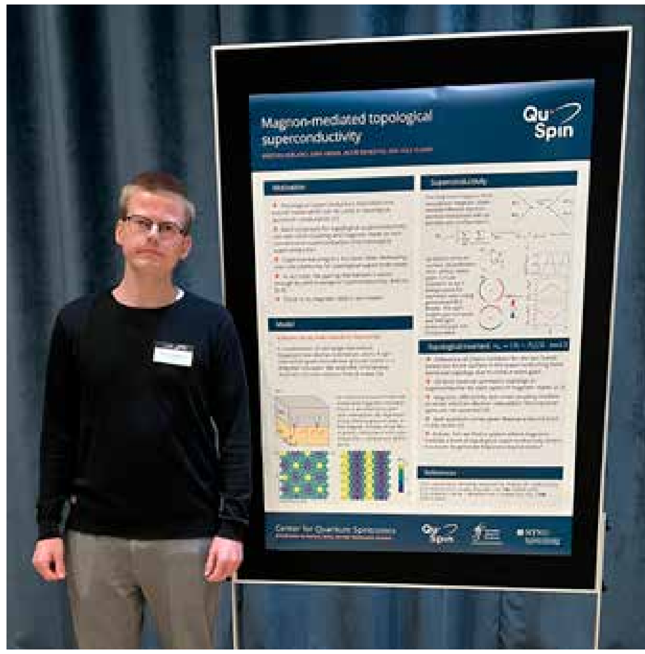
We also included poster sessions presenting work from our center and other participants. This created a basis for many fruitful and enjoyable discussions among fellow researchers and has resulted in concrete collaborations between international researchers. On the last day, we handed out the Best Poster Award 2024.

Our conferences are not all work and no play. We invited everyone to an informal guided walk through the old parts of the city with its famous cathedral Nidarosdomen, the old wooden warehouses and the tiny streets with the characteristic low wooden houses. The conference dinner was held at the old warft nearby, at Dokkhuset Scene, which holds the center of the vibrant classical and jazz scene in our student town. We were presented for improvisational jazz by two internationally renowned jazz musicians, linking the creativity of physics with music.

We look forward to opening up our next three-day conference, in June 4-6, 2025, to a larger audience.

QUANTUM SPINTRONICS 2024

Here are some glimpses from the conference showing researchers at work as well as enjoying social activities.



Glimpses from Our Center

Our Center's researchers have their roots in twelve different countries. They come from different walks of life, cultures, and ethnicities. They speak a variety of languages and are of diverse genders. We spend time and resources on developing a prosocial and robust research culture. We build arenas where people can meet, co-create and interact. And we enjoy sharing this with the outer world.

In 2024 we invited a group of curious young students who participate in the high school "Abel Competition" (Abelkonkurransen) to see the research activities in our ARPES lab. As another example of outreach, our PhD candidate Therese Frostad shared her research in the magazine Gemini under the heading *This could make today's ultra-fast computers seem slow*. As traditional technology is approaching a limit, researchers are looking for new ways to transfer information. One possible solution lies in exploiting the spin of electrons.

We use every opportunity for social gatherings, celebrating successful publications in the Physical Review Letter (PRL), Christmas and Easter holidays, as well as giving master's students and PhD candidates moving on to a career within academia, the industry or the public sector, a good send-off.

We welcomed the summer season and celebrated our great scientific work and results from the past year with a nice dinner at Bifrons, a restaurant in the historical dwelling of the city's bishop in olden times.

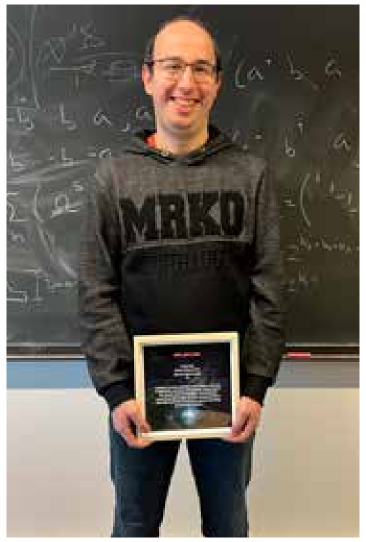
At the end of 2024, Postdoc Pavlo Sukhachov, PhD candidate Stefanie Brinkman and senior researcher Alireza Qaiumzadeh were awarded QuSpin Diplomas. The diploma is a recognition of outstanding scientific contributions to the Center, or a remarkable contribution to our scientific and social culture.

Honoring Postdoc Dr. Pavlo Sukhachov for competently, relentlessly and passionately pursuing the discovery of new theoretical insights regarding unconventional magnetic and interacting systems, publishing four papers in less than one year, including one in PRL, and for advocating scientific discussions and collaborations across QuSpin.

Honoring PhD candidate Stefanie Brinkman for her extraordinary commitment in shaping the activities of the newly established ARPES group, for engaging in fruitful collaborations in and beyond Quspin, and for outstanding research achievements in the realm of orbital physics, publishing one first-author paper in PRL which was awarded recognition as "Editor`s suggestion".

Honoring senior researcher Alireza Qaiumzadeh for setting a great example over many years by frequently hosting researchers for guest-stays at QuSpin, scientifically enriching the center with their presentations and discussions with others and promoting an inviting culture.

We also had the pleasure of welcoming four new PhD candidates: Erlend Syljuåsen, Karl Bergson Hallberg, Kristoffer Leerand and Maxim Tjøtta. We hope that our newcomers and all our other colleagues thrive in our research environment!







PhD Defenses and Completed Master Theses

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

COMPLETED PHD'S

Brekke, Bjørnulf. PhD Defense September 6th, 2024. Title: *Crystal Asymmetry in Magnets and Superconductors.*
Supervisor professor Arne Brataas. Co-supervisor associate professor Christoph Brüne.

Frostad, Therese. PhD defense March 1st, 2024. Title: *Control of Magnon Condensates.*
Supervisor professor Arne Brataas. Co-supervisor Justin Wells.

Mæland, Kristian. PhD Defense August 23rd, 2024. Title: *Many-body effects and topology in magnets and superconductors.*
Supervisor professor Asle Sudbø. Co-supervisor professor Jacob Linder.

Åsland, Anna Cecilie. PhD Defense November 8th, 2024. Title: *A Photoemission Journey: From Core-Level Spectroscopy on Anti-Icing Coatings to Spin-Resolved Band Mapping of Topological Surface States.*
Supervisor professor Justin Wells. Co-supervisors Dr. Charlotte Sanders, Central Laser Facility, UK and associate professor Ida-Marie Høyvik, NTNU.

Bjørnulf Brekke and Arne Brataas.

Therese Frostad and Arne Brataas.

Kristian Mæland and Asle Sudbø.

Justin Wells and Anna Cecilie Åsland.

COMPLETED MASTER THESES

Bruland, Martin Tang. Title: *Supercurrent-Induced Spin-Spin Interactions in Bilayers of Superconductors and Magnetic Insulators.*
Supervisor professor Jacob Linder

Eckle, Håkon Kvitvik. Title: *Introduction to Numerical Quantum Scattering and Dynamical Formulation of Time-Independent Scattering.*
Supervisor senior researcher Alireza Qaiumzadeh.

Heinrich, Kjell. Title: *Curvature-Induced Phenomena in Superconductors and Josephson Junctions.*
Supervisor senior researcher Sol H. Jacobsen.

Holsæter, Ida Asperheim. Title: *Methodological Exploration of the Variational Quantum Eigensolver for Accurate Ground State Predictions in Molecular Systems.*
Supervisors: Professor Jeroen Danon, NTNU and Dr. Franz Fuchs, SINTEF/UiO.

Hågensen, Frida. Title: *Ferromagnetic Nano-Oscillators for Neuromorphic Computing.*
Supervisor senior researcher Alireza Qaiumzadeh.

Kaarbø, Henrik Tidemann. Title: *Colossal enhancement of photomagnonic coupling in antiferromagnet-topological insulator heterostructures.*
Supervisor senior researcher Sol H. Jacobsen.

Leraand, Kristoffer. Title: *Nernst effect in 2D Dirac Materials.*
Supervisor senior researcher Alireza Qaiumzadeh.

Matre, Bjarte. Title: *Fingerprinting of quantum ground state manifolds: Applying group- and representation theory to derive properties of ground states.*
Supervisor professor John Ove Fjærestad.

Syljuåasen, Erlend. Title: *Transverse quantum transport in multiband Bose systems.*
Supervisor professor Asle Sudbø.

Tjøtta, Maxim. Title: *Superconductive transport in curved thin film ferromagnets.*
Supervisor senior researcher Sol H. Jacobsen.

Ursin, Sofie Helene. Title: *Superfluid stiffness and optical conductivity in spin-polarized superconductors.*
Supervisor professor Jacob Linder.

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.

The Research Council of Norway

RCN FRIPRO GRANT

The Professors Jacob Linder and **Jeroen Danon** received a 9 MNOK grant (funding two Ph.D positions) on the project "*Superconducting orbitronics in hybrid systems*".The research project will run from 2025-2028. The main research focus is on obtaining a fundamental understanding of how the combination of these can potentially be utilized for various types of quantum-based technologies. Electrons in materials have a property called orbital angular momentum, and the emerging field of orbitronics studies the behavior of this property and how it can be used in nanoscale devices to achieve for instance efficient information transfer. In this project, the interplay between orbital angular momentum and superconductors (materials which expel magnetic fields and carry electricity with zero resistance) will be determined.

The Research Council of Norway

RCN FRIPRO GRANT

Dr. senior researcher Alireza Qaiumzadeh received a 12 MNOK grant on the project "*Unconventional Thermoelectric Quantum Transport in Novel 2D Magnetic Heterostructures*". The research project will run from 2025-2029.
The research proposal focuses on exploring new two-dimensional magnetic materials that may exhibit exotic many-body properties. By employing advanced theories and computational methods, we aim to understand and control emerging phenomena in these materials, enhancing our understanding of phases of matter and potentially leading to the development of new quantum devices. The insights gained from this research could impact faster data processing, energy harvesting, and future quantum computing technologies.

The Research Council of Norway

RCN FRIPRO GRANT

Dr. senior researcher Sol H. Jacobsen received a 12 MNOK grant on the project **Flexible Superconducting Spintronics: Geometric control of low-dissipation, long-distance information processing.** The main research focus is to examine how some materials' ability to conduct currents without heat loss (superconductivity) combines with other materials. Specifically, we will explore the role of geometry and strain/torsion, applying principles we have developed to new classes of materials and geometries, showing how these can be used to generate and control signals that can be used for computation. We aim to reveal novel methods for controlling and harnessing superconductivity, facilitate new device design, and enable synergies with other branches of quantum mechanics and relativity research.

APS | Physical Review Journals

EDITORIAL BOARD OF PHYSICAL REVIEW LETTERS

Primary Investigator, Professor Jacob Linder has been appointed to the editorial board of Physical Review Letters as a Divisional Associate Editor for condensed matter physics. Physical Review Letters is a flagship journal of the American Physical Society and considered one of the most prestigious in the field of physics. PRL Divisional Associate Editors are leading researchers who are selected and vetted both by an APS division and by the PRL editors. They are appointed for three years and play an important role in the editorial process by serving as referee in the adjudication of difficult cases and formal appeals, offering advice on journal policy, and identifying new referees.

PRL 2024 COLLECTION

PRL 2024 COLLECTION

This article published by researchers at QuSpin was selected to the PRL 2024 Collection. **Brinkman, SS; Tan, XL; (...); Bentmann, H.** *Chirality - Driven Orbital Angular Momentum and Circular Dichroism in CoSi.* Physical Review Letters 132 (19). 196402. Each year, PRL editors, making use of reviewer reports and informal advice from their Editorial Board Members and others, will choose about one issue's worth of Letters across the broad range of topical areas PRL covers. With this highly selective sliver of the many great Letters published annually–about 2% of them–they aim to offer our readers an overview.

acatech NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

NATIONAL ACADEMY OF SCIENCE AND ENGINEERING IN GERMANY

Co-PI Professor Dr. Mathias Kläui elected to the National Academy of Science and Engineering in Germany (acatech). Based on his outstanding research achievements, Mathias Kläui was elected as one of the new members in 2024 of the National Academy of Science and Engineering (acatech). acatech has a mandate from the Federal Government and the Länder in Germany to contribute expert knowledge to the policymaking processes. Mathias Kläui is the fourth member from JGU including the president Georg Krausch.

Clarivate

ONE OF THE 2024 HIGHLY CITED RESEARCHERS

Co-PI Professor Dr. Mathias Kläui is one of the 2024 Highly Cited Researchers. Highly Cited Researchers have demonstrated significant and broad influence in their field(s) of research. Each researcher selected has authored multiple Highly Cited Papers™ which rank in the top 1% by citations for their field(s) and publication year in the Web of Science™ over the past decade. However, citation activity is not the sole selection indicator. This list, based on citation activity is then refined using qualitative analysis and expert judgment as we observe for evidence of community-wide recognition from an international and wide-ranging network of citing authors. Of the world's population of scientists and social scientists, Highly Cited Researchers are 1 in 1,000. Source: Clarivate.

AWARD BEST MASTER IN TECHNOLOGY 2024

Master student Martin Tang Bruland has received the Award from the Faculty of Natural Sciences, NTNU. The Faculty states the following: *"Bruland has a strong academic background. He has achieved top grades in most subjects, and has been an exchange student at École Polytechnique Fédérale de Lausanne, Switzerland.*
He received a challenging topic for his master thesis, namely to determine the interaction between a newly discovered form of magnetism called altermagnetism and superconductors under the supervision of Professor Jacob Linder at QuSpin.

Talks and Presentations

One of our key goals is to make physics in general, and the research at our Center in particular, attractive to other researchers and students. And by sharing the work through accessible language and tangible examples, illustrating why our research is crucial and worth funding. This year our researchers were giving various talks and presenting posters, both locally and internationally. Here is a rough overview.

JANUARY

2D Quantum Materials for Spintronics: 2DQMS 2024, Adam Mickiewicz University in Poznań, Poland.
Talk by senior researcher Alireza Qaiumzadeh. Title: *Crossed Andreev Reflection in AFM-SC-AFM heterostructures.*

Talk by PhD candidate Verena Brehm. Title: *Topological magnon gap engineering in 2D van der Waals CrI3 ferromagnets.*

Tubingen physics seminar series, University of Tübingen, Germany.
Talk by senior researcher Sol H. Jacobsen. Title: *New directions for combining superconductivity and magnetism, from spintronics to remote sensing.*

MARCH

APS March meeting, Minneapolis, USA.
Talk by professor Asle Sudbø. Title: *Topological superconductivity induced by quantum spin fluctuations.*

Talk by PhD candidate Niels Henrik Aase. Title: *Multiband strong-coupling superconductors with spontaneously broken time-reversal symmetry.*

DPG Spring Meeting, Berlin, Germany.
Talk by senior researcher Alireza Qaiumzadeh. Title: *Tunable topological magnon-polaron states and intrinsic anomalous Hall phenomena in 2D ferromagnetic insulators.*

Talk by PhD candidate Verena Brehm. Title: *Topological magnon gap engineering in 2D van der Waals CrI3 ferromagnets.*

Talk by PhD candidate Stefanie Brinkman. Title: *Orbital-momentum locking in chiral topological semimetal CoSi'.*

Talk by PhD candidate Hans Glöckner Giil. Title: *Super-conductor-altermagnet memory functionality without stray fields.*

Talk by Postdoc Henning Goa Hugdal. Title: *Dichroic cavity mode splitting and lifetimes from interactions with a ferromagnetic metal.*

Talk by PhD candidate Christian Svingen Johnsen. Title: *Nonlocal Spin Dynamics Arising From Induced Interactions at the Interface of a Topological Insulator and a Ferromagnet.*

Talk by PhD candidate Kristian Mæland. Title: *TT 36.7: Exceeding the Chandrasekhar-Clogston limit in flat-band superconductors: A multiband strong-coupling approach.*

Talk by PhD Jacob Benestad. Title: *Machine-learned tuning of artificial Kitaev chains to Majorana sweet spots.*

DPG spring meeting Dresden, Germany.
PhD candidate Verena Brehm. Talk: *Impact of DM on magnonic antiferromagnetic leaky integrate-and-fire neuronal networks.*

Realfagsdagene, NTNU
PhD candidate Verena Brehm and PhD candidate Bjørnulf Brekke. Participants at the Table of talk with PhD candidates within maths and physics.

APRIL

International Conference on Superconductivity and Magnetism - ICSM2024, Fethiye, Turkey.
Talk by senior researcher Alireza Qaiumzadeh. Title: *Engineering of topological magnons and magnon-polarons in CrI3 ferromagnets*

Condensed matter seminar, York, United Kingdom
Invited talk by PhD candidate Verena Brehm. Title: *Magnon dispersions and spin transport in 2D materials.*

I0P Magnetism Manchester, United Kingdom.
PhD candidate Verena Brehm. Poster: *Non-volatile leaky integrate-and-fire neurons with domain walls in antiferromagnetic insulators.*

MAY

IOP Magnetism, Sheffield, UK.
Talk by PhD candidate Verena Brehm. Title: *Topological magnon gap engineering in 2D van der Waals CrI3 ferromagnets.*

Chalmers physics seminar series, Chalmers University of Technology, Sweden.Chalmers
Talk by senior researcher Sol H. Jacobsen. Title: *Tuning and sensing superconductivity with magnets.*

Theory of Nanoscale Systems seminar, Utrecht University, the Netherlands
Invited talk by PhD candidate Verena Brehm. Title: *A glimpse into atomistic spin simulations in 2D magnetic insulators: Spin transport and magnon condensates*

Applied Spin Phenomena Group Seminar Kaiserslautern, Germany
Invited talk by PhD candidate Verena Brehm. Title: *Atomistic spin simulations of antiferromagnetic magnon BECs.*

Pint of Science Cologne, Germany
Talk by PhD candidate Verena Brehm. Title: *Das Labor im Computer und wie magnetische Wellen vielleicht die Welt verändern werden.*

Condensed matter seminar Leeds, United Kingdom
Talk by PhD candidate Verena Brehm. Title: *Simulation of magnon dispersion rations and magnonic transport in 2D magnetic insulators.*

JUNE

Quantum Spintronics International Conference 2024, NTNU, Norway.
Talk by senior researcher Sol H. Jacobsen. Title: *Into the light: How cavity photons can reveal new physics in old materials.*

Talk by senior researcher Alireza Qaiumzadeh. Title: *Engineering of topological magnons and magnon-polarons in CrI3 ferromagnets.*

Talk by Pavlo Sukhachov. Title: *Thermoelectric Effect in Altermagnet-Superconductor Junctions.*

JULY

International Conference on Magnetism, Bologna, Italy.
Talk by senior researcher Sol H. Jacobsen. Title: *Tuning superconductivity with curved magnets.*

GRS/GRC Spin Dynamics in Nanostructures Les Diablerets, Switzerland.
PhD candidate Verena Brehm. Leader in Session *Spin Textures, Magnetism and Topology in Low-Dimensional Systems.* Poster: *Micromagnetic study of spin transport in easy-plane antiferromagnetic insulators.*

AUGUST

New Avenues for Quantum Materials, Chalmers University of Technology, Sweden.
Talk by senior researcher Sol H. Jacobsen. Title: *Microwave coupling, sensing and cavity engineering with magnets and superconductors.*

JEMS Madrid, Spain.
PhD candidate Verena Brehm. Poster: *Atomistic spin simulation of magnon dispersion relations and spin transport in Cris and Young.* Researchers flash talk. Title: *A little story about Hall effects when they should not be there.*

SEPTEMBER

Magnons on an Island, Texel Island, the Netherlands.
Talk by senior researcher Sol H. Jacobsen. Title: *Tuning and sensing with magnet-photon interactions in cavities.*

Researchers' Night - Ungdommens forskernatt ved NTNU Trondheim, Norway.
PhD candidate Verena Brehm. Stand: Outreach to pupils. Title: *Big brain time hierneinspirert databehandling.*

OCTOBER

Magtop, Warzaw, Poland.
Talk by professor Jacob Linder. Title: *Superconducting transport in altermagnets.*

Neuromorphic computing: problems and prospects, Østfold University College, Norway.
Talk by senior researcher Alireza Qaiumzadeh. Title: *Spintronic-Based Neuromorphic: A Proposal for LIF Neurons by Magnetic Textures.*

Another physics is possible Uppsala, Sweden.
PhD candidate Verena Brehm. Active participation workshop about *inclusive teaching and equity in physics didactics.*

NOVEMBER

Workshop on active learning Trondheim, Norway.
PhD candidate Verena Brehm. Active participation workshop about *inclusive teaching and equity in physics didactics.*

DECEMBER

Monthly Colloquia, Wuhan University of Technology, Wuhan and Fudan University, Shanghai in China.
Two talks by senior researcher Alireza Qaiumzadeh. Title: *Engineering of topological magnons and magnon-phonon hybrid modes in magnetic vdW layers.*

Highlights

MARCH

PhD Defense
Therese Frostad

JUNE

Award Best Master in Technology 2024
Martin Tang Bruland

AUGUST

PhD Defense
Kristian Mæland

SEPTEMBER

RCN Fripro Grant
Dr. Senior researcher
Alireza Qaiumzadeh

RCN Fripro Grant
Professor Jacob Linder
Professor Jeroen Danon

PhD Defense
Bjørnulf Brekke

OCTOBER

Professor Jacob Linder **has been appointed to the editorial board of Physical Review Letters as a Divisional Associate Editor for condensed matter physics.**

NOVEMBER

PhD Defense
Anna Cecilie Åsland

Honored as Highly Cited Researcher 2024
Co-PI Professor
Dr. Mathias Kläui

Elected to the National Academy of Science and Engineering in Germany (acatech)
Co-PI Professor
Dr. Mathias Kläui

DECEMBER

RCN Fripro Grant
Dr. Senior researcher
Sol H. Jacobsen

PRL 2024 Collection
Brinkman, SS; Tan, XL; (...); Bentmann, H. *Chirality-Driven Orbital Angular Momentum and Circular Dichroism in CoSi.* **Physical Review Letters 132** (19). 196402.

Scientific Publications

We are privileged to have the work of our researchers published in journals such as Physical Review Letters, Physical Review B, Nature, Nature Physics, Nature Materials and the following listed publications.

1. Brekke, Bjørnulf; Sukhachov, Pavlo; Giil, Hans Gløckner; Brataas, Arne; Linder, Jacob Wüsthoff. *Minimal Models and Transport Properties of Unconventional p -Wave Magnets.* **Physical Review Letters;** Volum 133. (23). 10889

2. Brinkman, SS; Tan, XL; (...); Bentmann, H. *Chirality-Driven Orbital Angular Momentum and Circular Dichroism in CoSi.* **Physical Review Letters** 132 (19). 196402. PRL Collection of the Year 2024.

3. Kamra, Lina Johnsen; Linder, Jacob Wüsthoff. *Inverse Spin-Hall Effect and Spin Swapping in Spin-Split Superconductors.* **Physical Review Letters** ;Volum 132.(22). 226002

4. C. Tong, F. Ginzel, W. W. Huang, A. Kurzmann, R. Garreis, K. Watanabe, T. Taniguchi, G. Burkard, J. Danon, T. Ihn, and K. Ensslin. *Three-carrier spin blockade and coupling in bilayer graphene double quantum dots.* **Physical Review Letters 133.** 017001

5. Amundsen, Morten; Brataas, Arne; Linder, Jacob Wüsthoff. *RKKY interaction in Rashba altermagnets.* **Physical review B (PRB)** ;Volum 110.(5). 054427

6. Aunsmo, Sigrid; Linder, Jacob Wüsthoff. *Converting a triplet Cooper pair supercurrent into a spin signal.* **Physical review B (PRB)** 2024 ;Volum 109.(2). 024503

7. J. Benestad, A. Tsintzis, R. Seoane Souto, M. Leijnse, E. van Nieuwenburg, and J. Danon. *Machine-learned tuning of artificial Kitaev chains from tunneling-spectroscopy measurements.* **Physical review B (PRB)** ;110. 075402

8. Brehm, Verena Johanna; Sobieszczyk, Pawel; Kløgetvedt, Jostein Nygård; Evans, Richard; Santos, Elton; Qaiumzadeh, Alireza. *Topological magnon gap engineering in van der Waals CrI_3 ferromagnets.* **Physical review B (PRB)** ;Volum 109.(17). 174425

9. Falch, Vemund; Danon, Jeroen; Qaiumzadeh, Alireza; Brataas, Arne. *Impact of spin torques and spin-pumping phenomena on magnon-plasmon polaritons in antiferromagnetic insulator-semiconductor heterostructures.* **Physical review B (PRB)** ;Volum 109.(21). 214436. Editor's suggestion 2024

10. Fyhn, Eirik Holm; Bentmann, Hendrik; Linder, Jacob Wüsthoff. *Barrier and finite-size effects on the extension of topological surface states into magnetic insulators ;* **Physical review B (PRB)** 109. 045409

11. Giil, Hans Gløckner; Linder, Jacob Wüsthoff. *Superconductor-altermagnet memory functionality without stray fields.* **Physical review B (PRB)** ;Volum 109.(13). 134511

12. Giil, Hans Gløckner and Brataas, Arne. *Quantum theory of spin transfer and spin pumping in collinear antiferromagnets and ferrimagnets.* **Physical review B (PRB).** Volum 109, 184408

13. Giil, Hans Gløckner; Brekke, Bjørnulf; Linder, Jacob Wüsthoff; Brataas, Arne. *Quasiclassical theory of superconducting spin-splitter effects and spin-filtering via altermagnets.* **Physical review B (PRB)**. 140506

14. Herasymchuk, A.A.; Gorbar, E.V.; Sukhachov, Pavlo. *Viscoelastic response and anisotropic hydrodynamics in Weyl semimetals.* **Physical review B (PRB)** ;Volum 110.(3). 035133

15. Hodt, Erik Wegner; Linder, Jacob Wüsthoff. *Spin pumping in an altermagnet/normal-metal bilayer.* **Physical review B (PRB)** Volum 109.(17). 174438

16. Hodt, Erik Wegner; Sukhachov, Pavlo; Linder, Jacob Wüsthoff. *Interface-induced magnetization in altermagnets and antiferromagnets.* **Physical review B (PRB).** 054446

17. Hodt, Erik Wegner; Cirillo, Carla; Di Bernardo, Angelo; Attanasio, Carmine; Linder, Jacob Wüsthoff. *Critical temperature of triplet superconductor-ferromagnet bilayers as a probe for pairing symmetry.* **Physical review B (PRB)** ;Volum 110.(9). 094512

18. Hugdal, Henning Goa; Høydalsvik, Eirik Jaccheri; Jacobsen, Sol Hernæs. *Dichroic cavity mode splitting and lifetimes from interactions with a ferromagnetic metal.* **Physical review B (PRB)** ;Volum 110.(16). L161102

19. Lundemo, Sondre Duna; Sudbø, Asle. *Topological superconductivity induced by a Kitaev spin liquid.* **Physical Review B (PRB)** ;Volum 109.(18). 184508.

20. Mæland, Kristian; Brekke, Bjørnulf; Sudbø, Asle. *Many-body effects on superconductivity mediated by double-magnon processes in altermagnets.* **Physical Review B (PRB)** ;Volum 109.(13). 134515

21. Ouassou, Jabir Ali; Yokoyama, Takehito; Linder, Jacob Wüsthoff. *RKKY interaction in triplet superconductors: Dzyaloshinskii-Moriya-type interaction mediated by spin-polarized Cooper pairs.* **Physical review B (PRB)** 2024 ;Volum 109.(17). 174506

22. Røst, Håkon; Mazzola, Federico; Bakkelund, Johannes; Åsland, Anna Cecilie; Hu, Jinbang; Cooil, Simon Phillip; Polley, Craig; Wells, Justin William. *Disentangling electron-boson interactions on the surface of a familiar ferromagnet.* **Physical review B (PRB)** ;Volum 109. s. 1-9. 035137

23. Salamone, Tancredi; Midttun, Magnus Skjærpe; Hugdal, Henning Goa; Amundsen, Morten; Jacobsen, Sol Hernæs. *Interface probe for antiferromagnets using geometric curvature.* **Physical review B (PRB)** ;Volum 109.(9). 094508

24. Saroka, VA; Kong, F; (...); Sun, XK. *Flat band, tunable chiral anomaly, and pitchfork bifurcation in a honeycomb lattice.* **Physical review B (PRB)** 110 (19). 195143

25. Sepehrinia, Reza; Eskandari, Siavash; Qaiumzadeh Javinani, Alireza. *AC conductivity and magnetic dichroism of two-dimensional antiferromagnetic Dirac semimetals.* **Physical review B (PRB)** ;Volum 110.(1). 014440

26. Sukhachov, Pavlo; Hodt, Erik Wegner; Linder, Jacob Wüsthoff. *Thermoelectric Effect in Altermagnet-Superconductor Junctions.* **Physical review B (PRB).** 094508

27. Sukhachov, Pavlo; Linder, Jacob Wüsthoff. *Impurity-induced Friedel oscillations in altermagnets and p -wave magnets.* **Physical review B (PRB)** ;Volum 110.(20). 205114

28. Sun, Chi; Linder, Jacob Wüsthoff. *Supercurrent-induced spin switching via indirect exchange interaction.* **Physical review B (PRB)** 2024 ;Volum 109.(21). 214409

29. Sun, Chi; Mæland, Kristian; Thingstad, Even; Sudbø, Asle. *Strong-coupling approach to temperature dependence of competing orders of superconductivity: Possible time-reversal symmetry breaking and nontrivial topology.* **Physical review B (PRB)** ;Volum 109.(17). 174520

30. Sun, Chi; Linder, Jacob Wüsthoff. *Josephson transistor and robust supercurrent enhancement with spin-split superconductors.* **Physical Review B. Condensed Matter and Materials Physics.** 224512

31. Tjernshaugen, Johanne Bratland; Amundsen, Morten; Linder, Jacob Wüsthoff. *Superconducting phase diagram and spin diode effect via spin accumulation.* **Physical review B (PRB)** ;Volum 109.(9). 094516

32. Tjernshaugen, Johanne Bratland; Amundsen, Morten; Linder, Jacob Wüsthoff. *Crossed Andreev reflection revealed by self-consistent Keldysh-Usadel formalism.* **Physical review B (PRB)** ;Volum 110.(22). 18191

33. Zarezad, Amir N.; Qaiumzadeh Javinani, Alireza; Barnaś, Józef; Dyrdał, Anna. *Topological charge and spin Hall effects due to skyrmions in canted antiferromagnets.* **Physical review B (PRB)** 2024 ;Volum 110.(5). 054431

34. Aase, Niels Henrik; Hodt, Erik Wegner; Linder, Jacob Wüsthoff; Sudbø, Asle. *Orbital currents in lattice multiorbital systems: Continuity equation, torques, and RKKY interaction.* **Physical review B (PRB).** 104423

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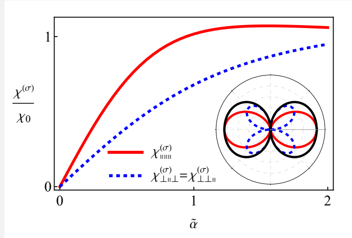
Custom built low temperature radiofrequency scanning tunneling microscope for local magneto-dynamic characterization.

Featured Articles

This was yet another year where QuSpin Researchers published groundbreaking results in the world's premier physics journals. We have chosen to highlight three of them: Two of the works are theoretical, and the third paper is an experimental work.



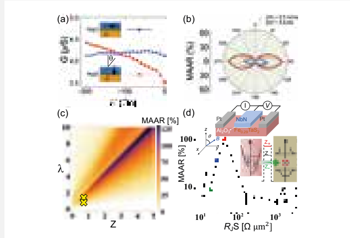
Minimal Models and Transport Properties of Unconventional *p*-Wave Magnets

Bjørnulf Brekke, Pavlo Sukhachov, Hans Gløckner Giil, Arne Brataas and Jacob Linder.

Phys. Rev. Lett. 133, 236703 – Published 3 December, 2024.

Abstract

New unconventional compensated magnets with a p-wave spin polarization protected by a composite time-reversal translation symmetry have been proposed in the wake of altermagnets. To facilitate the experimental discovery and applications of these unconventional magnets, we construct an effective analytical model. The effective model is based on a minimal tight-binding model for unconventional p-wave magnets that clarifies the relation to other magnets with p-wave spin-polarized bands. One of the most prominent advantages of our analytical model is the possibility to employ various analytical approaches while capturing essential features of p-wave magnets. We illustrate the effective model by evaluating the tunneling conductance in junctions with p-wave magnets, revealing a large magnetoresistance, spin filtering, and anisotropic bulk spin conductivity beyond linear response despite the absence of a net magnetization...



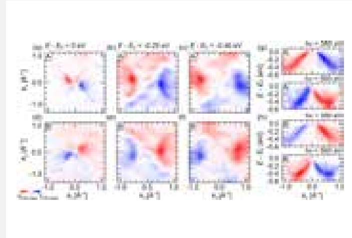
Colloquium: Spin-orbit effects in superconducting hybrid structures

Morten Amundsen, Jacob Linder, Jason W. A. Robinson, Igor Žutić and Niladri Banerjee.

Rev. Mod. Phys. 96, 021003 – Published 28 May, 2024.

Abstract

Spin-orbit coupling (SOC) relates to the interaction between an electron's motion and its spin and is ubiquitous in solid-state systems. Although the effect of SOC in normal-state phenomena has been extensively studied, its role in superconducting hybrid structures and devices elicits many unexplored questions. In conjunction with broken symmetries and material inhomogeneities within superconducting hybrid structures, SOC may have contributions beyond its effects in homogeneous materials. Notably, even with well-established magnetic or nonmagnetic materials and conventional s-wave spin-singlet superconductors, SOC leads to emergent phenomena including equal-spin-triplet pairing and topological superconductivity (hosting Majorana states), a modified current-phase relationship in Josephson junctions, and nonreciprocal transport, including superconducting diode effects...



Chirality-Driven Orbital Angular Momentum and Circular Dichroism in CoSi

Stefanie Suzanne Brinkman, Xin Liang Tan, Bjørnulf Brekke, Anders Christian Mathisen, Øyvind Finnseth, Richard Justin Schenk, Kenta Hagiwara, Meng-Jie Huang, Jens Buck, M. Kalläne, M. Hoesch, K. Rossnagel, Kui-Hon Ou Yang, Minn-Tsong Lin, Guo-Jiun Shu, Ying-Jiun Chen, C. Tusche, and H. Bentmann.

Phys. Rev. Lett. 132, 196402 – Published 10 May, 2024.

Abstract

Chiral crystals and molecules were recently predicted to form an intriguing platform for unconventional orbital physics. Here, we report the observation of chirality-driven orbital textures in the bulk electronic structure of CoSi, a prototype member of the cubic B20 family of chiral crystals. Using circular dichroism in soft x-ray angle-resolved photoemission, we demonstrate the formation of a bulk orbital-angular-momentum texture and monopolelike orbital-momentum locking that depends on crystal handedness. We introduce the intrinsic chiral circular dichroism, $ic\,\mathrm{CD}$, as a differential photoemission observable and a natural probe of chiral electron states. Our findings render chiral crystals promising for spin-orbitronics applications.

Facts

As of 2024.12.31.

9
PROFESSOR/ASS.PROF.

2
SENIOR RESEARCHERS

2
POSTDOCS

20
PHD CANDIDATES

11
MASTER STUDENTS

1
ADMINISTRATOR

12
DIFFERENT NATIONALITIES

23
VISITING RESEARCHERS

62
PUBLICATIONS

* Note: In addition we have a 25 % Finance Officer position, Head Engineer from the Department of Physics/NTNU, two Co-Principal Investigators in 17% and 20% positions, and one Prof. II position.

Funding

FUNDING 2024 (NOK)

The Research Council of Norway, Center of Excellence	13 825 000
Norwegian University of Science and Technology	7 177 000
SUM	**21 002 000**
The Research Council of Norway (Center of Excellence)	6 893 000
International Funding	0
Other Public	0
SUM	**6 893 000**
TOTAL FUNDING	**27 895 000**

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Colleagues who left QuSpin before 2024.12.31 are marked with an *

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Professor/Head of Department of Physics
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Senior Researcher
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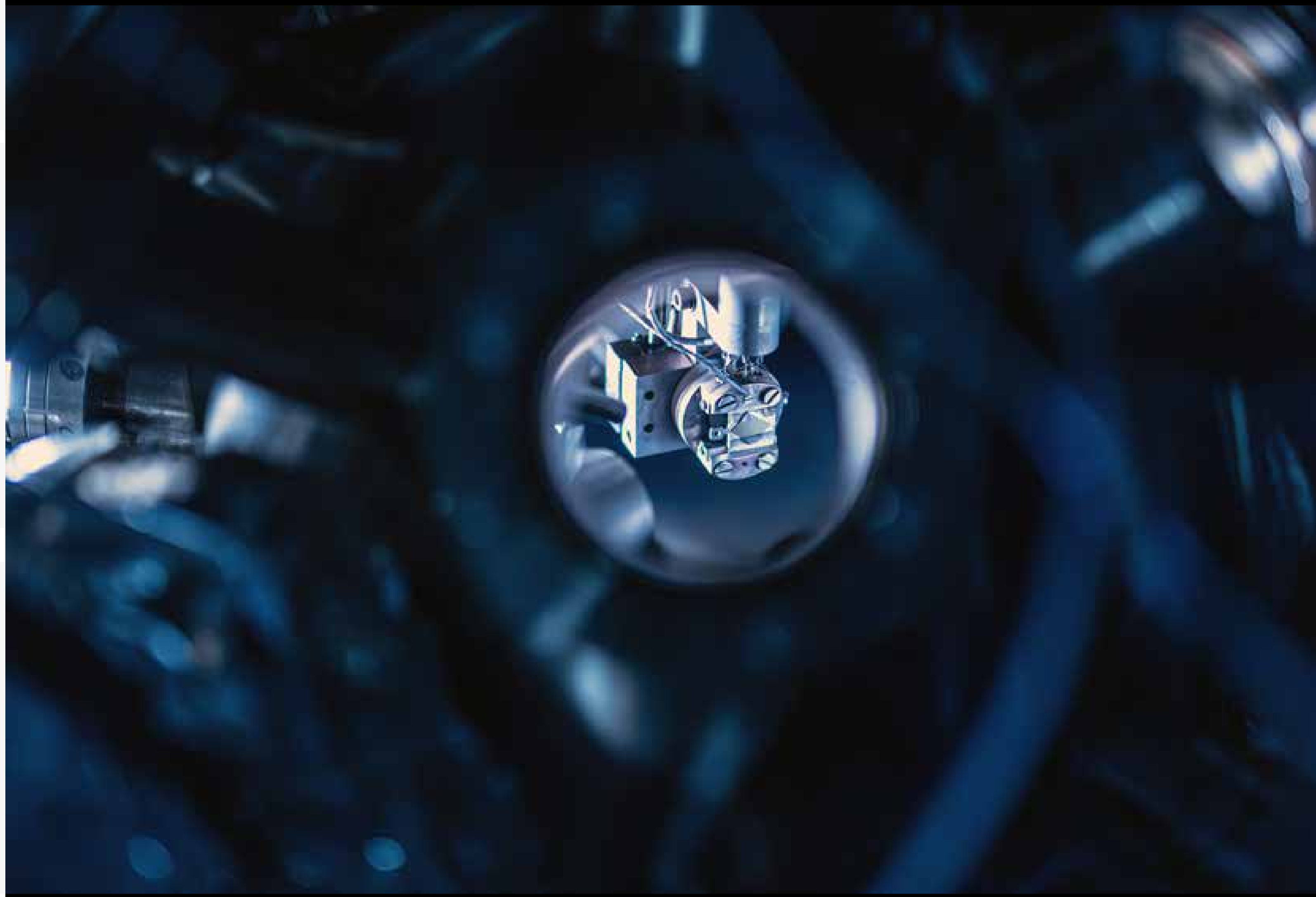

Photo from the ARPES lab showing a detail in the instrument.

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University of Hamburg, Germany

QuSpin Alumni

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

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Next position: Postdoctoral researcher at MIT, USA.

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Friendly conversation in the QuSpin corridor between associate professor Christoph Brüne and center coordinator Karen-Elisabeth Sødahl.

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Bjørnulf Brekke (page): 63 (article 1)
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