QUANTUM THEORY OF LIGHT AND MATTER

We study a broad range of topics within the framework of the Theory Division that spans from the electronic, magnetic and optical properties of 2D materials, topological order and superconductivity, to the development of the theory of quantum transport and strongly-coupled non-equilibrium phenomena, quantum thermodynamics, quantum noise, open quantum systems, nanoplasmonics and nanophotonics. The study of complex quantum systems involves a diverse array of tools, including advanced quantum-field-theoretical techniques (Feynman diagrams, path integrals, non-equilibrium Green's functions), quantum kinetic and transport theory, master equations, and group theory, using both numerical and analytical approaches. The strong connection to experimental groups at the School of Physics and Astronomy and the National Graphene Institute allows prompt testing of newly developed theories, especially in relation to studies of physical phenomena in two-dimensional materials, which remain a distinctive research beacon of the University of Manchester and were the subject of the 2010 Nobel Prize in Physics.

Possible projects are available on topics similar to those listed below under the individual members of staff. Other projects may be available. Some projects will involve joint supervision between two or more members of staff.

Condensed matter theory

Theory of Quantum Nanomaterials

Prof. Vladimir Fal'ko (vladimir.falko@manchester.ac.uk)

Professor Vladimir Fal'ko studies electronic and optical properties of two-dimensional (2D) materials and their heterostructures. 2D materials are atomically thin crystals which electronic and optical properties are dominated by quantum physics not only in cryogenic conditions, but even at the room temperature. His current projects include:

- many-body phases of electronic liquids in 2D materials, including the quantum Hall effect in 2D materials with multi-valley spectra, where electrons are characterised by valley quantum numbers additional to their spin state;
- quantum properties of minibands generated by moiré superlattices generic for heterostructures of 2D materials with slightly incommensurate periods and for twisted homo-bilayers of all 2D materials;
- modelling optical properties of 2D materials, from THz range (intersubband transitions in few-layer films and modelling of new types of cascade lasers) to

single photon emissions from excitonic complexes (trions, biexcitons, quintons, etc) in heterostructures, including the influence of moiré superlattice effects.

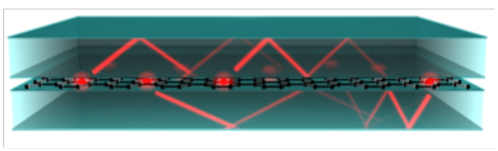
- Modelling heat transport in 2D materials and related thermoelectric properties.

These projects will enable students to learn field theoretical methods in condensed matter theory; analytical and computational quantum transport theory; group theory and symmetry applications in solid state physics. The studies will be carried out in collaboration with experimental groups involved in the European Graphene Flagship at Manchester, Geneva, ETH Zurich, LNCMI-CNRS in Grenoble, and our partners in the European Quantum Technologies Flagship at Cambridge and ICFO in Barcelona.

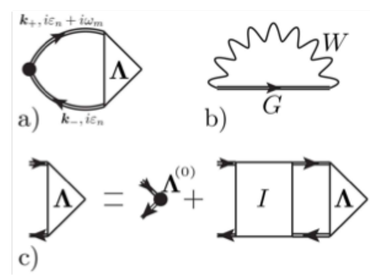
http://www.graphene.manchester.ac.uk/discover/the-people/vladimir-falko/
http://www.royce.ac.uk/about-us/professor-vladimir-falko/

Theory of strongly interacting quantum materials and many-body systems

Dr. Alessandro Principi (alessandro.principi@manchester.ac.uk)



Dr. Alessandro Principi studies the impact of interactions on equilibrium and non-equilibrium properties of 2D systems. Examples are the electronic and thermal transport in 2D materials, the viscous flow of strongly interacting electrons, the interplay between electrons, magnetism, topological order and superconductivity. The approach to these problems is mainly analytical; numerical techniques are used to evaluate the resulting integral, perform linear algebra manipulations, etc. The techniques used are similar to those of quantum field theory (Feynman diagrams, path integrals, non-equilibrium Green's functions, quantum kinetic equation, etc.) but applied to many-body problems in 2D systems.



Examples of Principi's research interests include (please contact me for more details):

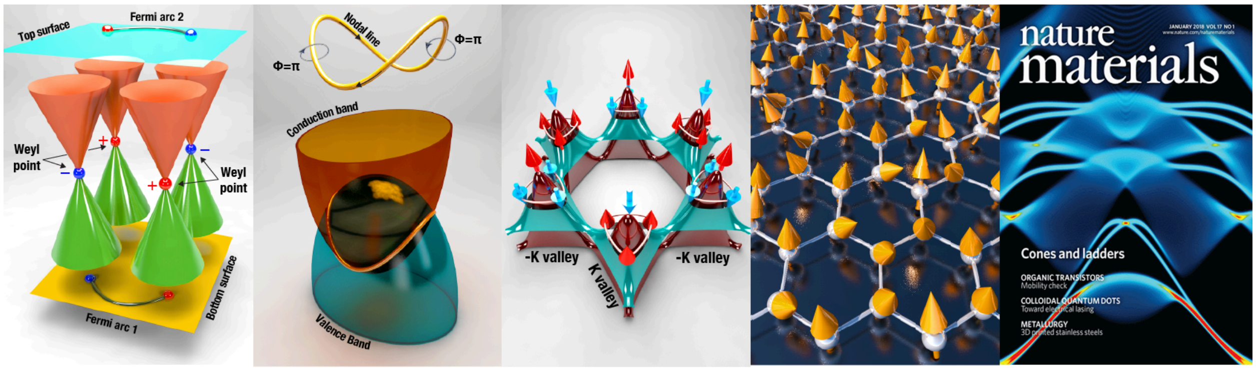
- Quantum magnetism and topological order, in particular of quantum spin liquids and their anyonic excitations, in twisted 2D materials
- Finding new ways to detect, address and control emergent quasiparticles with anyonic statistics, with application to topological quantum computation
- The charge, thermal, and thermoelectric transport in strongly correlated systems
- The complex interplay between topology, Berry curvature and strong electron-electron interactions

Students will learn advanced analytical quantum-field-theory techniques, group theory and quantum transport methods. Co-supervision with other group members is possible, as well collaborations with theoretical and experimental groups in Manchester, Lancaster, Cambridge, ICFO&ICN2 (Barcelona), Pisa, MIT/Harvard (USA), Singapore.

Personal webpage; Full list of publications

First-principles modelling of emergent quantum phenomena in cross-correlated materials

Dr Mohammad Saeed Bahramy (m.saeed.bahramy@manchester.ac.uk)



Topological Weyl semimetals and related quantum phenomena | Topological Nodal semimetals and related quantum phenomena | Valleytronic properties of transition metal dichalcogenides | Magnetism in two-dimensional vdW materails

Dr Mohammad Saeed Bahramy's research is focused on the study of exotic states of quantum matter using a range of computational techniques based on density functional theory, dynamical mean field theory, tight-binding modelling and, lately, machine learning. He is particularly interested in studying topological phases of matter, quantum confinement phenomena at the interface of heterogeneous materials, thermopower generation and manipulation in low-dimensional systems, strongly correlated electron systems, and superconductivity. He also seeks to understand how rich collective properties of materials, such as symmetry breaking, structural phase transition, and many-body effects, can lead to new phases of quantum matter. The ultimate goal of Dr Bahramy's research is to develop new guiding principles for the study and design of next-generation quantum materials with advanced functionalities suitable for future energy and information technologies.

Bahramy lab's current projects include:

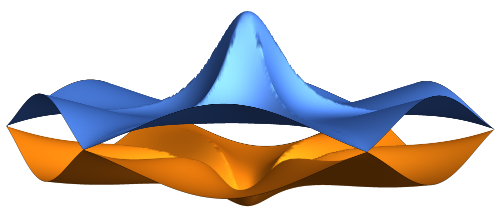
- Development of machine-learning-based methods for designing artificial two-dimensional materials and superstructures.
- Theoretical study and design of functional materials with non-trivial topological properties.
- First-principles modelling of exotic superconductivity and magnetism in strongly correlated materials.
- Quantum simulation of quasiparticle interferences in structurally-frustrated electronic systems.
- Thermopower generation and waste heat harvesting in low-dimensional materials.

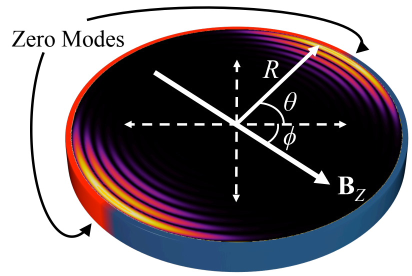
These projects will be performed in close collaboration with experimental groups in Japan (Univ. Tokyo, Univ. Osaka and RIKEN), the UK (Univ. St. Andrews, Diamond and UoM), China (Nanjing Univ.) and the USA (Stanford and Delaware Univ.). For further information, please contact Dr Bahramy or visit his group's website: https://personalpages.manchester.ac.uk/staff/m.saeed.bahramy/index.html

Theoretical and computational approaches to 2D materials

Prof. Niels Walet (niels.walet@manchester.ac.uk)

Professor Walet has broad interest in condensed matter physics, ranging from the study of many-body effects in strongly correlated systems to the description of the properties of graphene. His work is characterised by a mixture between theoretical and computational approaches, where computation is used to understand the theory. Computationally intensive projects are available as well.





A large variety of projects are available, largely in collaboration with other theorists in the group. Examples of possible research projects include:

- the study of Majorana edge states in novels devices
- the development of practical approaches for quantum information processing with such devices
- A description of the distortion of layered materials with approximate alignment
- a correct description of flat bands and twisted bilayer graphene
- the nature of topological effects in graphene heterostructures,
- electronic structure of superconductivity in 2D materials
- development of many-body theory (coupled cluster and the functional renormalisation group) for the study of strongly interacting systems.

Training in the relevant techniques, as well as in advanced computational methods, if applicable, will be provided.

https://www.research.manchester.ac.uk/portal/niels.walet.html

Quantum many-body theories and their applications in condensed matter physics

Dr. Yang Xian (yang.xian@manchester.ac.uk)

Dr. Yang Xian offers projects on quantum many-body theories and their applications in condensed matter physics. Many interesting physical phenomena are often the results of a combination of dynamic interaction between particles and their quantum mechanical nature. Magnetism, superfluidity, superconductivity, and fractional quantum Hall effects are such examples. Project are available on the following topics:

- Applications of quantum many-body theories to the ground and excited states of strongly correlated systems such as high-Tc superconductors (cuprates and iron pnictides) and quantum spin liquids (two-dimensional frustrated antiferromagnetic spin lattices such as RuCl3), with emphasis in the further improvement of the variational coupled-cluster method initially developed in our group;
- Dynamics of strongly correlated systems such as low-dimensional antiferromagnetic lattices, graphene ribbons and allied materials, with particular emphasis on their longitudinal modes;
- Topological properties, including the thermal Hall effect, of two-dimensional layered ferromagnets (chromium trihalides) and antiferromagnets with a Dzyaloshinskii-Moriya interaction and/or Kekule distortions. The aim is to provide quantitative support for development of magnon-based devices.

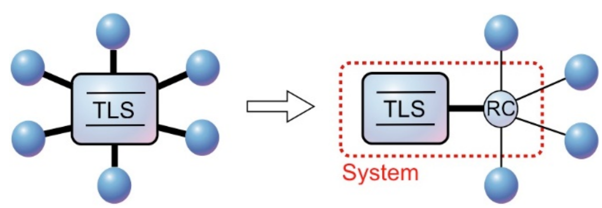
During the project, the student will learn several quantum many-body theories, particularly the coupled-cluster methods (CCM) and its extensions, and apply these techniques to find the physical properties of the relevant physical systems.

http://www.theory.physics.manchester.ac.uk/~xian/

Non-equilibrium quantum physics

Theory of open quantum systems: non-equilibrium dynamics and thermodynamics

Dr. Ahsan Nazir (ahsan.nazir@manchester.ac.uk)



Dr. Ahsan Nazir offers theoretical projects on the thermodynamics and non-equilibrium dynamics of open quantum systems. Open quantum systems theory describes the behaviour of quantum systems that are not isolated, but instead in contact with their surrounding environmental degrees of freedom. It is a topic of primary importance in physics and chemistry, and is becoming increasingly relevant in biology as well. Dr. Nazir develops new theoretical techniques to understand the behaviour of open quantum systems both in and out of equilibrium. Applications range from quantum thermodynamics to solid-state quantum technology, quantum transport, and the behaviour of molecular nanosystems. Potential projects include:

- fundamental developments in the theory of open quantum systems and applications to many-body systems;
- the impact of quantum correlations on the laws of thermodynamics and quantum scale thermal machines;
- the effects of environmental interactions in solid-state quantum technology (with established experimental collaborations);
- strong light-matter interactions in quantum electrodynamics;

- vibrational influences in the optical and electronic properties of natural and artificial molecular aggregates, with applications to solar energy harvesting.

http://personalpages.manchester.ac.uk/staff/ahsan.nazir/

Open quantum systems theory and quantum technologies

Dr. Jake Iles-Smith (jake.iles-smith@manchester.ac.uk)

Dr. Jake Iles-Smith studies the behaviour of quantum systems interacting with their environment, with particular focus on emerging quantum technologies.

All quantum systems are in principle ‘open’: that is, a quantum system is influenced in some way by its external environment. In many cases this induces complex behaviour that cannot be captured using traditional theoretical methods. Dr. Iles-Smith develops novel analytic and computational methods capable of describing the behaviour of open quantum systems that are strongly coupled to their environment. These tools are used to understand how environmental interactions impact emerging quantum technologies (e.g. nitrogen vacancy centres in diamond), with the overarching goal of developing novel quantum technologies that are robust against noise. Potential projects include:

- Development of analytic methods to describe open quantum systems in strong coupling regimes.
- Tensor network methods for describing nonequilibrium open quantum systems.
- Developing new quantum optics methods for solid-state quantum emitters (with established experimental collaborations).
- Methods to engineer an environment to enhance quantum technologies.

These projects will provide students with the opportunity to learn advanced numerical and analytic methods, along with the possibility of collaborating with leading experimental groups in Copenhagen, Bristol, Imperial, and Sheffield.

https://www.research.manchester.ac.uk/portal/jake.iles-smith.html

Complex structure in quantum dynamics and physics of quantum information

Dr Thomas Elliott (thomas.elliott@manchester.ac.uk)

Dr Thomas Elliott uses tools from quantum information theory to explore the dual questions of how complex structure is manifest in complex dynamics, and how this complexity can be harnessed.

Even the smallest of quantum systems can give rise to seemingly complex behaviours. While this can make such systems hard to model with classical computers, it presents a valuable opportunity – to use quantum technologies to efficiently model and simulate other complex systems. Recently, Dr Elliott’s research has focussed on how quantum computers can be used to simulate highly non-Markovian (i.e., memoryful) stochastic processes with a considerably smaller memory overhead than possible with any classical counterpart, and how these results can be extended to the richer domain of adaptive agents – systems that modify their behaviour in response to environmental stimuli. Potential projects include:

- Exploring the interplay between quantum memory advantages and increased thermal efficiency, to e.g., design quantum protocols for extracting work from stochastic processes.
- Improving and extending the design of quantum-enhanced adaptive agents, and/or developing their potential areas of application.
- Enhancing the quantum memory advantage and reducing the requisite technological requirements, by using tools from quantum many-body physics and/or quantum machine learning.
- Methods for characterising complex structure in quantum stochastic processes, and developing techniques for their efficient simulation.

The projects will be mostly analytical, with scope for a significant numerical/computational element. Students will develop a strong background in quantum information theory, and one or more of: open quantum systems; quantum stochastic processes; tensor networks; quantum thermodynamics; and quantum machine learning.

https://www.research.manchester.ac.uk/portal/thomas.elliott.html
https://scholar.google.co.uk/citations?user=sDInixMAAAAJ

Complex systems and statistical physics

Glassy materials

Dr. Mike Godfrey (michael.j.godfrey@manchester.ac.uk)

Glasses are poorly understood amorphous materials that share features of both solids and liquids: at low temperatures, a glass becomes rigid like a solid, while its microscopic structure remains virtually identical to that of a liquid. Yet how can a material with a liquid-like structure be rigid? It is a fundamental unsolved problem in physics, which also has practical importance for many technologies, the food and pharmaceutical industries, and even for the understanding of the structure of proteins and the development of organs within embryos. Potential areas of research for a student include:

- Investigation of the connections between local microscopic structure and dynamics in glasses.
- Development and application of linear algebra techniques for computing the properties of disordered materials in low dimensions.
- Study of the so-called “Gardner transition”, which has been predicted to exist deep inside the glass phase, and at which glasses might lose their brittleness and become malleable, like metals.