Science, Technology and Innovation

Projects

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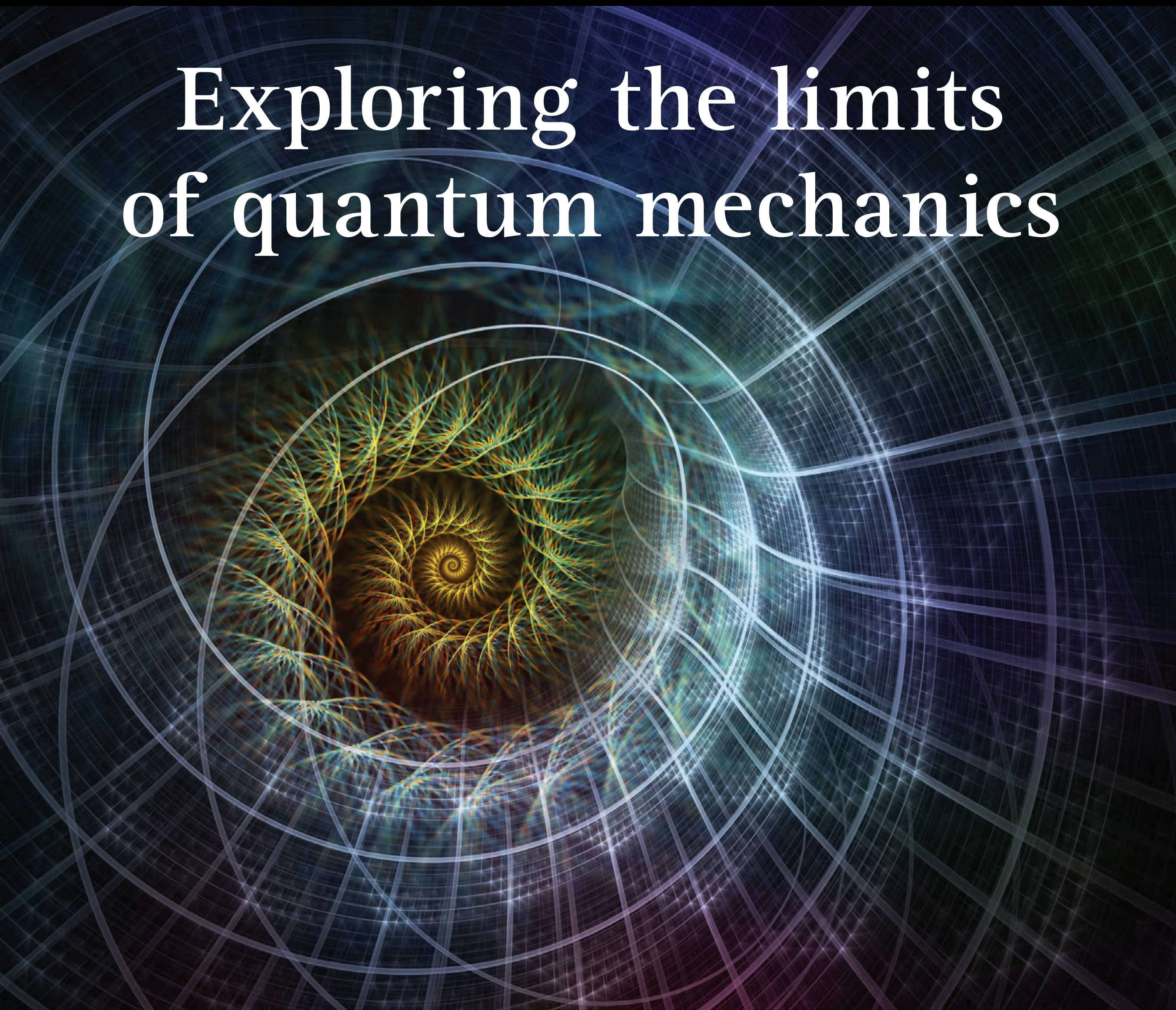
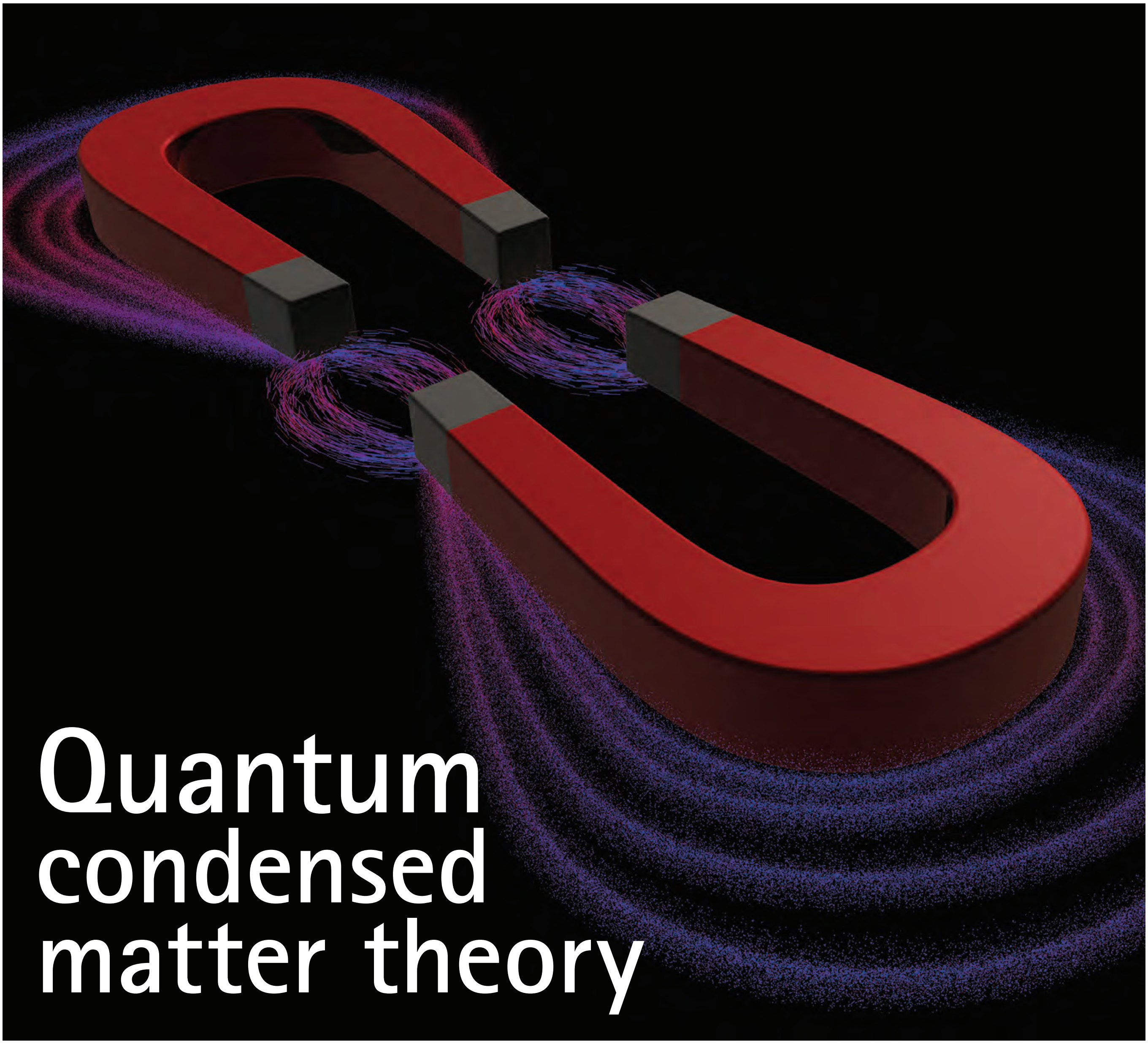
Quantum Theory Special Edition

Exploring the limits of quantum mechanics



Spin and charge flow in hybrid structures of unconventional superconductors and other novel materials

Quantum physics examines the physical behaviour of objects at minute scales. In this domain, interactions between atoms and subatomic particles determine the macroscopic behaviour of systems like solid-state materials. Through understanding and manipulating quantum mechanical phenomena such as magnetism and superconductivity, a research group from the Norwegian University of Science and Technology is seeking to unlock their potential for use in modern disciplines including spintronics and Dirac fermion based technology



Quantum condensed matter theory

With their dimensions reduced down to the nanoscale, conventional materials assume strange, unfamiliar properties. This is the realm in which scientists expect the unexpected – and where many laws of classical physics no longer apply. Matter, observed at quantum scales, begins to exhibit properties associated with both particles and waves, thus confounding typical categorisations. The physics behind these properties, known as quantum mechanics, is a field in which tangible progress is now being made. Far from being an obscure theoretical area of science, however, insights gleaned by researchers in quantum matter have begun to regularly enhance and engender transformative, mainstream applications.

At the Norwegian University of Science and Technology, a research group investigating quantum condensed matter theory and headed by Professor Jacob Linder is seeking to explore the theoretical quirks of quantum mechanics. "In quantum condensed matter physics, you encounter various phases of matter," he explains. "Classically you have only three types: solid, gas and liquid states. But when you study quantum physics, this classification of matter becomes more complicated. For instance, not all solid materials behave in the same way. You can have solid materials that are superconducting, and you can have solid materials that are magnetic. These attributes cannot be explained by classical physics, but are rather explained by quantum mechanical effects. They are thus described as quantum phases of matter."

It is these quantum phases that the group seeks to delve into at a theoretical level, and Linder believes they can ultimately stimulate the creation of radically improved new technologies and devices. The team, located in Trondheim, consists of Linder, one postdoctoral researcher, two PhD candidates, and six MSc students.

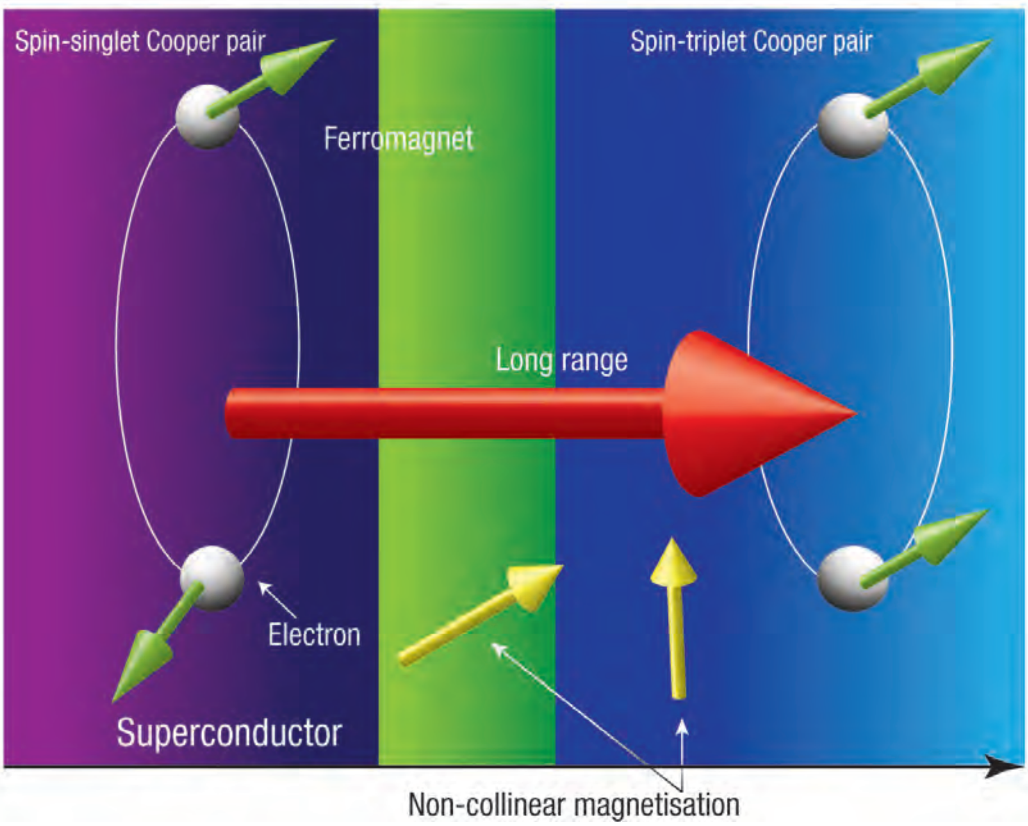
Superconducting spintronics

Magnetism at its most fundamental level is created by quantum mechanics, specifically by a property of electrons called 'spin'. An electron's spin, caused by its intrinsic angular momentum, can be detected as a magnetic field possessing one of two orientations, known as up and down. Whereas conventional electronics applications use the electron's charge as the fundamental ingredient, the spin of the electron is the key component in the field known as spintronics. By exploiting the quantum mechanical behavior of spin, it is thought that tools like hard drives and other electronic devices could be greatly improved, offering better processing power and storage capacity.

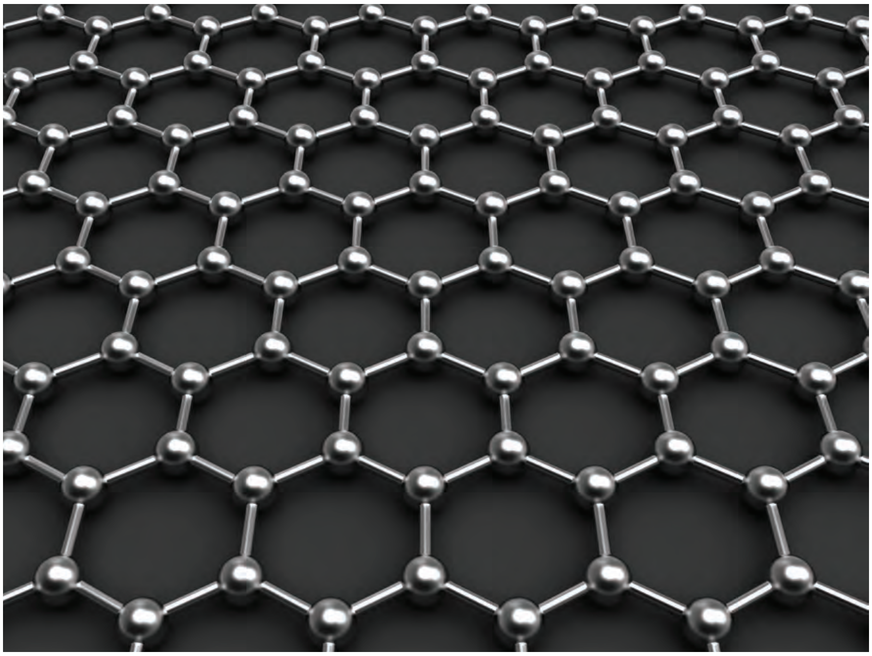
> "Magnetism at its most fundamental level is created by quantum mechanics, specifically by a property of electrons called 'spin'"

A major theme of Linder's research is the merging of spintronics with superconductors. Conventionally, superconductivity has been regarded as incompatible with magnetism, and thus spintronics. The zero-resistance encountered in superconductors is normally possible due to electrons being paired up into what are called 'Cooper pairs'. In these pairs, one electron traditionally has its spin up while the other must be down. Pass a Cooper pair through a magnet, however, and one of the two electrons will inevitably have the 'wrong' spin orientation compared to the magnetisation direction, leading to the destruction of Cooper pairs and thus the loss of superconductivity. However, recent research has suggested that it is indeed possible to retain the Cooper pair bonding, and thus superconductivity, with parallel spin electrons by controlling the magnetisation properties of magnetic materials

"If you create artificial structures which combine superconducting and magnetic materials together at the quantum scale, superconductivity will adapt to the presence of magnetism," explains Linder. "This is very important, since superconductivity allows for the transmission of a current without any resistance. Without superconductivity, spin currents will encounter resistance when passed through materials, which



In ordinary superconductors, electrons team up to form Cooper pairs with opposite spins – equalling zero total spin – which can carry electric currents without resistance. By combining superconducting and magnetic materials, it is possible to convert these spinless Cooper pairs into pairs where the electrons have spins pointing in the same direction, opening the possibility of transporting spin-currents without resistance.



"Graphene can be created in a two-dimensional form, which is advantageous when you are developing devices like cell phones and computers"

leads to heat and energy loss. But, if you can successfully combine magnetism with such a material – and experimental work exists which shows this is viable - you create the possibility of realising 'spin currents' with strongly reduced energy dissipation." Linder has, together with a collaborator from Cambridge University, recently written a review article on the topic of superconducting spintronics.

Dirac-fermion particles

Another area the group is looking at is materials that exploit the presence of Dirac-fermion particles. In some solids, it has been discovered that certain types of electrons behave relativistically and, under specific circumstances, even act as if they were massless. Scientists have used these particles to explain several phenomena in condensed-matter physics, including the exciting properties of two-dimensional graphene, which possesses electron mobility ten times higher than commercial grade silicone. When sandwiched between or next to other materials, graphene can strongly affect how the transport of a current occurs between them. "A significant advantage here is that graphene can be created in a two dimensional form, and other materials which exploit Dirac-fermion properties can also be very flat," explains Linder. "This compact structure can therefore save significant space, which is advantageous when you are developing devices like cell phones and computers. Moreover, considering their size, they are also very strong and durable."

When focusing on his theoretical work, Linder stresses, "my main arsenal is my pen, paper and computer." But he also acknowledges the importance of a practical dimension to his investigations, emphasising that "it is important, if one is to have an impact with one's research, to try and have good communication with experimentalists. You can do basically anything with theory, but if it has no consequence or measurable effect, then it can seem rather abstract. Therefore, when I'm developing theoretical frameworks to explain new transports of spin and charges in the quantum world, I try to consider how these ideas can be realised experimentally. I am highly focused on overcoming some fundamental challenges – like how to refine and boost the effects of spintronics, even without a superconductor – in order to discover new physical effects that eventually may result in practical applications."★

AT A GLANCE

Project Information

Project Title:
Spin and Charge Flow in Hybrid Structures of Unconventional Superconductors and Other Novel Materials

Project Objective:
We determine how quantum transport of spin and charge occurs in structures involving materials with different type of functionalities. This includes the interplay between unusual types of superconducting/superfluid states with magnetism. We examine this both in conventional metals and in exotic electronic environments such as low-dimensional Dirac systems.

Project Duration and Timing:
5 years (2011-2016)

Project Funding:
Norwegian Research Council

Project Partners:
Prof. Asle Sudbø

MAIN CONTACT

Jacob Linder
Prof. Jacob Linder leads a research group currently consisting of 9 postdocs/Ph.Ds/master-students, focusing mainly on spintronics phenomena both in superconducting and magnetic materials. He obtained his Ph.D in 2009 from NTNU and current research interests include quantum transport, magnetization dynamics, emergent Dirac fermions, and metamaterials.

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