

QUANTUM THEORY OF LIGHT AND MATTER

We study a broad range of topics in Quantum Statistical and Condensed Matter Theory within the framework of the Theory Division. Such topics range from the study of electronic, magnetic and optical properties of 2D materials, of topological orders and superconductivity, to the development of the theory of quantum transport phenomena, strongly-coupled non-equilibrium systems, quantum thermodynamics and nanophotonics. The study of such complex systems involves a broad range of tools, including advanced quantum-field-theoretical techniques (Feynman diagrams, path integrals, non-equilibrium Green's functions), quantum kinetic and transport theory and applications of group theory, using numerical and analytical approaches. The strong connection to experimental groups at the School of Physics and Astronomy and the National Graphene Institute allows testing immediately the newly developed theories, especially in relation to the studies of physical phenomena occurring in two-dimensional materials, which remain the distinctive research beacon of the University of Manchester, awarded 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.

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. The projects he offers include:



- many-body phases of electronic liquids in various 2D materials, including the quantum Hall effect liquids in 2D materials with multi-valley spectra (where electrons are characterised by quantum numbers additional to their spin state);
- quantum properties of minibands generated by moiré superlattices characteristic for heterostructures of 2D materials with slightly incommensurate periods and in twisted homobilayers of 2D materials;
- quantum optics of 2D materials, from TH 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 of two-dimensional semiconductors and their applications in quantum technologies.

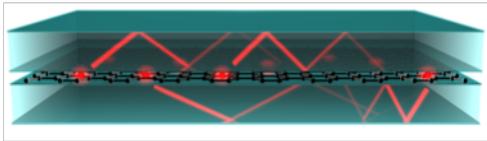
These projects will enable students to learn field theoretical methods in condensed matter theory; analytical and computational quantum transport theory; group theory and symmetry applications in solid state physics. The studies will be carried out in collaboration with experimental groups involved in 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/>

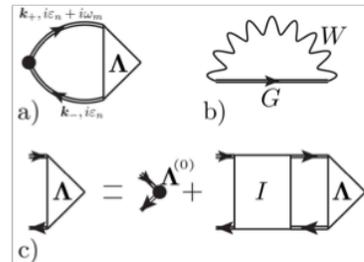
Quantum theory of strong interactions in low-dimensional systems

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



Dr. Alessandro Principi offers projects which involve the study of interactions and many-body physics (electron-electron, electron-phonon, electron-impurity, etc.) and their impact on the non-

equilibrium properties of 2D systems. Examples range from electronic and thermal transport in graphene, where electrons can behave as a very viscous fluid thanks to the strong electron-electron interactions, to topological materials and 2D systems featuring both itinerant electrons and various forms of (topological and not) magnetism or superconductivity. The main approach is analytical, with numerical techniques used for the resulting integrations and linear algebra, etc. We make use of advanced techniques taken from quantum field theory (such as Feynman diagrams, path integrals, non-equilibrium Green's functions, quantum kinetic equation). These are applied to problems arising in 2D systems. Examples of research projects include:



- Quantum electron hydrodynamics in topological materials: the interplay between topology, Berry curvature, quantum Hall effects and electron-electron interactions;
- Polarons, polaron superfluidity and bi-polaron superconductivity in twisted bilayer graphene as an alternative explanation of unconventional superconductivity;
- Topological collective excitations (plasmons) in 2D superlattices and gratings. Their impact on resonant photodetection, vertical tunnelling, and nanoplasmonics.
- Electrical/optical control of order parameters and of their excitations. Applications to topological superconductivity, magnetism, quantum spin liquids and topological-quantum computation;
- Plasmon-enabled quantum entanglement and entangled two-photon nanosources in van-der-Waals heterostructures;

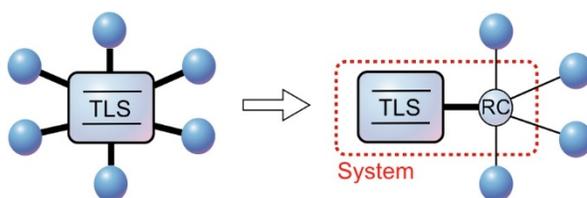
The projects will enable students to learn advanced analytical and numerical quantum-field theoretical, quantum transport and quantum kinetic equation methods. They offer the possibility of co-supervision by other members of staff, as well collaborations with theoretical and experimental groups in Manchester, Lancaster, Cambridge, ICFO (Barcelona), Pisa, MIT/Harvard (USA), Singapore.

www.alessandroprincipi.com

Thermodynamics and non-equilibrium dynamics of open quantum systems

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 study such systems, and applies these approaches to understand the behaviour of quantum systems both in and out of equilibrium. 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;
- strong light-matter interactions in quantum electrodynamics;
- vibrational influences in the optical and excitation properties of natural and artificial molecular aggregates, with applications to solar energy harvesting.

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

Novel aspects of two-dimensional materials

Prof. Paco Guinea (francisco.guinea@manchester.ac.uk)

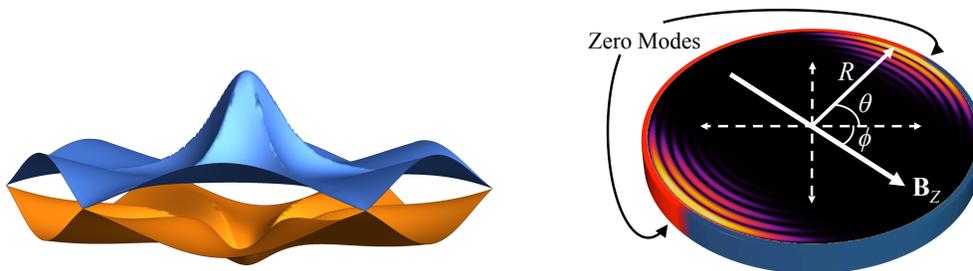
Professor Francisco Guinea works on problems in condensed matter theory with emphasis on novel aspects of two-dimensional systems. The emphasis is on topics with interesting fundamental content, and those which are at the interface between different disciplines. Some selected problems are:

- Electronic structure, superconductivity, and interactions in twisted bilayer graphene and related materials.
- Effects of the geometry of two-dimensional materials on their electronic and optical properties.
- Topological superconductivity. Macroscopic properties, role of defects.
- Interplay between atomic interaction and macroscopic shapes in membranes. Anharmonicity, formation of bubbles, ripples, and other curved structures.
- Novel properties of electronic states confined to defects, edges, and internal boundaries in two dimensional materials.

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 novel 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-T_c 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/>