Summer trainee projects 2024

Department of Applied Physics

Research group: Quantum Computing and Devices (QCD)
Group website: Click here!
Group intro video: Click here!
Contact person: Prof. Mikko Möttönen (mikko.mottonen@aalto.fi)
Site of research: Aalto University, QCD group, Otaniemi

Your site of research will be the premises of Quantum Computing and Devices, the so-called QCD Labs, on the Otaniemi campus of Aalto University. There are both theorists and experimentalists working in the group. See our webpage.

QCD group photo last summer.

Preface

Congratulations for making it this far to read about the exciting research topics that the QCD group has to offer for this summer. We are looking for excellent students to train them to do excellent science together with our great team! Below, I provide you an introduction to the high-level topics of possible summer trainee projects. Have a look and see which topics interest you most in general. Then we can discuss in the interviews more and if you decide to join, we will fine tune the project for your needs.

I have added here a table of contents that you may use to navigate the document.

Good luck!

-mikko

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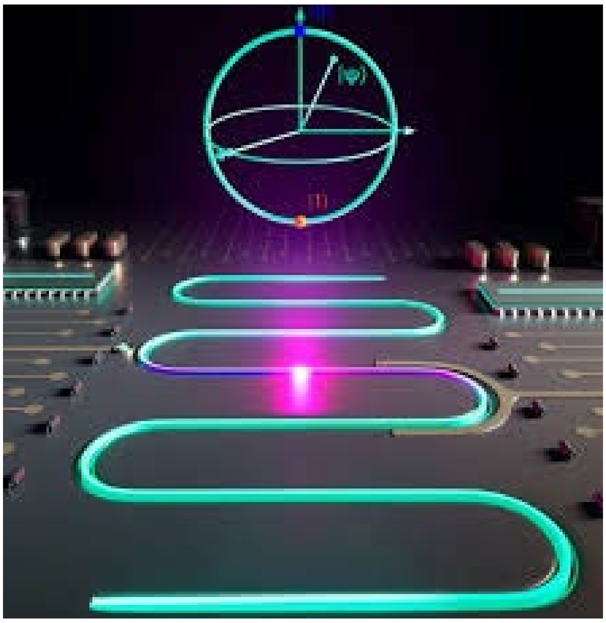
Unimon qubit

(project title)

Field of research: Superconducting quantum electronics
Topic instructors: Dr. Suman Kundu, Dr. Yoshiki Sunada, Dr. Vasilii Vadimov
Topic website: Click here!
Level of student: applications from all students are welcome
(also for people applying for a Mater’s or PhD thesis project)

Introduction

Quantum computer is an emerging computational device that can potentially solve some problems of practical interest that are impossible for the classical computer due to the required computational resources. Quantum bits, qubits, are the key ingredient of the quantum computer. Qubits can be employed to store and process quantum information, and they can be measured to extract classical information out of the quantum world.



One of the greatest developments of quantum technologies in the recent years has been the rise of circuit quantum electrodynamics (cQED). Here, superconducting qubits are coupled to microwave cavities and waveguides working at microwave frequencies. This allows not only to reproduce quantum optics experiments carried out with optical photons but also for a spectrum new physics and applications.

The transmon qubit has been the most popular and successful superconducting qubit for more than a decade. It has lead to quantum processors of hundreds of qubits and so high accuracies in the computation than it can run it native quantum-logic circuits faster than any classical computer can solve the corresponding problem. However, transmon is only weakly anharmonic which limits the speed of operations, and hence leaves time for noise to cause errors.

Project goals

Your aim in this project is to measure and study the properties of newly discovered unimon qubit that has higher anharmonicity than the transmon and has hence high potential in providing faster and more accurate quantum operations.

Working methods

Experiments on the topic will be carried out during your project using a sample already existing in the group. Furthermore, the measurement setup and scripts are well developed, but can always be improved! It is also possible to focus more on theoretical modelling of the electromagnetic circuit to optimize the qubit design on the chip.

Thesis possibilities

Depending on your level, this project can be adjusted for a BSc thesis, special assignment, MSc thesis, or a PhD thesis project. Some knowledge of quantum mechanics and an excellent study record is preferred.

Further reading and watching

More understanding on the QCD efforts on this topic can be found at:

(The backup links for arXiv versions of the papers can be used in the case if you cannot access the original journal paper.)

- Video (in Finnish) on quantum computers
- Eric Hyyppä's talk at APS on the unimon
- Nature Communications paper on the unimon qubit (backup link)

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Control of dissipation in superconducting qubits

(project title)

Field of research: Superconducting quantum electronics
Topic instructors: Dr. Wallace Teixeira, M.Sc. Heidi Kivijärvi, Dr. Vasilii Vadimov
Topic website: Click here!
Level of student: applications from all students are welcome
(also for people applying for a Mater's or PhD thesis project)

Introduction

For the quantum computer, one of the outstanding problems is the precise and fast initialization of the qubit register. Some of our ideas is to employ tunable dissipative environments to carry out the initialization process. These environments could be then decoupled from the qubits to allow for their coherent operation.

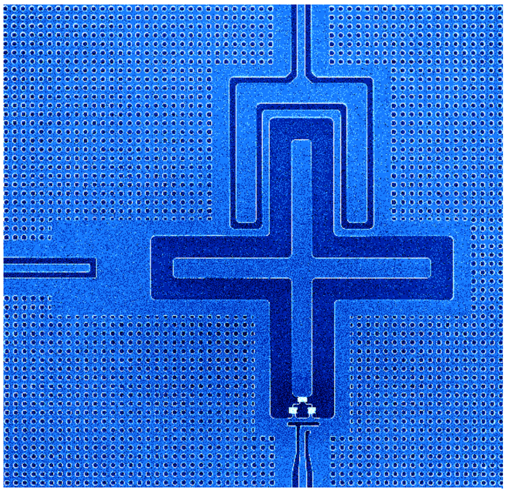

Figure. Scanning electron microscope image of a superconducting qubit (the cross-shaped bright region in the middle) fabricated by the QCD group. Figure credit: Jan Goetz/QCD.

Traditionally, normal-metal–insulator–superconductor (NIS) tunnel junctions have been utilized, for example, in measuring and controlling the electron temperature on nanoscale conducting islands. More recently, we have found them useful in implementing dissipation on demand on quantum circuits. We refer to this small device on the chip as a quantum-circuit refrigerator.

The linked recent papers provide two different approaches to implement tunable environments: using a tunnel junction controlled by a voltage source or a superconducting quantum interference device.

Project goals

Your aim in this project is to employ artificial quantum-mechanical environments and their control protocols for cooling quantum microwave circuits such as resonators and superconducting quantum bits. Possibilities include fast qubit reset and observation of new dissipation-induced phenomena.

Working methods

The main focus of the project can be adjusted according to your level and interests.

The work may be adjusted to either more theoretical or more experimental direction. Theoretical work involves modeling of microwaves in superconducting waveguides and analytical calculations. In experimental work, you design and implement measurements, and analyze the data.

Thesis possibilities

Depending on your level, this project can be adjusted for a BSc thesis, special assignment, MSc thesis, or a PhD thesis project. Some knowledge of quantum mechanics and an excellent study record is preferred.

Further reading and watching

More understanding on the QCD efforts on this topic can be found at:

(The backup links for arXiv versions of the papers can be used in the case if you cannot access the original journal paper.)

- Funny video on quantum-circuit refrigerator
- Most recent paper on using QCR to cool a superconducting resonator, the photon number states of which are measured by a qubit
- Nature Physics paper on observation of the Lamb shift using QCR (backup link)
- Paper on rf-controlled QCR (backup link)
- Paper on fast control of dissipation using QCR (backup link)
- Theoretical paper on QCD coupled to qubits (backup link)
- Original QCR invention paper in Nature Communications (backup link)

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Quantum control and measurement of superconducting qubits

(project title)

Field of research: Superconducting quantum electronics
Topic instructors: M.Sc. Aashish Sah, M.Sc. Marton Gunyho, Dr. Yoshiki Sunada and Dr. Qiming Chen
Topic website: Click here!
Level of student: applications from all students are welcome
(also for people applying for a Mater's or PhD thesis project)

Introduction

Quantum computer is an emerging computational device that can potentially solve some problems of practical interest that are impossible for the classical computer due to the required computational resources. Quantum bits, qubits, are the key ingredient of the quantum computer. Qubits can be employed to store and process quantum information, and they can be measured to extract classical information out of the quantum world.

One of the greatest developments of quantum technologies in the recent years has been the rise of circuit quantum electrodynamics (cQED). Here, superconducting qubits are coupled to microwave resonators and waveguides working at microwave frequencies. This allows not only to reproduce quantum optics experiments carried out with optical photons but also for a spectrum new physics and applications. For the quantum computer, one of the outstanding problems is the implementation of fast and precise qubit operations and measurements.

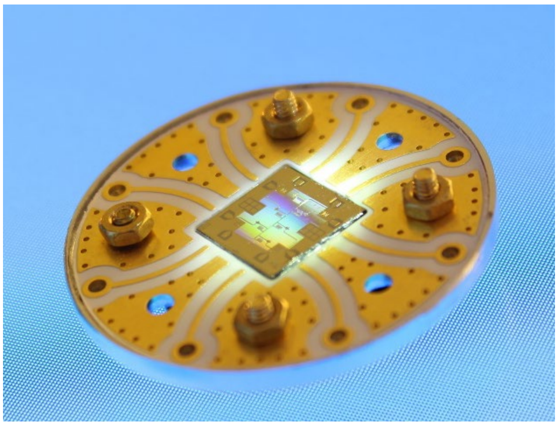

Figure. Sample holder together with a silicon chip in the center. There are six superconducting qubits on the chip made in QCD Labs. Figure credit: Jan Goetz/QCD

Project goals

Your aims in this project may include the following: (i) characterize freshly made superconducting qubits (lifetime, frequency, coupling strengths etc.), (ii) implement and/or model the effects of the quantum features of the drive field on the driven qubit, (iii) simulate the electromagnetics of superconducting qubits and resonators, (iv) implement fast and accurate single-qubit gates, and/or (v) develop techniques to measure qubits more accurately using a bolometer (see also next topic) and multichannel driving. Mostly we are still doing these experiments with transmon qubits but this project can also be combined with unimons.

Working methods

The main focus of the project can be adjusted according to your level and interests.

Most of the above-mentioned goals are experimental, i.e., implementation of known schemes for qubits which have already been fabricated before the summer. This requires studying the theory and programming the measurement equipment. However, in the development of novel methods, deep theoretical knowledge is to be obtained and analytical calculations and numerical simulations need to be carried out.

Thesis possibilities

Depending on your level, this project can be adjusted for a BSc thesis, special assignment, MSc thesis, or a PhD thesis project. Some knowledge of quantum mechanics and an excellent study record is preferred.

Further reading and watching

(The backup links for arXiv versions of the papers can be used in the case if you cannot access the original journal paper.)

- Most recent paper on bolometric readout of qubits
- Video on our recently developed multichannel readout technique
- Joni's scientific talk on the multichannel readout
- Our original paper on the multichannel readout (backup link)
- Our paper on energy-efficient quantum computing (backup link)

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Ulrasensitive microwave detector

(project title)

Field of research: Superconducting nanoelectronics

Topic instructors: Dr. Priyank Singh, Dr. Jian Ma, Dr. Yoshiki Sunada, and M.Sc. Marton Gunyho

Topic website: Click here!

Level of student: applications from all students are welcome (also for people applying for a Mater's or PhD thesis project)

Introduction

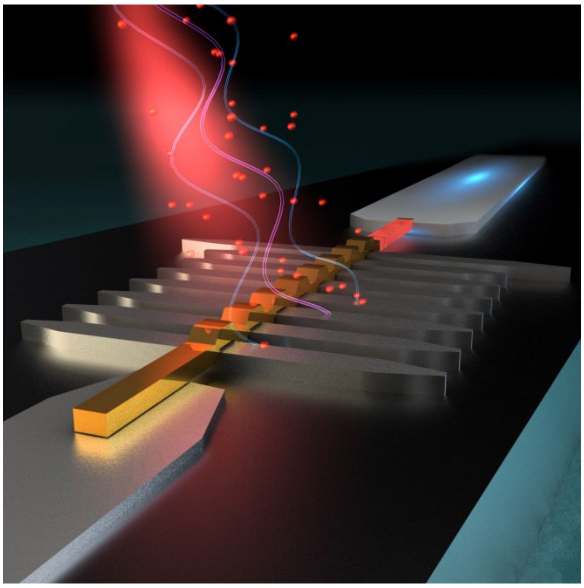

Figure. Artistic image of our microwave detector in operation. See the linked articles for details. Credit: Ella Maru Studios.

One of the greatest developments in the recent years has been the rise of circuit quantum electrodynamics (cQED). Here, superconducting qubits are coupled to microwave cavities and waveguides working at microwave frequencies. This allows not only to reproduce quantum optics experiments carried out with optical photons but also for a spectrum new physics and applications. One of these applications is an already built on-demand high-fidelity single-photon source, a device that is lacking in the optical range. Furthermore, some superconducting devices have nonlinear character that can be used to couple the photons. Thus, this opens up the avenue for a quantum computer based on single microwave photons.

We have recently demonstrated the most sensitive bolometer in the world (see the attached article). This detector can ultimately be used as a measurement device for the single microwave photon qubits. First however, we aim to use this device in more standard qubit readout and also as an extremely sensitive sensor of thermal radiation.

Project goals

Your aim in this project can be the following: (i) use our microwave bolometer to observe ultrasmall energy packets in a continuous mode to go beyond the single-zeptojoule regime that is currently the world record, (ii) build a more detailed theoretical model for the operation of the electromagnetic circuit, which again could be used to analyze and optimize experiments, (iii) develop the bolometer towards a cryogenic spectrum analyzer, (iv) multiplex bolometer readout, or (v) use the bolometer to readout qubits or transitions of single electrons (see previous topic as well).

Working methods

Experiments on the topic will be carried out during your project using a sample already fabricated in the group. Furthermore, the measurement setup and scripts are well developed, but can always be improved! It is also possible to focus more on theoretical modelling of the electromagnetic circuit.

Thesis possibilities

Depending on your level, this project can be adjusted for a BSc thesis, special assignment, MSc thesis, or a PhD thesis project. Some knowledge of quantum mechanics and an excellent study record is preferred.

Further reading and watching

More understanding on the QCD efforts on this topic can be found at:

(The backup links for arXiv versions of the papers can be used in the case if you cannot access the original journal paper.)

- Most recent paper on bolometric readout of qubits
- Video on the Nature paper we published recently
- Old video when we started the bolometer development (check out my hair!)
- Our recent Nature paper on the graphene bolometer (backup link)
- Nature Communications paper on world-record-low bolometer noise (backup)
- Our first bolometer paper showing zeptojoule resolution in latching mode (backup link)

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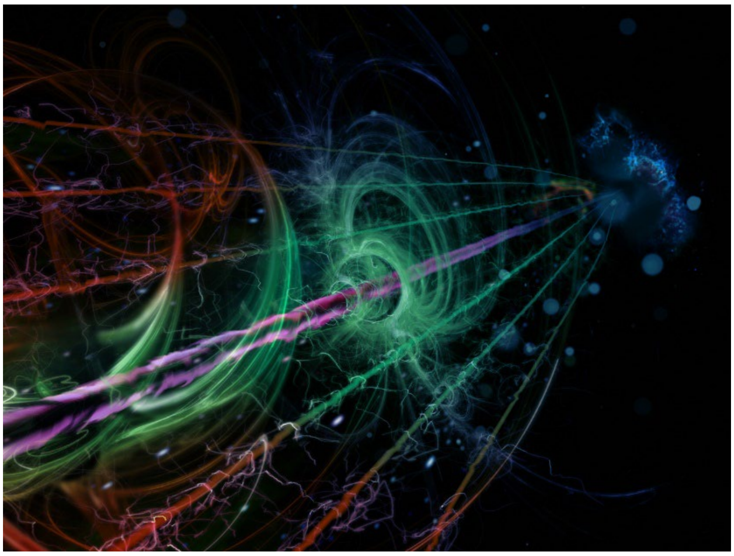
Quantum sensing and communications

(project title)

Field of research: Superconducting quantum electronics
Topic instructors: M.Sc. Aarne Keränen and Dr. Qiming Chen
Topic website: Click here!
Level of student: applications from all students are welcome
(also for people applying for a Mater's or PhD thesis project)

Introduction



In addition to quantum computers, quantum sensing and communications forms a solid pillar of quantum technology. Here, the quantum properties of photons or other quantum systems are used to gain advantage over the classical protocols. For example, in a quantum radar, entanglement between photons is utilized to achieve higher signal-to-noise ratio than what is possible in a classical radar. In quantum key distribution, on the other hand, quantum superposition of single photonic qubits is used to achieve eavesdrop-free communications.

Project goals

Your aim in this project is to measure high-order correlation functions of propagating microwave fields using linear amplifiers and bolometers. The project may also involve an implementation of an on-demand single-photon source and its characterization. These experiments pave the wave for new quantum communication protocols.

Working methods

Experiments on the topic will be carried out during your project using a sample already fabricated in the group. Furthermore, the measurement setup and scripts are well developed, but can always be improved! It is also possible to focus more on theoretical calculations on a new type of a quantum radar.

Thesis possibilities

Depending on your level, this project can be adjusted for a BSc thesis, special assignment, MSc thesis, or a PhD thesis project. Some knowledge of quantum mechanics and an excellent study record is preferred.

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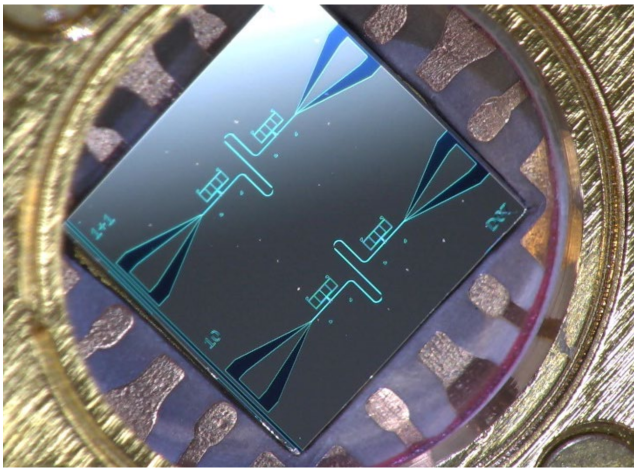
Quantum heat engine and refrigerator

(project title)

Field of research: Superconducting quantum electronics
Topic instructors: M.Sc. Miika Rasola, M.Sc. Heidi Kivijärvi, and Vasilii Vadimov
Topic website: Click here!
Level of student: applications from all students are welcome
(also for people applying for a Mater's or PhD thesis project)

Introduction



For many years, we have been building high-quality superconducting quantum electric circuits and quantum-circuit refrigerators that may be used to provide engineered tunable environments to these devices. Now we wish to collect all this knowledge to make an impact on a hot topic: quantum heat engines and refrigerators.

Quantum heat engines are much like classical heat engines in the sense that they provide work from the heat that flows through them from a hot bath to a cold bath. However, the quantum heat engines operate at the level of individual quantum levels and hence face a challenge: how to obtain more work out than is put in to control the engine. A related topic here is a refrigerator that works on heat, i.e., we heat one end of the device and another end cools down.

Project goals

Your aim in this project is to study a new quantum-heat-engine or refrigerator design.

Working methods

Experiments on the topic will be carried out during your project using a sample already fabricated in the group. It is also possible to focus more on theoretical modelling of the electromagnetic circuit.

Thesis possibilities

Depending on your level, this project can be adjusted for a BSc thesis, special assignment, MSc thesis, or a PhD thesis project. Some knowledge of quantum mechanics and an excellent study record is preferred.

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Quantum knots and monopoles

(project title)

Field of research: Topological phenomena in dilute Bose-Einstein condensates
Project instructor: Dr. Toni Annala (instructing remotely)
Website Click here!
Level of student: applications from all students are welcome
(also for people applying for a Mater's or PhD thesis project)

Introduction

Bose-Einstein condensation is a manifestation of macroscopic occupation of a single quantum state. The idea of such a macroscopic occupation dates back to 1924–1925, when Albert Einstein extended the statistical arguments presented by Satyendra Nath Bose to systems consisting of a conserved number of bosonic particles. Einstein realized that at sufficiently low temperatures the quantum statistical distribution of an ideal gas of bosons shows *condensation* of a macroscopic fraction of the material into the ground state of the system. This phenomenon, subsequently coined Bose–Einstein condensation (BEC), is a unique, purely quantum mechanical phase transition in the sense that it occurs in principle even in noninteracting bosonic systems. Nowadays, BECs are routinely produced in research laboratories around the world and they provide a unique opportunity to study fundamental quantum phenomena.

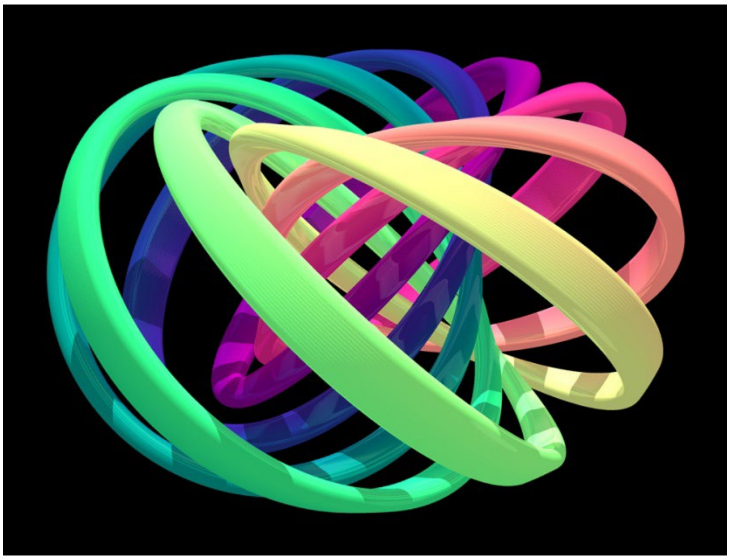

Figure. Visualization of the first quantum knot. (Credit: David Hall)

Recently, we created and observe knot-like structures referred to as knot solitons in quantum-mechanical order parameter describing a BEC. See the attached manuscript that was published in Nature Physics. Although knots have been tied in the classical ropes for millennia and considered in classical fields for more than a century, no one had previously observed a single knot in the context of quantum dynamics.

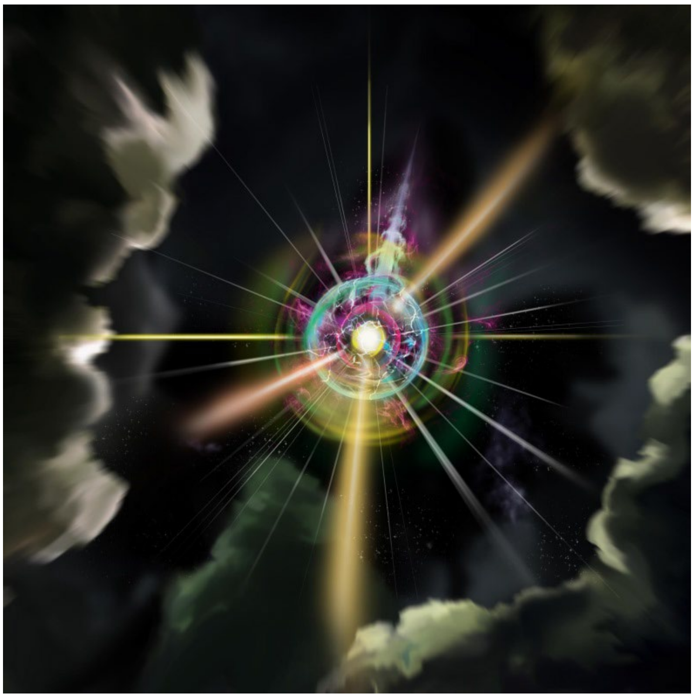

Figure. Artistic image of a Dirac monopole in a BEC. (Credit: Heikka Valja)

More than 80 years ago, Paul A. M. Dirac was the first scientist to find a feasible solution for an electron wavefunction in the magnetic field produced by a magnetic monopole. This celebrated result also reveals that electronic charge must be quantized provided that even a single magnetic monopole exists in nature. However, no magnetic monpoles have been convincingly found. Even the experimental observation of the quantum-mechanical structure acquired by the electron wavefunction found by Dirac has been lacking. In fact, there has been no confirmed experimental observations of monopoles in any quantum field prior to our work. In 2014, we published in Nature an article (attached) reporting the first experimental observations of Dirac monopoles in the so-called synthetic magnetic field produced in our spinor BEC. In 2015, we published in Science the first experimental observations of topological point defects, that is, isolated monopoles, in the quantum-mechanical order parameter describing the BEC.

Project goals

TBD

Working methods

Your work will involve building the theoretical understanding of topological properties of BECs and knots. You will also carry out numerical modeling.

Thesis possibilities

Depending on your level, this project can be adjusted for a BSc thesis, special assignment, MSc thesis, or a PhD thesis project. Prior knowledge of quantum mechanics and an excellent study record is a prerequisite.

Further reading and watching

More understanding on the QCD efforts on this topic can be found at:

(The backup links for arXiv versions of the papers can be used in the case if you cannot access the original journal paper.)

- Video on the creation of the first Dirac monopoles in the world
- Video on the creation of the first quantum knots in the world
- Video on the creation of the first quantum-mechanical monopoles
- Our Nature paper on the creation of the Dirac monopole (backup link)
- Our Science paper on the creation of the quantum-mechanical monopole
- Our Nature Physics paper on the creation of the quantum knot (backup link)
- Our Science Advances paper on the creation of the Shankar skyrmion a.k.s. quantum ball lighting

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