Introduction

We're delighted that you're interested in doctoral research with the EPSRC Centre for Doctoral Training (CDT) in Quantum Technology Engineering, which spans Southampton's Faculty of Engineering & Physical Sciences and involves the Schools of Physics & Astronomy, Chemistry, Electronics & Computer Science, Engineering and the Optoelectronics Research Centre, as well as the Faculty's nanofabrication cleanrooms and Institute for Sound & Vibration Research.

The following pages outline the projects currently being offered for PhD students starting in the autumn of 2024; it's likely that a few more will be added during the year. In general, the exact details will be refined in discussion with the student, both to refine the scientific approaches and objectives and to match students' interests and inclinations. Please therefore use these descriptions as a way to identify supervisors in areas that interest you, and contact the supervisors individually to discuss things further.

As well as your PhD research, your doctoral studies will include a 12-week placement with one of our commercial partners, and an exciting new programme of practical training to give you the skills, knowledge and experience for a future career in Quantum Technology Engineering, whether it be developing devices, systems and components in the thriving industry sector or advancing our fundamental understanding and underpinning techniques in university research.

While we're delighted to discuss projects, study details etc. with you informally, we hope you'll in due course make a formal application via the webpage

https://www.southampton.ac.uk/study/postgraduate-research/apply

Please select the programme type 'Research' and the 'Faculty of Engineering & Physical Sciences' and search for "quantum" to find the programme "PhD Quantum Tech Eng".

We look forward to hearing from you.

Tim Freegarde, Marina Carravetta, Peter Horak qte-admissions@soton.ac.uk

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1 General Purpose Machine Learning Tool-Kit for Bragg Coherent Diffraction Imaging

Dr Marcus Newton, Dr Dan Porter[1], Prof Steve Collins[1], Prof Paul Quinn[2]
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Deep learning has emerged as a powerful alternative to the iterative phase retrieval approach, that can provide robust reconstruction of Fourier-space diffraction pattern data where iterative methods often fail to solve the phase retrieval problem. Although emphasis to date has focussed on inversion from Fourier-space to real-space images, the process of recovering real-space images remains unclear due to the inherent and currently intractable complexity of deep learning methods. In this project you will develop Physics-Aware Super-Resolution convolutional neural network tools to enhance the visibility of Fourier-space diffraction patterns thus enabling rapid and accurate reconstruction of phase information.

This project is a collaboration with the Ada Lovelace Institute and Diamond Light Source.

2 Experiments for testing gravity of small masses

h.ulbricht@soton.ac.uk Prof Hendrik Ulbricht

We aim to set up two-mass (source mass & probe mass) experiments in low noise settings for probing the inverse square law scaling for accelerations below 10^{-11} m/s^2. Modifications of gravity, such as by new particles and interactions, predict deviations from Newton's law and indeed the general relativistic scaling with distance. We will probe gravity in a new regime for small acceleration and small source masses. Experiments are in the domain of levitated mechanics, where optical, electric or magnetic fields are used to trap nanometre to micrometre sized particles in vacuum, which are superb probes of gravity, and are optimised to reduce systemic effects. The ultimate goal is to put the source mass in a quantum superposition state and probe its gravity.

3 Experiments to generate macroscopic quantum states

h.ulbricht@soton.ac.uk Prof Hendrik Ulbricht

We aim to generate macroscopic quantum states by putting nanoparticles in spatial superpositions analogous to matterwave interferometry. Modifications of quantum theory such as decoherence and collapse models are predicted to fail in this attempt fundamentally at computable levels of macroscopicity. We will generate superpositions by Talbot interferometry and by measurement-based schemes using dynamical non-linearities. Experiments are based on optical, electric and magnetic trapping of nanoparticles and microparticles in vacuum. The ultimate goal is to test any limitations of quantum mechanics in the macroscopic domain for particles spanning from atomic scales all the way up to particles visible without a magnifying glass.

4 Sensors for small acceleration detection for gravimetry and magnetometry in real world environments & in space

h.ulbricht@soton.ac.uk Prof Hendrik Ulbricht

We aim to provide sensors to operate at real world setting to the acceleration noise level of 10^{-10} $m/s^2/\sqrt{Hz}$. Such sensors will allow to significantly improve our ability to track masses to monitor their movement and change as well as to detect magnetic fields at record low levels. Sensors are based on optical and magnetic trapping of millimetre-sized particles in vacuum and are realised on compact platforms in remote operation. Some sensors are optimised for use of small satellites for geodesy and consistent data production for processes relevant from climate change. Other sensors are portable on ground including under water. The operation of multiple sensors as integrated network will be used to enhance spatial as well as temporal resolution for specific sensing applications.

5 Room temperature mid-infrared quantum technologies

s.de-liberato@soton.ac.uk Prof Simone De Liberato

Quantum technologies usually work at milli-Kelvin temperatures, which require the use of cumbersome dilution fridges. This is a major problem, because a single fridge is large as a small room and costs more than $1M. In this project we aim to exploit recent results in the coherent control of phonons, photons, and defects in crystal lattices to develop a novel quantum technology platform which can work at room temperature. The project is theoretical and it will allow the PhD candidate to use both numerical and analytical techniques.

6 Quantum Meta-Optics

bruce.ou@soton.ac.uk Dr Bruce Ou, Prof Otto Muskens

Meta-optics, harnessing subwavelength 2D nanostructures, commonly referred to as meta-atoms, arranged in either a periodic or aperiodic fashion, have garnered growing interest for their extraordinary ability to control light in both classical and quantum domains. These meta-optics serve as an ideal and distinctive foundation for creating quantum light sources with a range of characteristics previously beyond reach. Additionally, their flexibility, compactness, and versatility position meta-optics to supplant cumbersome optical components in the realm of quantum state engineering for applications in photonic quantum technologies.

This PhD project, sponsored by QinetiQ, will focus on developing quantum meta-optics to control and manipulate complex interaction between quantum light and matters.

7 Quantum well membrane laser integrated with metasurface

bruce.ou@soton.ac.uk Dr Bruce Ou, Prof Vasilis Apostolopoulos

Membrane quantum well waveguide lasers are a more flexible route to hybrid silicon/III-V laser structures in which a III-V quantum well membrane laser is contact-bonded onto the surface of silica on silicon substrates (see Optics Express 30, 32174 (2022)). We have the capability to release these membranes and position them in the integrated photonics cleanroom. The membrane quantum well lasers can provide lasing in-plane as a single laser or an array of coherent lasers without the use of an external cavity. They show the potential to be integrated with silicon photonics as the light source. Here we want to combine these laser sources with meta-surfaces. Meta-surfaces, harnessing subwavelength 2D nanostructures, commonly referred to as meta-atoms, arranged in either a periodic or aperiodic fashion, have garnered growing interest for their extraordinary ability to control light in both classical and quantum light (see Nature Photonics 15, 327 (2021)).

This PhD project will focus on developing the quantum well membrane laser integrated with meta-surface to manipulate the emission properties such as direction of emission, coherence, polarisation and so on.

8 Quantum well membrane lasers for generation of vortex beams

v.apostolopoulos@soton.ac.uk Prof Vasilis Apostolopoulos, Dr Bruce Ou

Membrane quantum well lasers contact-bonded onto the surface of sapphire or silicon carbide have been demonstrated to create perfect Gaussian beams. We have the capability to release these membranes and position them in the integrated photonics cleanroom on top of substrates and we have demonstrated external cavity lasing with them. We will work to create optical vortex beams using these Lasers and incorporate in the cavities meta-surfaces to be able to control the beam output. Meta-surfaces, harnessing subwavelength 2D nanostructures, commonly referred to as meta-atoms, arranged in either a periodic or aperiodic fashion, have garnered growing interest for their extraordinary ability to control light in both classical and quantum light (see Nature Photonics 15, 327 (2021)).

This PhD project will focus on developing the quantum well membrane lasers in combination with meta-surfaces to manipulate the emission properties and chirality. Vortex beams have applications in imaging, quantum computing, optical tweezers and communications.

9 Quantum Sensor Network

Dr Bruce Ou, Dr Alberto Politi, Prof Jize Yan[1]
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Quantum information technology is transforming the landscape of information gathering, encoding, manipulation, transmission, and storage. Photons, among the diverse quantum information carriers, exhibit resilience at room temperature, compatibility with existing communication and sensing infrastructure, and the presence of optical devices.

The field of photonic quantum information technology has unlocked a range of capabilities in communication, sensing, and computing that surpass the potential of classical technology. Leveraging entanglement-based quantum information technology in applications such as sensing, imaging, spectroscopy, data processing, and communication offers a significantly enhanced signal-to-noise ratio compared to classical approaches. Harnessing the quantum phenomenon of entanglement, which enables the connection of photons across the universe, enhances the accuracy and speed of sensors in detecting motion, gravity, and magnetic fields.

This PhD project will focus on developing entangled quantum sensor network for force and displacement sensing at the nanoscale.

10 Tantalum pentoxide resonators for single photon generation and microcombs

v.apostolopoulos@soton.ac.uk Prof Vasilis Apostolopoulos, Prof Alberto Politi

We aim to realise optical frequency micro-combs and single photon emitters based on efficient nonlinear optical waveguide micro-resonators that exhibit the Kerr effect. We will use our tantalum pentoxide waveguide system for the development of micro-resonators that can support soliton formation at excitation wavelengths between 1 μm and 1.5 μm to achieve single photon emission through four wave mixing and Kerr combs. Single photon sources and Kerr combs are useful tools in Quantum computing and cryptography and we will pave the way towards integration of devices with laser sources.

11 Vibrational properties and strain in perovskite semiconductors

silvia.motti@soton.ac.uk Dr Silvia Motti

The main challenge for the commercial viability of perovskite solar cells is long-term stability. Perovskite semiconductors are characterised by soft ionic lattices and large phonon anharmonicity that underpins many of their optoelectronic properties, from charge transport to phase segregation. Understanding and managing lattice dynamics is critical for mitigating ionic migration and preventing degradation. The vibrational properties can be regulated by chemical composition, morphology, and dimensionality. However, many of these factors and their impact on lattice dynamics still need to be understood, such as the coupling between vibrations of the inorganic framework and different organic cations, the effect of surfaces and particle size on lattice expansion or contraction, and the role of strain around heterogeneities. This project aims to understand phonon anharmonicity and polaronic effects in perovskite semiconductors and to identify, develop, and implement vibrational engineering strategies to improve charge transport and material stability. Work would involve fabrication heterostructures, film deposition, optical characterisation, Raman, THz and MIR spectroscopy to study phonon modes and polaron formation.

12 Developing a new generation of tunable single photon emitters

silvia.motti@soton.ac.uk Dr Silvia Motti

Perovskite nanocrystals can be easily fabricated in colloidal suspensions and offer a wide range of colour tunability with high radiative efficiency, making them excellent candidates for light emission applications. Nanoparticles of size comparable with the exciton Bohr radius present quantum confinement and provide another degree of tunability. In addition to classical light emitters, these crystals present promising properties for novel quantum technologies, and they have demonstrated very interesting potential for single-photon emitters. Further development is required to improve stability, minimise blinking, and to understand and optimise the factors that regulate single photon purity. As an additional effort to develop these materials for quantum applications, the choice of capping ligands may be optimised to minimise the impact of phonon scattering and improve coherence lifetimes. This project would involve the colloidal preparation of perovskite nanoparticles, their optical characterisation, the investigation of photon correlation, and optimisation of chemical composition for improved brightness and purity.

13 Integrated solid-state quantum memories for light

p.ledingham@soton.ac.uk Dr Patrick Ledingham

This project aims to fabricate silicon nitride photonic waveguides and microresonators on top of a crystalline substrate doped with rare-earth-ions. The integrated photonic circuits enhance the light-matter coupling to the rare-earth-ions, overcoming the inherently weak transition strengths, to build high-bandwidth quantum optical memories.

This project will develop skills and expertise in experimental physics, solid-state physics, photonic integrated circuits, nanofabrication and quantum optics.

14 Interfacing semiconductor quantum dots with alkali-atom-based quantum memories

p.ledingham@soton.ac.uk Dr Patrick Ledingham

Semiconductor light sources are capable of delivering high rates of entangled photons for quantum technologies applications. This project aim to build a quantum memory based on warm alkali vapours to store and recall these quantum states on demand as a means to synchronisation in a large-scale quantum network.

This project will develop skills and expertise in experimental physics, atomic physics, semi-conductor physics and quantum optics.

15 Molecular design of rare-earth-ion complexes for quantum light-matter interactions on nanophotonic platforms

p.ledingham@soton.ac.uk Dr Patrick Ledingham

Rare-earth-ion complexes are a promising new platform for coherent light-matter interactions. This project aims to synthesize suitable complexes to be integrated into nanophotonic platforms for enhanced interactions.

This project will develop skills and expertise in experimental physics, solid-state physics, photonic integrated circuits, nanofabrication and quantum optics.

16 A compact quantum inertial sensor using atom interferometry

Dr Tim Freegarde, David Harvey[1], Dr Andrei Dragomir[2]
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Quantum inertial sensors, based upon atom interferometry, promise advantages in bias and scale factor stability, but have so far required large, delicate equipment that is difficult to test outside the laboratory. The sensor head's vacuum and optical components in particular have so far been fragile and bulky, with developments mainly limited to scaling down conventional parts with no reduction in component count.

In this project, you'll assemble a quantum inertial sensor aimed at navigation applications. The sensor head will use a new, compact and robust vacuum system to achieve a small, simple and mechanically stable design, with laser and optical systems from an existing atom interferometry system. You'll explore further miniaturization using a novel planar-fabricated atom chip that combines the atom source, vacuum maintenance and optical routing in a sealed-off, postage stamp sized package; and you'll be able to characterize the sensor using the facilities of Southampton's *Institute for Sound & Vibration Research* and undertake practical trials at the *National Oceanography Centre Southampton*. The project will help you to develop skills and expertise in quantum technologies, atomic and laser physics, microfabrication, photonics, imaging, control and instrumentation.

This project is in association with Thales R&T UK and Aquark Technologies Ltd.

17 High fidelity quantum control for sensing and computing

Dr Tim Freegarde, Prof Ilya Kuprov[1]
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Quantum technologies for computing, timekeeping and sensing require atomic wavefunctions to be split and recombined with precision and fidelity. Often, these operations are performed using pulses of laser light, and are affected when atoms move to different beam intensities or incur Doppler shifts. Intriguingly, in the analogous field of magnetic resonance, pulses have been designed that tolerate such variations by shaping the phase and amplitude within each pulse. We have already used these NMR optimal control techniques to design individual ‘mirror’ and ‘beamsplitter’ pulses for atom interferometry.

In this project, you’ll build upon our previous work to investigate pulses whose ‘apparent origin’ are unaffected by movement and intensity variations, so that the calibration scale factor of quantum sensors is better defined. You’ll optimize not just individual pulses but whole interferometer sequences, allowing early errors to be compensated at a later stage; and you’ll introduce ‘dynamical decoupling’ to make the sequences more immune to noise. You’ll look into the origins of intriguing features that emerge during computational optimization. Finally, you’ll be able to demonstrate each of these aspects experimentally. Throughout, you’ll develop skills and expertise in quantum technologies, atomic and laser physics, supercomputing, digital modelling, photonics, control and instrumentation.

This project offers scope for one or two students addressing a combination of computational optimization and simulation, theoretical analysis, and experimental validation and characterization.

18 Momentum-state quantum computer

tim.freegarde@soton.ac.uk Dr Tim Freegarde

The interactions between cold quasi-2-level atoms and the optical field of counter-propagating laser beams allow a new type of quantum computer based upon the ladder of momentum states that the atoms can occupy and their representation as binary numbers. As a computational device, this quantum computer would be terrible, for its size scales exponentially with the number of qubits. However, all information has a physical manifestation, and the value of the momentum-state quantum computer is that it allows complex physical manipulations to be designed from simple operations – for example, the combination of individual laser pulses into complex sequences that cool an atomic cloud by halving each atom’s velocity.

In this project, you’ll demonstrate the momentum state quantum computer for the first time and characterize it experimentally, by combining a new laser system for higher intensities with optimal control pulses designed to maintain fidelity throughout the pulse sequence. In doing so, you’ll develop skills and expertise in quantum technologies, atomic and laser physics, photonics, imaging, digital modelling, control and instrumentation.

19 Quantum control of magnetic processes

i.kuprov@soton.ac.uk Prof Ilya Kuprov, Dr Marina Carravetta

Magnetic resonance spectroscopy and imaging are quantum technologies that use spin – a property of elementary particles that gives them magnetic moments. Strong magnetic fields do not harm chemical systems or biological tissues, they are therefore widely used in chemistry, pharmacology, and medicine.

Both technologies require elaborate hardware, control algorithms, and data processing methods; this project is about improving those. You will be using quantum control theory and machine learning methods to improve speed, sensitivity, and resolution of magnetic resonance spectroscopy and imaging.

This project will develop skills and expertise in supercomputing, artificial intelligence, digital modelling, quantum technologies, nuclear magnetic resonance and magnetic resonance imaging.

20 Magnetic resonance spectroscopy & imaging at the quantum mechanical performance limit

i.kuprov@soton.ac.uk Prof Ilya Kuprov, Dr Marina Carravetta

Magnetic resonance spectroscopy and imaging are quantum technologies that use spin – a property of elementary particles that gives them magnetic moments. Strong magnetic fields do not harm chemical systems or biological tissues, they are therefore widely used in chemistry, pharmacology, and medicine.

Quantum mechanics sets fundamental limits on how quickly and precisely magnetic processes can run; this matters in MRI where the time a patient spends inside the magnet must be minimised. Modern equipment performs far below those limits, and the objective of this project is to design magnetic resonance methods that achieve the best performance permitted by the fundamental constraints of quantum theory.

This project will develop skills and expertise in supercomputing, artificial intelligence, digital modelling, quantum technologies, nuclear magnetic resonance and magnetic resonance imaging.

21 Quantum spin dynamics and how to make it faster

i.kuprov@soton.ac.uk Prof Ilya Kuprov, Dr Marina Carravetta

Spin is a relativistic property of elementary particles that is responsible for all magnetic processes used in chemistry, engineering, medicine, and computer science: magnetic data recording, magnetic resonance spectroscopy and imaging, magnetoresistance in conductors, multiferroic materials, etc.

There are unsolved fundamental questions about how quickly a magnetic process can run – quantum mechanical uncertainty relations create a delicate balance between speed and accuracy of spin dynamics. This project will explore the deep quantum mechanics of magnetisation transport in magnetic resonance spectroscopy and imaging, and find ways to improve the speed and sensitivity of scientific, industrial, and medical devices (NMR spectrometers, MRI machines, etc.) that use spin.

This project will develop skills and expertise in supercomputing, artificial intelligence, digital modelling, quantum technologies, nuclear magnetic resonance and magnetic resonance imaging.

22 Quantum optimal control of quadrupolar nuclei for solid state magnetic resonance

Dr Marina Carravetta, Prof Ilya Kuprov, Dr Matt Potter[1]
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Catalysis is a central process in pharmacology and industrial chemistry that allows sophisticated chemical reactions to proceed with high yield at moderate pressures and temperatures. Catalysts are needed, in particular, for carbon dioxide capture and recycling. However, a common problem is that chemists do not actually know how some empirically discovered catalysts work. One of the ways of finding out is nuclear magnetic resonance - a quantum technology that uses the magnetic moments associated with nuclear spin.

Magnetic resonance spectroscopy of carbon capture catalysts uses atomic nuclei (such as ^{27}Al and ^{14}N) that are not spherical. They are informative, but hard to use because they also have an electric quadrupole moment. This project will develop quantum control methods that facilitate magnetic resonance with quadrupolar nuclei, with the end goal of improving the catalytic performance of these materials, as well as to advance the corresponding magnetic resonance techniques for other applications.

Application of this research will be directed to the investigation of the 14N for amines tethered on porous materials (provided from our collaborator in Bath), which are cutting edge materials for capturing carbon dioxide from the atmosphere, i.e., direct air capture

This project will develop skills and expertise in quantum theory, quantum control, supercomputing, microelectronics and magnetic fields, and nuclear magnetic resonance.

23 Optimal control methods for strongly coupled spin systems in solid materials

m.carravetta@soton.ac.uk Dr Marina Carravetta, Prof Ilya Kuprov, Dr Peter Wells

Solid state nuclear magnetic resonance (NMR), a spectroscopy that uses magnetic moments associated with nuclear spin in a magnetic field, is a non-destructive, powerful technique for investigation of materials in a range of physical states and temperature regimes. However, as most quantum mechanical methods at the moment, it is very far from the sensitivity and accuracy that it could potentially have. Magnetic resonance spectroscopy of solid materials has low sensitivity when it deals with large nuclear spin systems, systems, i.e., for heteronuclear correlations or higher order multiple quantum excitation: our current ability to control nuclear spin dynamics is limited and many existing methods are highly inefficient. The plan is to use quantum optimal control theory to design magnetic resonance methods with radically better performance, and demonstrate experimentally the new approaches. Applications will include gaining a better understanding of catalytic processes; for example using these advancements to follow hydrogen spillover processes on supported metal nanoparticles.

This project will develop skills and expertise in quantum theory, quantum control, supercomputing, microelectronics and magnetic fields, and nuclear magnetic resonance.

24 Symmetry-based optimal control of nuclear spins

mhl@soton.ac.uk Prof Malcolm Levitt, Dr Marina Carravetta, Prof Ilya Kuprov

We will combine the complementary principles of quantum optimal control and symmetry-based pulse sequence design to achieve highly controlled and robust manipulations of nuclear spins in the context of nuclear magnetic resonance (NMR), with applications over a range of areas including biomolecular structure determination and hyperpolarised magnetic resonance imaging. The project will be a combination of theory, simulation, and experiment.

This project will develop skills and expertise in quantum theory, quantum control, supercomputing and nuclear magnetic resonance.

25 Driven propagation of spin order down a nuclear spin wire

mhl@soton.ac.uk Prof Malcolm Levitt, Dr Marina Carravetta, Prof Ilya Kuprov

The concept of a “nuclear spin wire” refers to a molecular arrangement in which a set of nuclear spins are coupled to each other in an extended, roughly linear, arrangement. We will develop and demonstrate methods for driving nuclear spin order from one end of the wire to the other, with applications to nuclear hyperpolarisation, and biomolecular NMR.

This project will develop skills and expertise in quantum theory, quantum control, supercomputing and nuclear magnetic resonance.

26 Integrated photonics for ion-trap quantum computing

peh@orc.soton.ac.uk Dr Peter Horak, Dr James Gates

We will design integrated photonic waveguides and Bragg gratings for delivering light with well-defined beam shape and polarization to single trapped ions on quantum computing chips. Similar designs will also be developed for capturing photons emitted from trapped ions for optical readout and quantum communication.

27 Micro-cavity design for enhanced quantum processing

peh@orc.soton.ac.uk Dr Peter Horak, Dr James Gates

We will investigate novel designs of optical micro-cavities to enhance photon-matter interaction for quantum processing applications. Such designs could be based on freeform optics and may require machine learning tools for efficient optimization.

28 Optimisation of antiresonant hollow core fibres for quantum computing, communications and memories

frap@orc.soton.ac.uk Prof Francesco Poletti, Dr Ghafour Amouzad Mahdiraji

State-of-the-art hollow core fibres developed in Southampton offer the promise to revolutionise the optical communication's physical layer by offering ultralow loss at any desired wavelength. In this project, optimised fibres for various quantum applications will be designed, fabricated and shared with various partners for ground-braking experiments.

The project is supported by Microsoft Azure.

29 Efficient Qubit channeling: interconnecting single photon sources to ground-breaking hollow core light-pipes

r.slavik@soton.ac.uk Prof Radan Slavik, Dr Yongmin Jung, Prof Francesco Poletti

Hollow core fibres are emerging as one of the most exciting waveguiding technology for quantum applications due to their absence of nonlinearity and low attenuation at arbitrary wavelengths. In this project we will develop novel ways to physically interconnect these fibres with single photon sources and detectors used in quantum memories, computers and networks.

The project is supported by Microsoft Azure.

30 Manufacture of atom and ion traps via ultra-precision diamond machining

j.gates@soton.ac.uk Dr James Gates, Dr Paul Gow

Quantum Technologies present new challenges for manufacturing engineering. Southampton has been developing ultra-precision machining systems as a route to the scalable manufacture of atom and ion trap quantum systems. The project will work with leaders in the field (academia and industry) to create vacuum systems with integrated photonic and electrical functionality. And also, develop the machines and processes to enable the growth of the quantum technology industry.

31 Parametric photonics for quantum technologies

corin.gawith@soton.ac.uk Prof Corin Gawith, Dr Goronwy Tawy

Nonlinear parametric photonics is used to control quantum systems as well as sources for photonic qubits. Researchers at the University of Southampton have led the development of quasi-phase non-linear systems. This project will combine novel fabrication approaches with well-developed commercial materials to expand the operation range into the blue and ultra-violet wavelength regions for atom and ion trap quantum systems.

32 Low-loss photonic memories for quantum networks

j.gates@soton.ac.uk Dr James Gates, Dr Rex Bannerman

Using Southampton's state-of-the-art fabrication facilities, we will develop core components for interfacing quantum computers and networks. Unlike optical telecoms, where losses are tolerated and compensated by amplifiers, in the world of Quantum Technology, every photon is precious. This project will create new ultra-low-loss optical components, reducing losses and allowing us to create large, entangled quantum states. In particular, the project will develop quantum memories and switchable delays.

33 Integrated ultra-high-Q ring resonators for the frequency stabilisation of atom-trap clocks

christopher.holmes@southampton.ac.uk Dr Chris Holmes, Dr James Gates

In conjunction with our partner (Caltech), we will develop ultra-high-Q ring resonators for the stabilisation and atom traps. These integrated resonators are a key component in stabilising atom trap clocks. We will also work with other collaborators (Aquark Technologies Ltd.) and PhD students to combine these resonators with miniature atom chip clocks.

34 Nano-opto-electro-mechanical Qubits

yt2@ecs.soton.ac.uk Prof Yoshi Tsuchiya

This project will investigate a novel nano-opto-electro-mechanical (NOEM) qubit that has been realised on a nanoscale suspended beam, controlled electrically and read out via optical interaction. Thanks to mechanical isolation of NOEM qubits from the materials surrounded, longer decoherence time is expected. Optical detection of the quantum state of NOEM qubits will be more energy-efficient than electrical detection. The project will collaborate with IMT Bucharest that possesses strong expertise on micro and nanoscale optical and photonic components. Starting from the design of a single NOEM qubit, a demonstration CNOT operation on double NOEM qubits on silicon nanobeams will be targeted within the PhD period.

This project is in association with IMT Bucharest.

35 RF MEMS switches for quantum technology

chdg@soton.ac.uk Prof Kees de Groot

RF switches are required as part of interfacing RF signals to control qubits, and these switches need to operate very close to 0 K, near the Qubits. The function of the RF switch is to multiplex and reconfigure filters, but solid-state based switches become non-operable at these very low temperatures. A very low loss RF switch is required at these temperatures, as any loss can be converted to heat which is extremely detrimental at cryogenic temperatures. Shrinking the MEMS switch is a core need of the overall technology. The project will focus on development of low-loss RF MEMS switches for qubit control at very low temperature.

This project is in association with Analog Devices.

36 Space-Time-varying superconducting surfaces for enhanced efficiency quantum computing and quantum wave processing applications

Dr Sajjad Taravati, Dr Jize Yan, Dr Mustafa Bakr[1]
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This groundbreaking research project is dedicated to advancing the field of wave engineering and transformation within superconducting quantum computers and quantum processors. The focal point of our investigation lies in the exploration of space-time-varying superconducting metasurfaces, aiming to push the boundaries of next-generation quantum computing. Our interdisciplinary approach combines analytical investigations, numerical simulations utilizing Matlab (FDTD code) and Comsol Multiphysics, and rigorous experimental verification. The primary goal of our research is to revolutionize the quantum computing landscape by addressing key challenges, including the enhancement of coupling between qubits, error correction, and scalability. We intend to leverage the unique properties of space-time-modulated superconductors to overcome these hurdles. Through a comprehensive analytical study, we aim to establish the fundamental principles governing space-time-varying superconducting metasurfaces in the specific context of quantum computing. Numerical simulations play a crucial role in our methodology. Using advanced tools such as Matlab (FDTD code) and Comsol Multiphysics, we model the behavior of space-time-varying superconducting surfaces. These simulations will provide invaluable insights into the performance of these metasurfaces, guiding our experimental design and validating theoretical predictions. Collaboration with material scientists is a key aspect of our approach. By working closely with experts in materials science, we aim to design and optimize superconducting materials tailored for space-time modulation. This collaborative effort ensures that the metasurfaces we develop are not only theoretically sound but also practically achievable, pushing the boundaries of what is currently possible in the realm of quantum computing. In summary, this project represents a significant step forward in the development of quantum computers. Through a holistic exploration of space-time-varying superconducting metasurfaces, we aim to contribute to the creation of more robust, scalable, and efficient quantum processors, ultimately advancing the capabilities of quantum computing for future technological applications.

37 Nonreciprocal quantum metasurfaces for next generation telecommunication systems

s.taravati@soton.ac.uk Dr Sajjad Taravati, Dr Jize Yan

This cutting-edge research initiative focuses on the development of Nonreciprocal quantum metasurfaces for the next generation of telecommunication systems, merging academic excellence with a strong emphasis on enterprise collaborations. While static metasurfaces have proven efficient in manipulating electromagnetic waves, they are constrained by inherent reciprocity and fixed time-/frequency-invariant responses. In response to these limitations, our project introduces a groundbreaking approach: active nonreciprocal quantum metasurfaces. The role of nonreciprocal quantum metasurfaces in this project is paramount. These dynamic solutions enable the generation, guidance, and control of quantum states of light. This breakthrough technology holds immense promise for applications in free-space quantum communication, quantum information processing, quantum computation, and quantum imaging. By providing versatility, reciprocity control, and the ability to translate frequencies for electromagnetic waves, these metasurfaces have the potential to revolutionize the field of telecommunications. A distinctive feature of this project is its strategic design to foster robust industrial collaborations. By actively seeking partnerships with industry leaders, we aim to drive enterprise efforts and create opportunities for spinouts and commercialization. This collaborative approach ensures that the research outcomes are not only academically significant but also commercially viable, contributing to the broader technological landscape. The project employs innovative techniques such as spatiotemporal decomposition, quantum scattering and diffraction, digital coding, nonreciprocal transmission, pure frequency conversion, parametric wave amplification, and multifunctional operations. These techniques form the basis for pushing the boundaries of light manipulation, opening new avenues for the development of advanced telecommunication systems. In summary, this transformative project stands at the forefront of research in nonreciprocal quantum metasurfaces, aiming to redefine the possibilities in telecommunications. Through a combination of academic rigor and strategic industry collaborations, we aspire to not only advance the scientific understanding of quantum metasurfaces but also pave the way for practical applications that will shape the future of telecommunication systems.

38 Mimicking quantum phenomenon on a silicon photonic chip

x.fang@soton.ac.uk Dr Xu Fang

Based on the similarity between the Schrodinger equation and the Maxwell's equations, many intriguing quantum phenomena can be imitated in the classical regime, by manipulating photons on a nanofabricated photonic chip. Such imitation inspires new ideas for photonics research, and have resulted in a series of new and influential discoveries. This project will start with the phenomenon of bound states in the continuum, which has attracted a lot of research attention recently due to its potential for novel sensing [e.g., as the project supervisor and his collaborators reported recently in Advanced Optical Materials 11, 2301979 (2023)]. One of the major goals of this project is to demonstrate utilizing this phenomenon for automotive LiDAR (light detection and ranging) sensing, which could accelerate the arrival of the era of fully autonomous driving.

39 On-chip quantum cryptography using two-dimensional materials

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Existing techniques to encrypt data in our Internet networks are vulnerable to being easily breakable by emerging quantum computers. IBM has recently released a 1000 qubit quantum computer and the challenge of finding alternative techniques to encrypt our data is becoming ever more urgent. Fortunately, quantum cryptography is a suitable solution to overcome this challenge. However, quantum cryptography requires unique lasers that can emit single photons and entangled photon pairs. In this PhD project, you will use two-dimensional (2D) materials as single-photon light sources. Strain and defect engineering in 2D materials can result in in-gap discrete energy levels in the electronic structure of the material, leading to the creation of single and entangled photon sources. The wavelength can vary from visible to near IR depending on the chosen material. Once the photo-emitters are generated in the 2D materials, they can be transferred onto almost any arbitrary substrates including silicon photonic circuits (waveguides, couplers, photonic crystal cavities, etc.), making them an even more attractive candidate for on-chip photon sources. Key challenges will be understanding the nature of the single and entangled photon emission in this family of materials and tailoring their properties to their potential usage in quantum communications.

40 Quantum nanomaterials revolution

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Quantum nanotechnology represents a cutting-edge field that harnesses the principles of quantum mechanics to manipulate materials at the nanoscale. At this level, quantum effects become increasingly pronounced, offering unique opportunities for designing and engineering materials with unprecedented properties. Nano materials, a key focus in this realm, play a pivotal role in shaping the future of technology and science. Nano materials in quantum nanotechnology also include carbon-based structures like graphene and carbon nanotubes. These materials possess exceptional strength, electrical conductivity, and thermal properties due to their unique atomic arrangements. They find applications in various industries, from flexible electronics to lightweight and robust materials for aerospace. Furthermore, the integration of quantum dots and nano materials is paving the way for quantum computing. Quantum bits or qubits, the fundamental units of quantum information, can be encoded in the quantum states of nano materials, allowing for the development of powerful quantum computers with the potential to solve complex problems exponentially faster than classical computers.

This project is in association with Quantum Base Ltd.

41 Using machine learning for designs of resource-aware variational quantum algorithms

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Recent research objectives in noisy intermediate-scale quantum (NISQ) algorithms seek to exploit hard-won gains in quantum hardware developments to access computational results that challenge classical computers. Variational quantum algorithms (VQA) are a family of methods that optimise the parameterisation of quantum circuits to approximate expectation values of properties measured on quantum states. The expressive power of these parameterised circuits in VQA depends on the ansätze designed for a particular problem. In addition to expressivity, limitations on error-correction in NISQ hardware imply the amplification of errors with the depth of quantum circuits, further constraining the design space. Machine learning (ML) methods are being developed to navigate this design space using hybrid methods, and this will be the focus of this project. ML methods that operate by reducing an appropriately defined loss function by gradient descent are also generically known to encounter a ‘barren valleys’ problem which hinders access to the parameterised space, prompting a further reconsideration of the circuit ansatz. A family of measurement based quantum algorithms have also been proposed that start with an entangled cluster state and well-chosen single qubit measurements alter the state of the network, propagating information via teleportation across the cluster. These measurement based variational quantum algorithms offer a different window into the space of states defining the computational state, as well as the compiled set of qubits that come with the noisy profiles that the neural network based algorithms will seek to ameliorate, within the constraints over the design space. Classical processing of information shared across nodes of a graph have been successful in graph neural network architectures; this project will explore the design of a suitable graph quantum neural network for measurement based variational quantum algorithms.

42 Efficient light harvesting in hybrid quantum dot tandem solar cells through luminescent downshifting

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Ever-increasing global energy demands have put tremendous pressure on current natural resources, creating a growing need for cheap and efficient renewable energy. Photovoltaic technologies have shown great promise to tackle these challenges with global energy production capacity exceeding 1TW in 2022 and rapidly growing. With a market share of over 95% and lab power conversion efficiency (PCE) exceeding 26%, silicon (Si) solar cells currently dominate the industry. As the extraction efficiency for photo-generated carriers is near the theoretical limit for such devices, new light management approaches are required to exceed cell efficiencies over the 29% Shockley–Queisser limit. Quantum Dots (QDs) possess unique properties of bandgap tunability and high absorption cross section compared to bulk semiconductor materials. Radiative combination is the basis for luminescent downshifting (LDS) - high-energy photons are absorbed by a luminescent material (such as QDs) which re-emits at a lower energy more efficiently utilized by the solar cell. Recent advancements in QD technology leveraging such effects as quantum cutting have made possible PLQYs greater than 140%, thus unlocking the tantalizing prospect of multi-photon LDS. Such an architecture could prove extremely efficient when combined with tandem solar cells.

This project is in association with National Physical Laboratory and Ossila Ltd.

43 Quantum topology optimisation for aerospace design

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Topology optimisation is one of the most powerful engineering design technologies. It is superior to shape and size optimisation as it can theoretically create an optimum object from scratch. There is an ever-growing interest in using topology optimisation in industries for different design problems. An ultimate example is aircraft configuration design. After more than a century of aviation, we still do not know what the optimum configuration for a flying vehicle is. In other words, if we want to transport a given amount of payload over a given distance using state-of-the-art technologies, how should the flying vehicle shape to e.g., minimise energy consumption and in-flight emissions? A topology optimisation technology might be able to answer this question. We have developed a technology for creating flying vehicle configurations using topology optimisation. However, it is still in very early development stages, i.e., it works for the aerodynamic design of micro-air vehicles at very low speeds. However, we need a few million design variables coupled with high-fidelity aerodynamic analysis for such a basic design. Extension of this technology towards more realistic design problems means the need for a few billion design variables coupled with multi-physics (e.g. fluid-structure interaction) solvers. The computational costs of the state-of-the-art technologies for multi-physics topology optimisation are prohibitive for such applications.

Quantum optimisation algorithms are in the early development stages; however, they showed promising potential for accelerating complex optimisation problems. This project aims to investigate the development and application of dedicated quantum optimisation algorithms to solve topology optimisation problems relevant to aerospace design.

44 Efficient end-to-end quantum machine learning strategies for imaging

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Near term quantum computers promise significant computational gains in a range of machine learning applications, including in image estimation, processing and classification. Whilst advantages due to quantum parallelism and entanglement have been shown in a range of applications, efficient encoding of classical information into an entangled quantum state is known to be computationally challenging in general. In this project, you will study and explore the entire computational chain, exploring the interaction of classical dimensionality reduction methods with subsequent quantum encoding strategies, coupled with efficient quantum machine learning performed on the low-dimensional, encoded state. Depending on the task, this will be coupled to a novel statistical decoding stage that will convert quantum measurements back into classical image information. This project has scope for the student to pursue their own interest and offers the opportunity to direct the focus on theoretical mathematical concepts, theoretical algorithm development and applied computational experiments.

45 Advancing quantum insights in memristor-based devices

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This PhD project aims to delve into the uncharted territories of quantum effects in memristive devices, with a specific focus on Silicon Carbide (SiC)-based memristors. The overarching goal is to harness quantum phenomena for advancing new information processing technologies. Recent studies have highlighted that memristive elements, known for their resistive switching capabilities through the electrochemical formation and rupture of conductive nanofilaments, also demonstrate quantum conductance effects at room temperature. This project will build upon this foundational knowledge to explore the potential of SiC-based memristors in quantum computing applications.

The research will encompass a thorough investigation of the fundamental electrochemical and physicochemical phenomena that underlie the functionalities of these devices. Special attention will be given to the electronic conduction in nanofilaments and its implications for quantum conductance. A significant part of the research will be devoted to developing methodologies for creating and controlling atomic-sized conductive filaments in SiC-based memristors.

Through this project, the PhD candidate will contribute to the field by addressing the current gap in understanding the quantum effects in memristive devices. The research outcomes are expected to pave the way for potential applications in next-generation memories, neuromorphic computing architectures, and integrated quantum systems, revolutionizing the landscape of information processing technologies. The student will have the opportunity to join a dynamic research team and have access to advanced nanofabrication as well as electronic characterization facilities in the state-of-art Southampton Nanofabrication Centre. The student will benefit from academic research expertise from a dynamic supervisory team from both ECS and Engineering.

46 Smart synthesis of colloidal quantum dots for quantum devices

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Colloidal quantum dots are semiconductor nanocrystals that sit in between molecular and bulk materials. Their small size (typically <10 nm in diameter) are comparable to the material's Bohr radius, leading to quantum confinement of excitons and size- and composition-tunable optoelectronic properties. Compared to other quantum-confined nanostructures (e.g. epitaxial quantum dots, wires or wells) they have the advantage of being solution-processable, which makes them well suited for mass production of devices.

In this project you will look at methods for efficiently producing device-quality quantum dots ready for making the quantum technology devices of the future. In particular, you will look at combining flow reactors with inline optical analysis methods and computer control, taking advantage of recent developments in reactor technology and algorithms to control reactions and explore reaction parameter space. You will autonomous reactors that can continuously produce high quality quantum dots, monitor the quality of them as they are produced, and independently determine optimum reaction parameters.

47 Quantum secure direct communications

sxn@ecs.soton.ac.uk Prof Michael Ng, Prof Lajos Hanzo, Dr Chao Xu

Quantum Secure Direct Communication (QSDC) represents a unique paradigm in secure information transmission, harnessing quantum states to ensure confidentiality and reliability in the face of a noisy, lossy, and wiretapped quantum channel. The method has demonstrated information-theoretical security, showcasing its potential to revolutionize secure communication technologies. Recent experimental breakthroughs underscore the viability of QSDC for long-distance communication and large-scale networking, particularly in the context of free-space communication, which presents unique advantages and promising prospects for practical, large-scale applications. Following a comprehensive review of the fundamental principles of QSDC, free-space QSDC will be investigated. Channel coding will be harnessed to enhance the reliability of the QSDC communication link. We aim to provide insights into the potential large-scale deployment of this technology in real-life scenarios.

48 Quantum coding assisted quantum key distribution

sxn@ecs.soton.ac.uk Prof Michael Ng, Prof Lajos Hanzo, Dr Chao Xu

Quantum Key Distribution (QKD) is one of the cornerstones in ultimately secure communication, leveraging the principles of quantum mechanics to establish cryptographic keys immune to eavesdropping. A wide variety of error correction coding techniques may be harnessed for enhancing the security of key distribution. In this context we seek to unveil compelling practical avenues for the integration of QKD techniques into real-world communication networks. Hence the purchase of a pair of QKD schemes is recommended, which would facilitate the completion of practical experiments.

49 Quantum control and Floquet engineering with quantum fields

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Controlling and manipulating quantum systems using electromagnetic fields underpins many cutting-edge quantum technologies. Typically, these fields are assumed to be classical. Recent work in the Quantum Optics Theory group at Southampton [Phys. Rev. Lett. **129**, 183603 (2022)] has proposed a new mathematical description of the quantum-to-semiclassical transition in light-matter interactions, challenging the assumption that fields containing many photons can always be treated classically. This project will develop that framework into practical mathematical and computational techniques for analysing the effects of field quantisation on quantum control. Applications in superconducting circuit QED, the basis of many leading quantum technology platforms, and in the emerging field of Floquet engineering will be explored, with opportunities to pursue experimental collaborations.

50 Exploring light-matter interaction for quantum materials engineering

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Our pioneering research has shown how interactions between matter and the quantum vacuum in nanophotonic devices can significantly alter the electronic and optical properties of materials.. Our goal is now to turn our discoveries into useful tools to design and fabricate engineered quantum materials enabling applications in sensing, quantum computing, and quantum optoelectronics.

In your PhD studies, you will engage in the theoretical investigation of light-matter coupling phenomena, with the aim to test and optimize accurate protocols for designing photonic and electronic states that can be dynamically modified in a controllable manner.

You will gain expertise in cavity-based quantum systems, ranging from atomic and molecular gases to solid-state semiconductor heterostructures and 2D metamaterial devices. Along the way, you will master a variety of scientific tools, including analytical techniques and numerical modelling methods, as well as gain experience with software like COMSOL and other multiphysics simulation tools.

The project involves collaboration with various experimental groups overseas, primarily in Europe, offering you the chance to travel, network, and work alongside leading experts in the fabrication and measurement of quantum nanostructures to test your theoretical predictions. You will also have opportunities to present your results at both national and international conferences and workshops.