Department of Physics and Astronomy

Postgraduate Project Booklet 2022/2023

Contents

ASTROPHYSICS

(THE JODRELL BANK CENTRE FOR ASTROPHYSICS)

The Jodrell Bank Centre for Astrophysics (JBCA) is one of the largest astronomy groups in the UK. It hosts around 30 academic staff and a total of approximately 180 researchers, including around 60 research students, working across a wide range of topics in astrophysics.

The JBCA is based on two sites: the Alan Turing Building is sited within the central University city campus in Manchester and hosts the UK ALMA regional centre node. JBCA also encompasses the Jodrell Bank Observatory, home to the Lovell Telescope, the e-MERLIN/VLBI National Facility, and the international headquarters of the Square Kilometre Array (SKA).

There are three research groups within JBCA: Cosmology; Pulsars and Time Domain Astrophysics; and Sun, Stars and Galaxies. In addition to these research areas the Interferometry Centre of Excellence aims to bring together the significant expertise we have in state-of-the-art radio astronomy data analysis techniques utilised by e-MERLIN and ALMA, and which are being developed towards future projects such as the SKA.

Further information on our research can be found on the JBCA research webpage:
http://www.jodrellbank.manchester.ac.uk/research/

General information on studying for a postgraduate degree within JBCA can be found at
http://www.jodrellbank.manchester.ac.uk/study/postgraduate/.

Research themes

Cosmology:

- Understanding the origins of the initial deviations for homogeneity that eventually lead to the formation of large scale structure.
- The origins of the cosmic acceleration.
- The nature of the dark matter thought to pervade the Universe.
- The formation of galaxies and clusters of galaxies.

Sun, stars and galaxies:

- Solar plasmas, including understanding solar corona heating, magnetic reconnection, and the origin of high-energy charged particles in solar flares.
- Astrophysical magnetism, masers and radiative transfer.
- Star and planet formation, stellar evolution, circumstellar and interstellar processes.
- Galactic interactions and clusters.
- Galaxies and active galactic nuclei.
- Multi-wavelength surveys.

Pulsars and time-domain astrophysics:

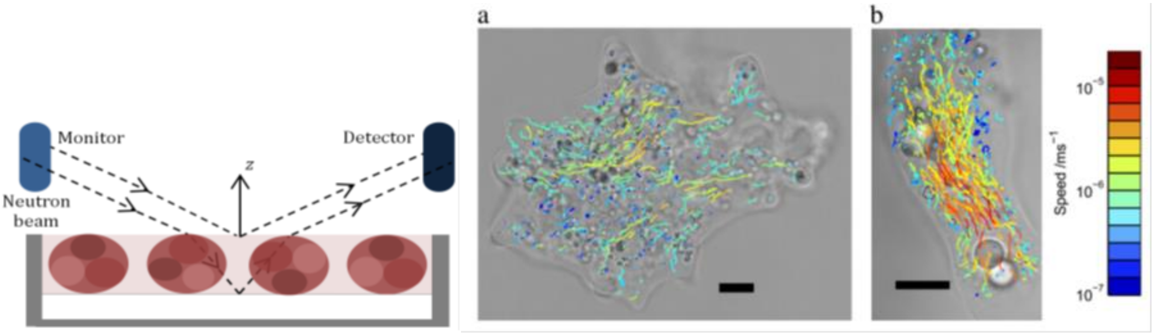
- Pulsar detection, characterisation and physics, including milli-second pulsars, pulsar timing, pulsar glitches, pulsar emission physics.

- Fast Radio Bursts (FRBs), including search techniques, and brightness and dispersion measures.
- Novae, including multi-frequency monitoring of outbursts, structural studies of ejecta, and hydrodynamic simulations of mass-loss.
- Extra-solar planets, including detection using the microlensing technique, and atmospheric detection and characterisation through transmission spectroscopy studies.
- SKA and next-generation instrumentation.

Project areas

The full list of our projects are available at the JBCA PhD projects webpage http://www.jodrellbank.manchester.ac.uk/study/postgraduate/phd-projects/

BIOLOGICAL PHYSICS



The main research theme of the Biological Physics Group is to use multiple experimental and computational approaches to investigate the fundamental physics of biological problems. Postgraduate projects are therefore closely related to this main theme, covering the investigation of biological problems connecting structure to function at molecular, cellular, tissue and whole organ levels. Projects on translational studies linking basic scientific research to potential industrial and clinical applications are also available. Briefly the projects are focused on, but not limited to the following topics:

Biointerface: this topic involves studying molecular and cellular structure under conditions mimicking biological and biomedical applications and applying the latest physical techniques to access direct information at molecular and cellular levels from various bio-interfacial processes.

Computational systems biology and medicine: this topic aims to develop multi-scale and multi-physics computer models of biological systems. New ways of analysing and interpreting experimental data and complexity of nonlinear dynamics of biological systems will be developed.

Biomolecular structure and dynamics: this topic involves the study of water around DNA, proteins and biopolymers using various neutron sources around the world.

Cellular tracking and self-assembly: this topic develops a range of new tools to examine the behaviour of bacteria, human cells and biomacromolecular aggregates. Specifically, new microscopy and microrheology based approaches will be used, combined with mesoscopic models for the molecular behaviour.

Biointerface
Prof. Jian Lu
(j.lu@manchester.ac.uk)

Neutron reflection study of protein adsorption.

Proteins are large biomacromolecules that perform many functions in living systems. They are folded up from one or several polypeptide chains. In order to perform their functional roles, they must retain their 3D structures. Once exposed to surface or interface, protein molecules tend to adsorb; some become struck and some could even desorb. These interfacial processes of adsorption and desorption tend to damage their 3D structures, deactivating them or causing adverse consequences. Neutron reflection could help determine the structural conformation of an adsorbed protein layer. The information could help us develop biocompatible surfaces and interfaces whilst improving our basic understanding. This project also has desire for computer modelling and is often developed in collaboration with scientists at Rutherford Laboratory and industry.

Self-assembly of short peptide amphiphiles and their interactions with biointerfaces.

There are many natural and unnatural amino acids that are polar, apolar and charged. We can design short, simple peptide sequences from them that resemble conventional surfactants with distinct hydrophilic head and hydrophobic tail moieties. Unlike conventional surfactants, the properties of these peptide amphiphiles are strongly influenced by hydrogen bonding. Light scattering, neutron scattering and computer modelling are often used together to help understand how a give set of peptide amphiphiles self-assemble to form a range of nanostructures such as nanorods, nanotubes, nanobelts and larger structures templated from them.

Interfacial processes underlying antimicrobial actions and biocompatibility.

A major antimicrobial action is to kill bacteria by disrupting their membranes, but antibiotics or equivalent must target bacteria very selectively with minimal damage to mammalian cell hosts. In collaboration with colleagues in biology and medicine, we have developed physical models to help understand the key mechanistic events at molecular and cell levels, by seeking the combined studies utilising skills and tools from both biology and physics.

Computational systems biology and medicine
Prof. Henggui Zhang
(henggui.zhang@manchester.ac.uk)

Development of the computer model of the heart for the study of electrical and mechanical dynamics of the heart.

A grand challenge for modern physics is to develop a biophysically detailed and accurate model for predicting the dynamical behaviours of the heart that paves the way leading to predictive life sciences. In collaboration with colleagues in biology and medicine, we aim to develop multi-scale physics models of the heart to investigate its nonlinear dynamics in electrical and mechanical behaviours ranging from molecular to cell and organ levels, by utilising combined skills of physics and high performance parallel computing.

Novel non-invasive technology for diagnosing cardiac arrhythmic origins.

Cardiac arrhythmias are the leading cause of sudden death. Current treatment of cardiac arrhythmias (e.g. atrial fibrillation) involves the use of catheter ablation. However, the success of catheter ablation relies on accurate identification of the cardiac arrhythmic origins, which is challenging at the moment. The aim of this project is to develop a new algorithm that solve the inverse problem of the heart, by which electrical excitation dynamics in the heart can be reconstructed from multi-channel ECG recordings from the human body surface. This will provide a new non-invasive technology for identifying the target for ablation, which will have significant practical values.

The virtual heart as a platform for new drug design and testing.

Cardiac arrhythmias are the leading cause of sudden death. Current treatment of cardiac arrhythmias by using of anti-arrhythmic drugs is unsatisfactory due to the toxic side effect of the drugs. The aim of this project is to develop a novel computer model of the heart for testing the efficacy and safety of the drugs. This will provide a new technology which has great potential application in the drug industry.

Artificial intelligence (AI) in diagnosing cardiac arrhythmias.

AI based on deep learning and machine learning may revolutionise the way of automatic clinical diagnosis. The aim of this project is to develop a new set of AI algorithms that analyse the nonlinear dynamics of heart from multi-channel ECG recordings from the human body surface. This will provide a new technology for accurate diagnosis of cardiac arrhythmias.

Biomolecular structure and dynamics
Dr. Jichen Li
(j.c.li@manchester.ac.uk)

Water flow in confined nano graphene channels.

Water transport through nanoscale channel is fundamental importance for us to understand biological processes, such as the transportation of ion through protein channels and drug deliveries. It potentially has also industrial applications such as gas separations. It is known that water molecules are transported in and out of cells selectively through the nanopores such as transmembrane proteins, aquaporin, and so on. Unfortunately, biological water channels often contain specific and complex structures, exhibiting extraordinary transport properties that are far from being understood completely. In this sense, the study of water transportation in a structurally less complex and controllable carbon nanotube or graphene channel becomes a fascinating alternative, where the conditions and parameters can be conveniently tuned by experimental techniques [1] or theoretical methods [2,3]. In the project, we will combine inelastic neutron scattering (INS) and molecular dynamics simulation (MD) techniques to investigate the diffusion of water the in graphene channels as function of temperatures and pressures. Since INS is very sensitive to scattering on water hydrogen, we expect to get direct information on vibrational spectra of confined water, the translational and librational modes of which are strongly affected by the local geometries and thesimulations will provide microscoptic details of the local water structures.

1. Nair, R.R.; Wu, H.A.; Jayaram, P.N.; Grigorieva, I.V.; Geim, A.K. Unimpeded permeation of water through helium-leak-tight graphene-based membranes. Science 2012, 335, 442-444.
2. The Observation of the Oxygen-Oxygen Interactions in Ices - Redefine the term of hydrogen-bonding between water – water molecules, Shun Chen, Zhiping Xu and Jichen Li, New J. Phys. 18 023052-58 (2016).
3. Effect of layered water structure on the anomalous transport through nanoscale graphene channels. S. Chen; X.C. Nie; H.P. Fang; N.R. Walet, Shiwu Gao and J.C. Li, to be published (2017).

Cellular tracking and self-assembly

Dr. Thomas Waigh
(t.a.waigh@manchester.ac.uk)

Super-resolution fluorescence imaging of bacterial biofilms (with Prof. Ian Roberts in Life Sciences)

A super-resolution fluorescence microscope (STORM) will be used to study biofilm formation in bacteria. Bacterial biofilms are a key issue in antibiotic resistance and are therefore a huge problem in modern medicine. Experiments in our laboratory have demonstrated bacteria can use electrical signalling during biofilm formation. Optogenetics methods are also possible to insert voltage sensitive fluorophores into bacteria to observe their activity.

Models for the creation of bacterial biofilms (with Prof. Ian Roberts in Life Sciences)

Statistical models to describe bacterial biofilms will be constructed. These will include ideas from agent based modelling, colloidal hydrodynamics and systems biology. Electrophysiological effects can also be incorporated into models to describe electrical signalling experiments. A range of medically important biofilms will be studied in collaboration with experimental physicists and microbiologists.

Optical coherence tomography to study the fluid mechanics of opaque solutions of DNA (with Dr Mark Dickinson)

Concentrated (opaque) DNA has a number of novel non-linear flow phenomena, such as turbulence at very low Reynolds number. This project will develop new optoelectronics equipment to study fluid mechanics based on optical fibre interferometry. It will then apply the techniques developed to medically important areas of research including the flow behaviour of DNA and bacteria.

Active cell movement in live tissue (with Dr Tom Millard in Life Sciences)

We want to understand how cells move inside complex living tissues and how the physical properties of the surrounding environment affect cell movement. Drosophila embryos are transparent and we will determine how cell motion is influenced by the spatial properties of the surrounding environment. New statistical tools will be developed to characterize the heterogeneous motility of immune cells.

COMPLEX SYSTEMS AND STATISTICAL PHYSICS

Dr. Tobias Galla
(tobias.galla@manchester.ac.uk)

Complex systems are composed of many interacting components, giving rise to emergent phenomena which cannot be understood from analysing the individual components in isolation. Examples include the emergence of traffic jams, stock market crashes or the take-over of a population by an invading mutant.

In our work we study complex systems using the tools and ideas of theoretical physics. Specifically we focus on "individual-based systems", where the word "individual" can represent stock market traders, players in a game, protein molecules, messenger RNA, members of a population in which a disease spreads or cancer cells in a tumour.

Many of these systems are modelled as random processes. We are interested in the mathematical theory for such systems, and in applying these methods to specific questions, often motivated in biology, evolutionary dynamics or game theory. Past PhD projects include path integral analyses to delay models in epidemiology and gene regulation, the statistical physics of fixation and equilibration in cancer populations, multi-player games, social learning in insects, the spread of languages, biological systems coupled to fast external environments, host-pathogen games, evolutionary dynamics in flows, etc.

This is a fast-moving field and it is hard to say what exactly your project will be. This will also depend on your interests and preferences. We promise an exciting mix of theoretical analysis, computer simulation and interdisciplinary work with colleagues in the life sciences, mathematics, healthcare/medicine, computer science and even linguistics.

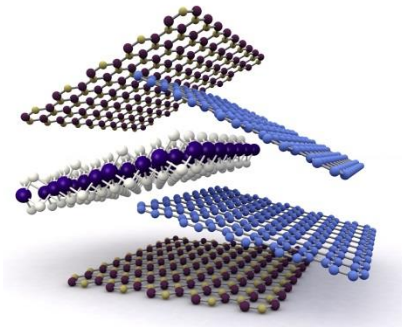
Most of our applicants have excellent marks, strong mathematical skills and programming experience. We are looking for energetic students with outstanding communication skills, and who are enthusiastic and able to drive this exciting field forward.

CONDENSED MATTER PHYSICS

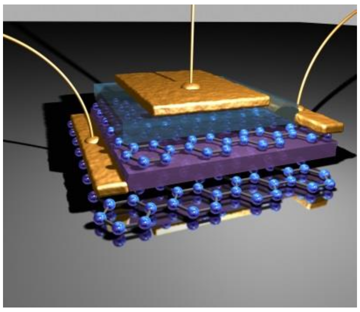
Research in the Condensed Matter physics group is exceptionally broad, from electronic, optical, mechanical and magnetic properties of a whole family of atomically thin, two-dimensional materials to the physics of quantum fluids, intercalation-induced superconductivity in layered and two-dimensional materials and mass transport through atomically thin channels in 2D-materials based membranes. The focus in 2D materials research is currently shifting from studying the properties of graphene to other 2D crystals with a variety of electronic properties - insulators (hBN), semiconductors (phosphorene, MoS2, WSe2, etc.), superconductors (NbSe2), 2D magnets (CrI3) – and the so-called heterostructures, where atomically thin layers with different properties are assembled with monolayer precision to produce 'materials by design'. Our research is supported by extensive cutting-edge facilities in the Schuster building and the National Graphene Institute, including clean-room microfabrication, measurements and characterisation. The quantum fluids research is supported by unique measurements systems, including ultra-low temperature rotating cryostats. More information is available at http://www.condmat.physics.manchester.ac.uk/ and http://www.graphene.manchester.ac.uk/.

Research areas led by individual academics are described in more detail below.

Rotating millikelvin cryostat that allows visualization of vortex lines in superfluid.



Layer-by-layer assembly of 2D heterostructures.



Graphene=based vertical transistor.

Physics and applications of 2D materials and their heterostructures
Prof Andre Geim
(andre.k.geim@manchester.ac.uk)

Prof Geim's current research focuses on developing van der Waals (vdW) heterostructures and smart Lego-style materials based on 2D crystals. This is a very broad field of research, encompassing many new systems that allow to access electronic, optical, transport and other properties not readily found in 'natural' materials. A number of current projects focus on exploiting non-trivial topology of graphene-based heterostructures, developing new systems that allow new types of measurements (for example, a recently developed technology for fabricating designer nanochannels with monolayer precision), and studying little explored properties of graphene, boron nitride and other atomically thin crystals for transport f subatomic particles (protons, deuterons). Available PhD projects are constantly evolving and interested students are encouraged to contact Prof Geim for latest opportunities.

Quantum fluids

Professor Andrei Golov and Dr. Paul Walmsley
(andrei.golov@manchester.ac.uk; paul.walmsley@manchester.ac.uk)

Currently, the Low Temperature Group (Prof. Andrei Golov, Dr. Paul Walmsley, Dr. Ivan Skachko) investigates turbulence in superfluid ^{4}He in the limit of zero temperatures. For further details, see
http://www.condmat.physics.manchester.ac.uk/researchthemes/quantumfluids/
and https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.118.134501 .

Superfluid helium is an ordered inviscid liquid, capable of maintaining flow without dissipation. Yet, a tangle of quantized vortices (a.k.a. Quantum Turbulence) decays even at T = 0, the energy being lost to elementary excitations of the superfluid. There exist several competing theories of processes involving the emission of phonons, rotons and small quantized vortex rings after short-wavelength perturbations of the shape of vortex lines grow in amplitude. However, nobody yet knows – which of them is correct, if any. We are going to take photographs and videos of vortex lines, which will allow to learn about the amplitude and spectrum of waves along vortex lines and the dynamics of their evolution. We are also developing different types of detectors, capable of recording the emission of phonons, rotons and small quantized vortex rings.

Projects:

1. Visualization of vortex lines in superfluid ^{4}He through fluorescence of molecules and nanoparticles, attached to vortices.
2. Investigation of elementary excitations in superfluid ^{4}He responsible for the removal of energy from tangles of vortex lines in the T=0 limit.

2D plasmonics in thin atomic layers

Prof Sasha Grigorenko

(alexander.grigorenko@manchester.ac.uk)

Recently, plasmons and polaritons in two-dimensional (2D) systems attracted a lot of attention due to isolation and availability of various 2D materials. Among these 2D materials one can easily find dielectrics (e.g., boron-nitride), semimetals (e.g., graphene) and semiconductors (various transitional metal dichalcogenides). At the same time, ultra-thin layers of metals down to single monolayer did not receive widespread attention despite they present an interesting and important part of LEGO-like van der Waals heterostructures. Recently, it was found that ultrathin layers of metals do possess nontrivial 2D plasmons, can show high temperature superconducting transition as well as truly 2D superconducting behaviour. The study of fascinating properties of ultrathin metals and their nanostructures is a timely and exciting topic in development of flatland optics and electronics.

In our group, we have all means necessary to fabricate, characterize and optimize thin layers of metals. Various fabrication technique will be used (deposition, cleaving, electrochemistry) with the objective to achieve extremely flat and homogenous films. Optical and electrical properties will be studied using the existing equipment (spectroscopic ellipsometry, reflection and transmission spectroscopy, dc conductivity and Hall effect in large temperature and spectral ranges). New optical and electrical properties will be targeted – with emphasis on photo catalysis for green energy and high temperature superconductivity.

Project: 2D plasmonics in thin atomic layers.

Superconductivity in layered and 2D materials; 2D materials for spintronics

Prof Irina Grigorieva

(irina.grigorieva@manchester.ac.uk)

Prof Grigorieva's current research focuses on three main areas: (i) tuning electronic properties of layered materials or stacks of atomically thin layers by intercalation, including induced superconductivity; (ii) two-dimensional and non-trivial superconductors; (iii) applications of 2D materials in spintronics. Superconducting paring in alkali-metal doped semiconductors or insulators often has a non-trivial nature either due to the interplay of the electronic states of the 2D layers and the intercalating metals or due to the non-trivial topology of the host material; there are also a number of bulk superconducting materials with non-trivial topology of electronic bands. We are looking for new experimental signatures of non-trivial superconductivity. In spintronics, the recently discovered possibility to make graphene ferromagnetic by proximity to known ferromagnetic materials can be exploited, for example, in magnetic tunnel junctions. We are currently looking for ways to either enhance this effect in graphene or find other promising 2D materials for such devices.

Projects:

1. Superconductivity in topologically non-trivial materials.
2. Control of electronic properties of 2D materials by intercalation.
3. 2D materials for magnetic tunnel junctions and other spintronics applications.

Bridging electronics and mechanics at the nanoscale

Dr Artem Mishchenko

(artem.mishchenko@manchester.ac.uk)

Our research is centred on van der Waals heterostructures – layer-by-layer assembled stacks of individual atomic planes. "What could we do with layered structures with just the right layers? What would the properties of materials be if we could really arrange the atoms the way we want them?" asked Richard Feynman in his visionary lecture "There's plenty of room at the bottom" back in 1959. In the light of a remarkable progress over the past few years, we are now on the verge of answering these questions. Currently, our research group focuses on the following main research directions within van der Waals heterostructures: (i) the nanoscale transport properties of novel materials and (ii) nanoscale electromechanical systems. The behaviour of charge carriers at the nanoscale is of paramount importance for a huge range of applications covering semiconductor industry, sensors, nanofluidics, and biophysics of living cells. Likewise, unravelling the interplay between mechanical and electronic domains at the atomic level will benefit all technology, especially in the fields of wearable computers, self-powered devices, smart materials, and medical and industrial nanorobots.

We work on advancing both of these directions by developing advanced measurement techniques, designing and prototyping a range of devices using cutting-edge microfabrication technologies, and by exploring the interactions between mechanical and electronic domains at the atomic level.

Projects:

1. Developing an innovative nanoscale transport imaging platform to explore novel materials and new physics.
2. Piezoelectric properties of van der Waals heterostructures: actuation and energy harvesting.
3. Electromagnetic and thermal actuation nanoelectromechanical systems.
4. Friction, superlubricity and stick-slip motion in 2D materials.

2D nanoelectronics beyond Moore's law based on spintronics and thermoelectrics

Dr Ivan Vera Marun

(ivan.veramarun@manchester.ac.uk)

Our basic research on 2D nanoelectronics paves the way towards alternative computing technologies beyond the use of charge in conventional electronics. In 1965 Gordon Moore made the observation that the number of components in an integrated circuit doubles every year. Fast forward to the present day and conventional electronics is expected to reach the atomic-scale limit by the next decade. To go beyond this limitation, we explore spin currents, heat transport, and other degrees of freedom to enable alternative logic and memory devices.

We use nanotechnology as an interface between the fields of magnetism, electronics, and thermal transport. Our work integrates spintronics (Nobel Prize in Physics 2007), nanoscale thermoelectrics, and graphene, the first two-dimensional material discovered in Manchester, to develop enhanced functionality, re-programmable and 'green' electronics.

Projects:

1. Spin transport in high-quality ballistic graphene transistors.
2. Nanoscale thermoelectrics in van der Waals heterostructures.
3. Spin-hall effect and related spin-orbit phenomena in 2D materials.

Scanning probe microscopy of 2D materials and nanoconfined molecules

Dr Laura Fumagalli

(laura.fumagalli@manchester.ac.uk)

Our group focuses on the study of the physical properties of matter at the nanoscale, mainly electrical and dielectric properties, by using scanning probe microscopy techniques. In recent years we have developed scanning dielectric microscopy which is able to probe electric polarizability on the nanoscale. This is a fundamental physical property with important implications in many disciplines, from physics to chemistry and biology, and yet it remains essentially unknown on such a small scale for lack of tools with sufficiently sensitivity. Hence, the applications of scanning dielectric microscopy are countless. Currently we are particularly interested in combining it with 2D materials and state-of-the-art 2D fabrication techniques to investigate the dielectric properties of fluids and solids under extreme confinement. We recently showed the power of this approach by succeeding in the long-standing challenge of probing the polarizability of few water layers confined into nanochannels made of 2D materials. Available projects aim to continue this research to better understand the role of electric polarizability in phenomena such as surface hydration, ion solvation, molecular transport, macromolecular assembly and chemical reactions.

Projects:

1. Dielectric polarization properties of 2D confined water.
2. Dielectric polarization properties of 2D confined macromolecules.
3. Development of high-resolution dielectric microscopy.

Developing new techniques for fabrication of ultraclean 2D heterostructures and devices based on 2D materials

Dr Roman Gorbachev
(roman@manchester.ac.uk)

My research area is experimental condensed matter physics, with an emphasis on fabrication of nanoscale low-dimensional devices. The availability of novel nanoscale materials, such as nanowires and atomically thin 2-dimensional crystals is enabling the assembly and study of composite electronics and mechanical devices, as well as the exploration of fundamental physics in these low-dimensional systems. The use of modern state-of-the-art semiconductor device fabrication techniques and the development of new methods of material synthesis/manipulation are essential parts of this research, which gives an ample space to explore the new physical phenomena and can bring an impact to future technologies.

Projects:

1. Ultra-clean van der Waals heterostructures fabricated in high vacuum.
2. Scanning probe microscopy of atomically thin crystals in vacuum.

One-atom-thick membranes

Dr. Marcelo Lozada-Hidalgo
(marcelo.lozadahidalgo@manchester.ac.uk)

2D crystal membranes exhibit exotic phenomena. They are impermeable to all atoms and molecules but they are highly permeable to protons. They also display subatomic selectivity: deuterons, nuclei of hydrogen's isotope deuterium, permeate ~10 times slower than protons. Unexpectedly, graphene membranes are also highly sensitive to solar light: A single photon impinging on graphene induces the transport of ~10,000 protons via a novel physical effect, the photo-proton effect. Encouragingly, these properties have been found using only a couple of 2D crystals – hundreds more remained unexplored. My research is focused both on finding more exotic properties and exploiting them in a number of energy applications such as fuel cells, photocatalytic water splitting or nuclear energy. PhD projects usually involve both fundamental science and industry applications.

Angstrom-scale fluidics

Dr Radha Boya

(radha.boya@manchester.ac.uk)

Our current research involves design and fabrication of capillary devices based on atomically thin 2D-materials assembled in 2D-heterostructures. The capillaries are layer-by-layer structures of 2D-materials such as graphene, with cavities running through the middle of a stack. To put it simply, we make atomic-scale channels with atomically smooth walls! This novel architecture of capillaries provides atomic-scale tunability of the nanochannel dimensions and ensures atomically smooth walls. Despite the Ångstrom (Å) scale, this is essentially a top-down lithographic technique which ensures its high reproducibility and flexibility. Using these precise capillaries, we study effects of confinement on water, ion, and gas flows which can impact the fields of molecular separation and membrane-based water desalination. For further details, please see https://radhaboya.weebly.com/.

Projects:

1. Confined material growth for new types of 2D materials.
2. Biomolecular sequencing using angstrom-capillaries.

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 occurring 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.

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:

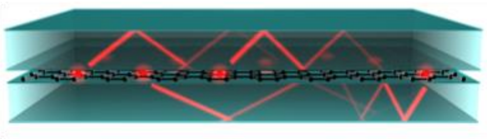
- many-body phases of electronic liquids in 2D materials, including the quantum Hall effect in 2D materials with multi-valley spectra, where electrons are characterised by valley quantum numbers additional to their spin state;
- quantum properties of minibands generated by moiré superlattices generic 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.

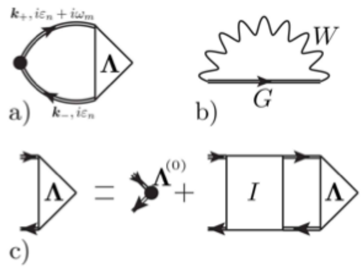
http://www.graphene.manchester.ac.uk/discover/the-people/vladimir-falko/
http://www.royce.ac.uk/about-us/professor-vladimir-falko/

Quantum theory of strong interactions in low-dimensional 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, topological plasmons, 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 research projects include: (please contact me for details)

- Magnetism and quantum/topological order in twisted 2D materials;
- Interplay between topology, Berry curvature and electron-electron interactions (in particular, impact on emergent electron hydrodynamics)
- Topological plasmonics at metal/dielectric interfaces
- Control of emergent quasiparticles. Applications to topological superconductivity, magnetism, quantum spin liquids and topological-quantum computation;

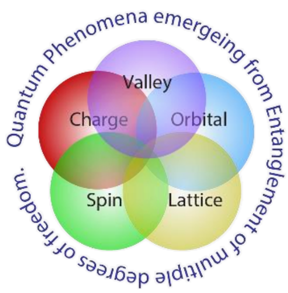
Students will learn advanced analytical quantum-field theory techniques, group theory and quantum transport methods. Co-supervision with other group members is possible, as well collaborations with theoretical and experimental groups in Manchester, Lancaster, Cambridge, ICFO&ICN2 (Barcelona), Pisa, MIT/Harvard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

Personal webpage; Full list of publications

Computational modelling and design of next generation quantum materials

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

Dr Mohammad Saeed Bahramy's research is focussed on the development and application of advanced computational methods to predict, design and study non-trivial quantum materials relevant for future energy and quantum information technologies. Quantum materials are a new paradigm in condensed matter physics, offering a unique platform for the realisation of novel electronic and magnetic phases with fundamental and applicative interests. Using the predictive power of high-throughput ab-inito simulations, Dr Bahramy examines ways in which such materials can be tuned to drive quantum phase transition, for example by electrical gating–a technique at the heart of semiconductor devices–as well as exposure to the external magnetic field and mechanical distortions. He also seeks to understand how rich collective properties of materials such as symmetry breaking, structural phase transition, and strong electronic correlation can lead to new topological phenomena. Current projects include:



- Development of machine-learning-based methods for designing artificial two-dimensional materials and superstructures.
- Development of ab-inito methods to study superconductivity and magnetism in low-dimensional systems including gated surface and heterogenous interfaces.
- First-principles modelling of topological quantum phenomena and quasiparticle interferences in structurally-frustrated heavy fermion systems.
- Thermopower generation and manipulation in cross-correlated materials.
- Magnetic generation and switching of topological phases through proximity effect.

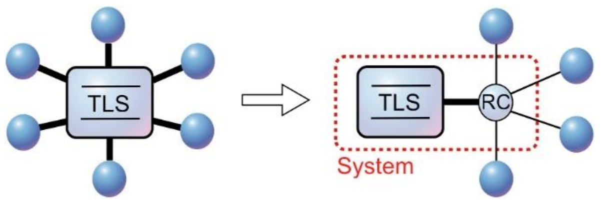
These projects will be performed in close collaboration with experimental groups in Japan (Univ. Tokyo, Univ. Osaka and RIKEN), the UK (Univ. St. Andrews, Diamond and UoM), China (Nanjing Univ.) and the USA (Stanford and Delaware Univ.).

https://personalpages.manchester.ac.uk/staff/m.saeed.bahramy/index.html

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 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.

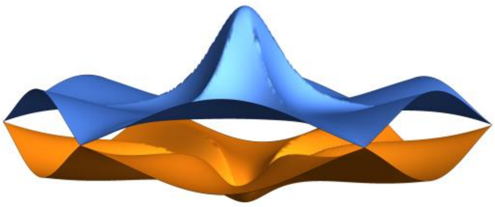
These projects will provide students with the opportunity to learn advanced numerical and analytic methods, along with the possibility of collaborating with leading experimental groups in Copenhagen, Bristol, Imperial, and Sheffield.

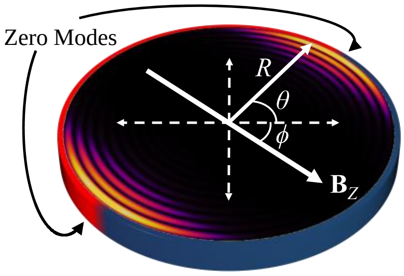
https://www.research.manchester.ac.uk/portal/jake.iles-smith.html

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/

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.

NUCLEAR PHYSICS

A project using novel ion manipulation techniques (Paul traps, electrostatic traps and RF coolers) in conjunction with precision laser spectroscopy is available.

Dr. Paul Campbell
(paul.campbell-3@manchester.ac.uk)

Aims: this STFC funded project aims to measure fundamental nuclear properties in exotic super-asymmetric fission fragments and atomic-nuclear processes in ultra-low lying nuclear excited states.

Details: The project is to be based at the IGISOL facility, JYFL, Jyvaskyla, Finland and ISOLDE, CERN. The research will exploit a recently constructed electrostatic ConeTrap and use it, for the first time, to facilitate high efficiency laser spectroscopy and then to use the developed spectroscopy to make precision measurements of nuclear parameters via the hyperfine structure and isotope shift.

The project is based at facilities where The University of Manchester and our national and international collaborators, from the UK, Belgium, Finland, Germany, Russia and Japan, have performed successful nuclear structure (and atomic) studies for many years. In the new work our objective is however to achieve spectroscopic efficiencies at an order of magnitude higher than that we have previously attained. Historical efficiencies have permitted in-flight studies of short-lived radioactive ions with lifetimes as short as 10 ms and production rates as low as 10 ions per second. We now intend to supersede these efficiencies and be capable of studying the most weakly produced and highest Z systems available at our on-line isotope separators.

Laser Spectroscopy at the limits of nuclear existence

Dr. Kieran Flanagan
(keiran.flanagan-2@manchester.ac.uk)

How three-nucleon forces influence nuclear structure and the limits of nuclear existence remains a compelling question in nuclear physics. There are currently many different approaches being utilized around the world to measure the properties of nuclei that may help answer this question. Since laser spectroscopy measures nuclear observables without introducing any assumptions associated with a particular nuclear model it has become a very popular method. Until recently it could only be used to study isotopes that are produced in relatively large amounts, which has limited its application. Over the last 5 years the CRIS collaboration at CERN has developed new techniques in laser spectroscopy that have permitted measurements on beams of less than 10 atoms per second. This has greatly extended the reach of laser spectroscopy and has allowed it to study the most exotic nuclei for the first time.

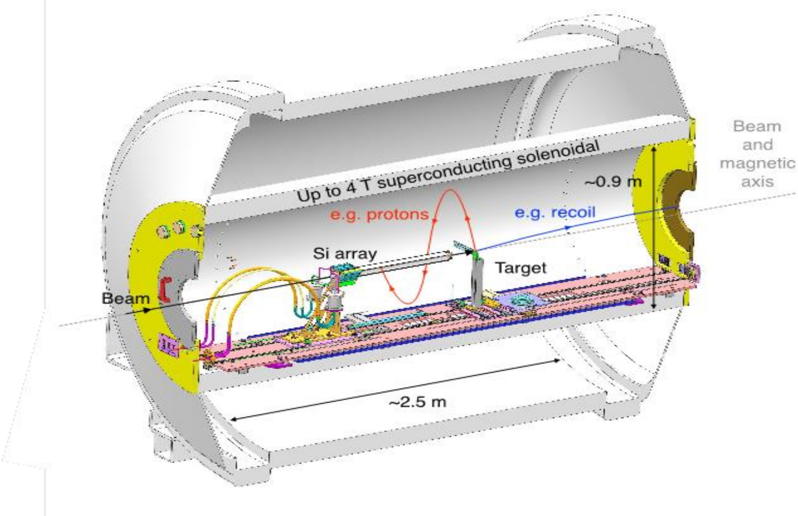
The project will be carried out at the ISOLDE facility, CERN, which is the premier radioactive beam facility at the precision frontier. There are currently PhD student projects in the area of ion trapping, production and application of negative ions for nuclear research and atomic physics. There is an opportunity in the project for students to spend a large fraction of their PhD at CERN.

Exploring the Changing Shell Structure of Nuclei

Dr David K Sharp
David.sharp@manchester.ac.uk

The introduction of the spin-orbit interaction by Maier and Jensen led to an understanding of the observed shell gaps and magic numbers in near-stable nuclei. The appearance of these ideas in undergraduate textbooks gives the impression of solidity and permanence to the well-known sequence of magic numbers. Recent observations, however, have challenged this basic assumption by suggesting that the sequence of single-particle states observed near stability is actually quite fragile; studies of nuclei far from the line of β stability have begun to indicate that the familiar shell gaps do not persist in exotic systems. Instead, shifts in the sequence of single-particle levels conspire to give gaps that change with changing nucleon number, fundamentally reshaping the basis of nuclear structure and producing new and unexpected phenomena. The reasons for these alterations to one of the basic tenets of nuclear physics are currently being debated and are of paramount interest in the development of the understanding of atomic nuclei.

Single-nucleon transfer reactions offer a suitable probe of the single-particle characteristics via the spectroscopic factor (SF), measuring the overlap of the wave function of a state with simple single-particle configurations. Being subject to sum rules, SFs allow access to the occupancies of underlying single-particle orbits.



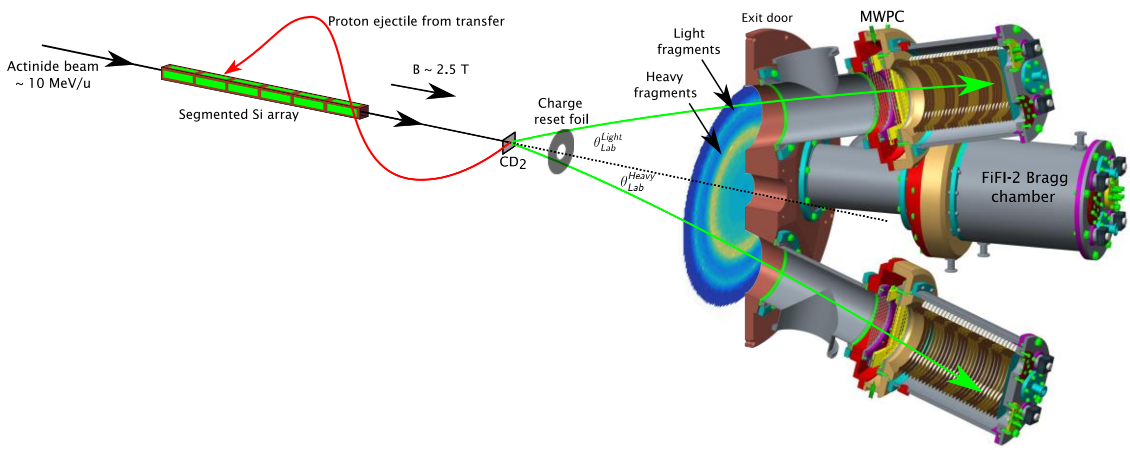
PhD projects in this area will involve using transfer reactions with radioactive beams to investigate the evolution of single-particle structure in to exotic regions of the nuclear chart. his work will predominantly take place at HIE-ISOLDE, CERN using the newly commissioned ISOLDE Solenoidal Spectrometer (ISS).

Fission dynamics and nuclear astrophysics measurements at CERN

Dr. Gavin Smith
(gavin.smith@manchester.ac.uk)

Projects involve the measurement of fission data from the Neutron Time-of-flight (n_TOF) facility at CERN. Neutrons of a broad spectrum of energies are produced by spallation of protons on a lead target. The neutrons are timed relative to the proton pulse and are used to induce fission on an actinide target in experimental area of the n_TOF facility. The SpectromeTer for Exotic Fission Fragments (STEFF) is a 2E-2v detector system, developed at the University of Manchester, which used to study the resulting fission fragments. It allows measurement of the velocities and energies of both fragments from the fission event. Mass may be measured independently in each arm. STEFF includes an array of 12 (5"x4") NaI scintillation detectors for gamma-ray detection. The fission fragments stop in Bragg detectors, the outputs of which are digitized as a function of time and are used to measure energy loss (dE/dx) and range; and hence are used to determine atomic-number distributions. The measured properties of fission and fission-fragment gamma decay are used in studies of the dynamics of the process and have applications in the nuclear-energy sector.

A new programme is commencing to use the ISOLDE Solenoidal Spectromter facility at CERN to use (d,p) reactions in inverse kinematic to induce fission in previously unaccessible systems to neutron irradiation techniques.



NUCLEAR THEORY

The Nuclear Theory at Manchester is interested in the connections between nuclear physics and the underlying theory of the strong interaction, Quantum Chromodynamics (QCD), and also in descriptions of nuclei from first principles. Our work ranges from studies of the properties of a single nucleon, through descriptions of the forces between two or three nucleons, to calculations of heavier nuclei. Key tools in this work are effective field theories (EFTs). These theories are expressed in terms of the relevant low-energy degrees of freedom, such as nucleons, pions and photons. They incorporate the symmetries of QCD including a chiral symmetry which reflects the existence of almost massless up and down quarks inside hadrons. This symmetry places important constraints on the interactions of pions with other particles. The work combines ideas from quantum field theory with methods for treating few- and many-body systems. It involves a combination of analytic and numerical calculations, the exact balance depending on the particular project. Possible projects are available on all of the topics listed below for individual members of staff.

Dr Judith McGovern's current interests are focussed on applications of chiral EFTs to the properties of protons and neutrons, and in particular to their electromagnetic polarisabilities. These quantities describe the response of a nucleon to external fields. Recent work has been on analyses of Compton scattering data for the proton and deuteron; extensions will determine the full range of proton and neutron polarisabilities from new experiments on protons and light nuclei. The same approach can be used to determine the contribution of two-photon exchange to the Lamb shift in muonic atoms. In work with Mike Birse, it has been applied to muonic hydrogen, and further work is needed to analyse recent experiments on other muonic atoms. The results of this will help to shed light on the "proton radius puzzle".

Prof Mike Birse works on nuclear forces within the framework of EFTs, and their applications to few-nucleon systems. A particular interest is the use of the renormalisation group to analyse the scaling behaviour of the interactions. In collaboration with Niels Walet, he is also developing an approach to many-body systems based on a functional version of the renormalisation group. This provides a tool for handling strongly interacting systems that does not rely on diagrammatic expansions.

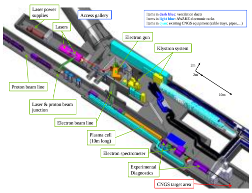
Prof Niels Walet has expertise with a variety of first principles approaches to many-body systems, in particular the coupled-cluster method. In work with Mike Birse, he has implemented a stochastic variational method to calculate the properties of few-nucleon systems. First applications of this have been made using simpler EFT without pions to describe nuclei with up to eight nucleons.

PARTICLE PHYSICS - ACCELERATOR

The Particle Accelerator Physics group studies the interactions between charged particle and electromagnetic fields. We are involved with a number of collaborations. In particular, we work on the High-Luminosity LHC upgrade, Anti-Matter research as part of ALPHA, acceleration through plasma as part of AWAKE at CERN, High Gradient acceleration through CLIC, THz radiation, and medical accelerators (both proton and high energy electron). This research has theoretical and experimental aspects to it. We conduct experiments at Daresbury laboratory (as part of the Cockcroft Institute), at CERN in Switzerland, The Christie and the Photon Science Institute in Manchester, XFEL in Hamburg, and FNAL in Illinois.

ALPHA Apparatus at CERN's Antiproton Decelerator facility.

Ultrafast laser systems at PSI.



AWAKE experiment at CERN.

VELA facility at Daresbury laboratory.

We have a strong connection to the Cockcroft Institute, which is a unique collaboration between academia, national laboratories and industry with the goal of bringing together the best accelerator scientists, engineers, educators and industrialists to conceive, design, construct and use innovative instruments of discovery and lead the UKs participation in flagship international experiments. Our group has 6 active academics who usually have funded Ph.D. opportunities.

Some details of current projects and future projects are indicated below. Students are encouraged to contact potential supervisors directly, or **Dr. Guoxing Xia** (guoxing.xia@manchester.ac.uk) for an overview of research opportunities.

NEG Coating Impact on Future Particle Accelerators:
https://www.findaphd.com/search/ProjectDetails.aspx?PJID=102276

Advanced Dielectric Structure Based Particle Accelerators:
https://www.findaphd.com/search/ProjectDetails.aspx?PJID=102012

A dispersive bunch decompressor and its potential:
https://www.findaphd.com/search/ProjectDetails.aspx?PJID=102015

Super-macro-particles:
https://www.findaphd.com/search/ProjectDetails.aspx?PJID=101658

Fundamental tests of antimatter gravitation with antihydrogen accelerators
Dr. William Bertsche
(william.bertsche@manchester.ac.uk)

One of the outstanding grand challenges in physics is to understand the fundamental differences between matter and antimatter that have left us with a universe that is largely composed of matter. The ALPHA experiment at CERN seeks to address this question by performing precise atomic physics measurements on trapped antihydrogen atoms in order to seek minute differences with equivalent measurements in hydrogen. The collaboration is building ALPHA-g, the next generation of antihydrogen traps intended to measure antimatter gravitation.

We are seeking a PhD student to design and perform gravitational free-fall measurements on antihydrogen atoms in order to directly measure antimatter gravitational acceleration as a test of the weak equivalence principle. The student will design and analyse experimental protocol and diagnostic technique for use in ALPHA-g intended to measure the gravitational acceleration g of antimatter on Earth. The student will also be expected to participate in ALPHA's general experimental programme with trapped antihydrogen atoms.

This is an interdisciplinary experimental project based at CERN with underpinnings spanning plasma, atomic and particle physics. The successful realisation of this project will require both experimental efforts as well as development of diagnostic tools for measuring and controlling the probe and background magnetic fields in the experiment. Particle and field behaviour will be modelled using software such as GPT, Opera, ANSYS and COMSOL. This is a 3.5 – year fully-funded PhD studentship with the University of Manchester where the majority of the studentship would be based at CERN in Geneva, Switzerland.

Terahertz driven linac: Shrinking the size and cost of particle accelerators
Dr Darren Graham and Dr. Robert Appleby
(robert.appleby@manchester.ac.uk and darren.graham@manchester.ac.uk)

Terahertz radiation, which sits between infrared and microwave radiation on the electromagnetic spectrum, has the potential to reduce the size and cost of particle accelerators, opening the door to new applications in compact medical therapy, security screening, and fundamental materials science with ultrafast electron or x-ray pulses. We are seeking PhD students to work on terahertz driven particle beam acceleration, joining a collaborative project at the Cockcroft Institute. The primary objective of this project will be to optimise high power ultrafast laser based terahertz radiation sources and investigate novel concepts for terahertz-based manipulation of the 5-50 MeV relativistic electron beams provided by the VELA accelerator at STFC Daresbury Laboratory. By developing new concepts for acceleration we seek to enable a new generation of table-top particle accelerators.

The Institute has been heavily involved in the design, commissioning and operation of the Versatile Electron Linear Accelerator (VELA) facility which is capable of delivering a highly stable, highly customisable, short pulse, high quality electron beam to a series of test enclosures.

This project will involve using a number of high-power ultrafast lasers, including state-of-the-art femtosecond laser systems in Dr Graham's lab at the Photon Science Institute, a Terawatt laser system at the Cockcroft Institute, and high-energy particle accelerators at STFC Daresbury Laboratory. Hands-on experience in the use of lasers and optical components is not essential, but the student is expected to have a keen interest in experimental physics.

Recent publication:
Nature Communications 8, Article number: 421 (2017) DOI:10.1038/s41467-017-00490-y

Novel Acceleration-Miniaturizing the Next Generation Energy Frontier Accelerators
Dr. Guoxing Xia
(guoxing.xia@manchester.ac.uk)

The development of plasma accelerators has achieved significant breakthroughs in the last three decades. Nowadays, the laser wakefield accelerator can routinely produce ~GeV level electron beam with percentage energy spread within only a few centimetre plasma cell and the accelerating gradient (~100 GeV/m) achieved is over three orders of magnitude higher than the fields in conventional RF based structures (in general less than 100 MeV/m). The electron beam driven plasma wakefield acceleration has successfully demonstrated the energy doubling of the electron beam (from an initial 42 GeV to a final 85 GeV) at the Stanford Linear Collider-SLC within an 85 cm plasma channel. A very recent proton driven plasma wakefield acceleration-AWAKE experiment at CERN has achieved for the first time ever the electron acceleration in a proton-driven plasma wakefield[1] [1]. All these achievements will revolutionize today's conventional particle acceleration technology and will be paving the way for next generation very compact and cost effective energy frontier particle accelerators or colliders based on this enabling plasma technology.

Our group is one of the first few proponents to propose the proton driven plasma wakefield acceleration experiment (CERN AWAKE). Currently we are focusing on several exciting research activities including proton beam, electron beam and laser driven plasma wakefield acceleration and advanced dielectric structure based particle accelerators. Through collaboration with CERN (on AWAKE), Daresbury Laboratory (electron driven plasma wakefield acceleration) and DESY in Germany (through the EU-funded EuPRAXIA project on laser wakefield acceleration) and other international labs, we are working on various topics related to plasma and dielectric structure based novel particle accelerators and radiation sources.

Projects:

- Proton-driven plasma wakefield acceleration - AWAKE at CERN.
- Key issues in electron driven plasma wakefield acceleration - Daresbury Lab.
- A compact plasma beam dump for next generation particle accelerators.
- Ultrashort electron beam driven dielectric wakefield acceleration.
- Smith-Purcell radiation based on ultrashort electron beam in grating structures.
- Accelerator on a chip - laser driven dielectric accelerator.
- Compact radiation sources (x-rays and gamma-rays) based on intense laser plasma interaction.

[1] AWAKE Collaboration, E. Adli, et al., Nature, 561, 363-368 (2018).

VHEE Radiotherapy at The Christie and CERN: Investigation of Dose Delivery Aspects and a Potential New Paradigm in Cancer Treatment

Prof. Roger M. Jones
(roger.jones@manchester.ac.uk)

Very high energy electrons (VHEE) have the potential to deliver radiotherapy rapidly, in a well-controlled manner, and with a more favourable dose distribution than conventional photon therapy, or indeed extant radiotherapy techniques. In addition, the technological advantages of rapid dose delivery, there may well be significant radiobiological advantages in terms more efficacious tumor control or indeed other target control for similar doses as that used in conventional radiotherapy. It is important to realize that VHEE can effectively "freeze" the patient motion, as the beam can be steered rapidly using deflectors familiar to those in RF engineering. This Ph.D. project will have analytical, simulation, and experimental aspects. It will necessarily entail both mathematical physics and medical physics.

In order to assess the potential benefits of VHEE over extant methods we need to investigate the dose distribution in phantoms, and the applicability of beam steering focussing and various other beam delivery aspects. In each case, this necessitates intensive computing, based upon application of Monte Carlo methods to track the particles within the media. Here we will utilize the well-known and well-validated code Geant4, Topas, and related codes to investigate the dose distribution in heterogeneous media. We plan to capitalize on massively parallel computing and special dose collation techniques.

Our short-term plans entail validating the dose delivery to water phantoms –with the experimental component being obtained via the unique facility in Daresbury laboratory known as VELA/CLARA (which is anticipated to allow experiments at 50 MeV in 2018). We will also consolidate initial experiments made by our students in this area with additional experiments at 250 MeV with the CALIFES (recently renamed CLEAR) facility at CERN. Based on these validations on dose-depth delivery we will also proceed to investigate, both with intensive simulations and with experiments at the aforementioned facilities, focusing within water phantoms. Initial simulations indicate that VHEE radiotherapy is insensitive to media intervening in between the path of the particle beam and that of the intended dose delivery point of cancerous tissue –i.e. it is insensitive to heterogeneities such as bone tissue, air bubbles and related materials. This is a significant advantage for particular radiotherapy treatments (such as lung and bowel for example) over extant radiotherapy treatments.

High-energy electron radiation therapy has important implications for a novel radiation treatment system for cancer. It may have significant benefits over other means of radiotherapy treatment. The CLARA facility at Daresbury Laboratory (DL) provides a unique facility to provide ground-breaking experiments in this area. There is opportunity for publication in high quality journals in this area.

Proton Radiotherapy & Synchrotron Radiation
Dr. Hywel Owen
(hywel.owen@manchester.ac.uk)

My work is focussed in two main areas: proton radiotherapy and synchrotron radiation facilities. Recent developments for the delivery of proton and ion beam therapy have been significant, and a number of technological solutions now exist for the creation and utilisation of these particles for the treatment of cancer. There is nonetheless the need for the development of particle accelerators used for external beam radiotherapy and more capable and cost-effective sources of particles. On-going projects entails gantry design and cyclotron design (the RF source to accelerate protons). Utilisation of massively parallel computation, and using the cloud services for example, could have impact on treatment planning.

An additional area of interest lies in the area of synchrotron radiation facilities, which demand progressively brighter sources of electron bunches to drive both spontaneous photon output and free-electron lasers, both storage rings and linear accelerators. Many physical phenomena must be understood to design such facilities, and this is a fertile area of research.

LHC
Dr. Robert Appleby
(robert.appleby@manchester.ac.uk)

We are very excited to design and build an upgraded Large Hadron Collider to make proton-proton collisions at a much higher collision rate, to probe the fundamental structure of matter, measure the Higgs boson and other new particles to an unprecedented level of precision and search for undiscovered particles of nature. There are often opportunities for students to participate in research in this area, on novel new cavities, such as crabbing cavities, on collimation, and on the beam dynamics of transporting high energy beam throughout the LHC. This research has analytical, simulation and experimental aspects to it.

PARTICLE PHYSICS: EXPERIMENTAL

The Experimental Particle Physics group performs world-leading research at a wide range of experimental facilities. Potential projects are available in the following areas:

- Flavour physics
  - LHCb: The charm and beauty of antimatter
  - BESIII: The Chinese flavor factory
  - Mu2e: Precision muons at Fermilab
  - g-2: The anomalous magnetic moment of the muon
- Neutrino Physics:
  - The SBN Programme (MicroBooNE and SBND)
  - Deep Underground Neutrino Experiment (DUNE)
  - The NEXT experiment
- Dark matter detection:
  - The search for dark matter with the DarkSide-20k experiment
- Energy Frontier Physics:
  - The ATLAS Experiment at the Large Hadron Collider
- 3D diamond detector R&D:
  - Development of a beam conditions monitor with 3D diamond for the ATLAS experiment

In some cases, it is possible for the above projects to include a component of theoretical research. Please indicate in your application if this would be of interest to you.

Flavour Physics

The group has a range of involvements in flavour physics experiments. PhD projects are possible within each of them but can also span more than one project.

Project: LHCb: The charm and beauty of antimatter

Main contact:

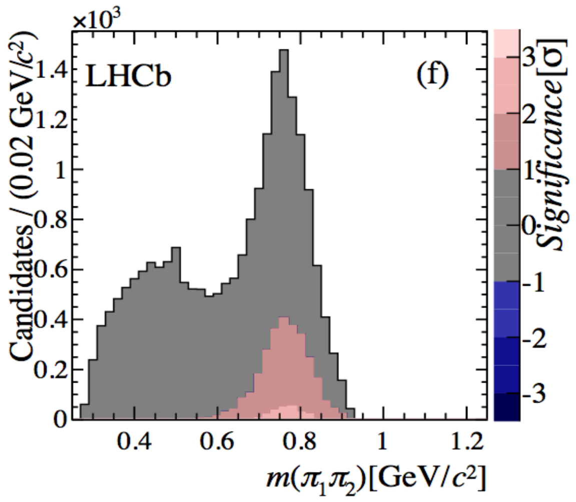
Dr. Marco Gersabeck (marco.gersabeck@manchester.ac.uk)

Other contacts:

Dr. Conor Fitzpatrick (conor.fitzpatrick@cern.ch)

Dr. Evelina Gersabeck (evelina.gersabeck@manchester.ac.uk)

Prof. Chris Parkes (chris.parkes@manchester.ac.uk)



Led by Manchester:
Hints of matter-antimatter asymmetries in charm?

Manchester is one of the larger university groups working on the LHCb experiment and is involved in all current and future aspects of the experiment. This experiment is designed to search for physics from beyond the Standard Model through the analysis of matter-antimatter differences and rare decays of hadrons involving bottom and charm quarks. The group has been responsible for world leading analyses in both areas. We have been involved in running the vertex detector of the experiment, the highest precision detector at the LHC, and in the design and construction of an upgraded detector for much higher luminosity.

We aim to give students a broad education and therefore they would be typically involved in two of the following areas. In most cases, the project will have a physics analysis as the main activity, but it may equally be focusing on technical aspects.

Flavour physics:

There are research projects in all our main areas of focus: matter anti-matter asymmetries (CP violation), precision tests with semi-leptonic decays, and rare decays. Our group is leading CP violation measurements in charm hadrons and has produced the world's most precise charm CP violation measurement. The group's work has been instrumental in the 2019 landmark discovery of CP violation in charm decays.

Our CP violation studies with bottom hadrons focus on two areas: searches for CP violation in baryons and CP violation measurements of B hadron decays to final states involving charm hadrons. Many of these are sensitive to the CKM angle gamma, but we also exploit these final states to determine other parameters. Some of the measurements within our group are performed exploiting synergies with the BESIII experiment.

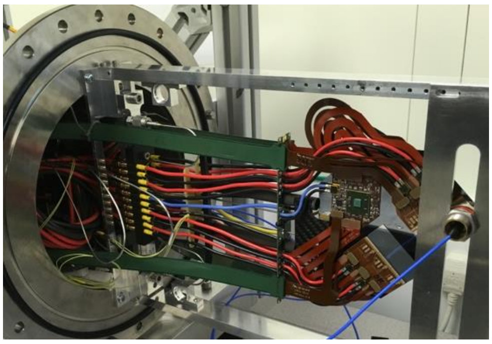
Another area of significant interest are measurements using semi-leptonic decays of charm and B hadrons, which primarily focus on tests of lepton universality, a fundamental principle of the Standard Model that has seen increasing tensions in a number of recent measurements.

Among rare decays our general focus is on lepton-flavour violating processes, which we study in tau lepton decays as well as in B and charm hadron decays to a mixture of electrons and muons. A recent study of charm decays led to over 20 world's best limits.

Our group drives innovation of analysis methods and we have been the first to exploit Graphical Processing Units (GPUs) in an LHCb analysis and have pioneered a fast simulation method that is now responsible for most simulated events in LHCb. In addition, we have had leading involvement in LHCb's Real-Time Analysis from the outset and remain committed to driving novel analysis approaches. In general, all our projects include a high degree of data science applications and training.

We are also in close contact with theory colleagues who work on the phenomenology of the LHCb physics programme. With Dr Stefan Schacht being part of the High-Energy Physics group, this also offers the opportunity of informal theory projects or even a joint experiment-theory PhD.

Preparing for the next-generation experiment:



LHCb VELO upgrade module

The LHCb experiment is currently being upgraded to a new detector for higher luminosity operation in 2022. One of our key work areas over the coming years will be the commissioning, and operation of the upgraded LHCb vertex detector. Our group is carrying out the assembly of the individual modules (see figure) of what will be the highest precision detector at the LHC. The detectors are based on 55 by 55 micron pitch silicon pixel detectors. They use an innovative micro-channel cooling system using liquid CO_2. Research projects in this area will focus on the commissioning and operation of the detector in areas in which the group has long-standing involvement through the decade-long operation of the predecessor vertex detector. This includes monitoring the data quality, including studies of radiation damage effects in particular, as well as studies of the data reconstruction and simulation.

We also have a leading role in the implementation of LHCb's real-time trigger, alignment and calibration system, which is a novel approach that permits the acquisition of ready-for-analysis data straight out of the detector, as well as in the data processing and analysis project. Future projects in this area will focus on translating the experience from the previous LHCb detector to the upgraded experiment and achieving an optimal trigger quality, efficiency and throughput, as well as the required micron-level alignment of the detector components.

Designing the long-term future of LHCb:

Particle physics experiments operate on long timescales and our group is consequently also involved in developing crucial future detector systems. One is a new semiconductor detector to be used in the innermost regions of the tracking stations following the LHCb dipole magnet. The system should be installed around 2026. Future projects in this area will play a key role in the R&D phase and in the construction of prototype detector elements.

The second system is a novel vertex detector that, in addition to high position resolution, can also deliver precise timing information. This requires an ambitious R&D project to deliver a system that can cope with a factor ten more particles compared to the upgraded LHCb VELO. Future projects will focus on R&D of advanced sensor technology, of novel cooling and support structures, as well as of the 4D reconstruction of particle tracks with this detector.

Project: BESIII: The Chinese flavour factory

Main contact:

Dr. Evelina Gersabeck

(evelina.gersabeck@manchester.ac.uk)

The BESIII experiment is a flavour physics experiment at the electron-positron BEPC II collider at IHEP, Beijing, China. The experiment has been designed to operate in the tau-charm energy region and it a broad physics program that includes QCD tests, tau-physics, light hadron spectroscopy, electroweak interactions and lepton universality tests, charmonium production and decay properties, charm physics and searches for physics beyond the Standard Model. The Manchester group is involved in the latter two. A unique feature of the experiment is the coherent production of quantum-entangled D0 anti-D0 meson states at the (3770) resonance threshold with no additional hadrons. This unique production mechanism is very powerful for identifying the flavour and separating the different CP eigenstates.

BESIII detector

Key attributes of the decays of the D mesons cannot be determined from other flavour physics experiments such as LHCb and Belle II; they require the use of quantum-entangled states that are accessible at BESIII. The quantum correlation of the charm pairs allows unique access to quantities such as the relative strong phase variation across the phase space of the decays of the charm meson and its antimatter partner. Such measurements have an important impact on understanding the different behaviour of matter and anti-matter. The complementarity and the synergy of BESIII and LHCb physics programmes carries a great potential to reduce to the minimum the limiting systematics in measurements of charm mixing parameters and CKM angle done at LHCb due to model or external inputs. Manchester is one of the two UK groups involved in both LHCb and BESIII.

The production mechanism of the charm particles and the low-background environment makes the experiment particularly attractive for precise measurements of the absolute branching fractions, lepton universality tests and searches for dark matter candidates. Students are expected to focus on a physics analysis but contributions to service tasks and detector operation and data taking are also expected.

Project: Mu2e: Precision muons at Fermilab

Main contact:

Prof. Mark Lancaster (mark.lancaster@manchester.ac.uk)

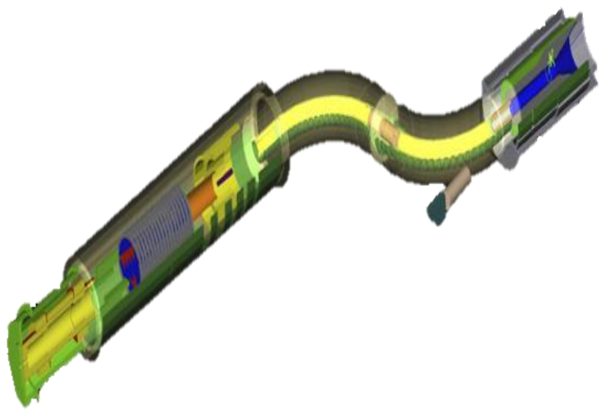
Other contacts:

Prof. Rob Appleby (robert.appleby@manchester.ac.uk)

Dr. Marco Gersabeck (marco.gersabeck@manchester.ac.uk)

The Mu2e experiment at Fermilab aims to improve the sensitivity in the search for neutrinoless muon-to-electron conversions (in nuclei) by four orders of magnitude. The rate is such conversions is essentially zero in the Standard Model and thus any observation would be a signal of new physics. The experiment is sensitive to a wide variety of new physics phenomena many of which cannot be directly detected at the LHC and is particularly timely given hints from the Fermilab muon (g-2) experiment and LHCb that muons are perhaps not quite behaving as predicted by the SM.

Our group is responsible for commissioning and operating an X-ray detector to record the number of muons captured by the target (in excess of 10^8/sec) in collaboration with other UK groups.



The FNAL Mu2e Experiment

In this project, a student will be commissioning the X-ray detector with the first muon beam and optimising its performance and making a precise determination of the muon flux: without which, the rate or limit of new interactions beyond the SM cannot be determined. In parallel, the project will involve optimising the performance of the straw-tracking detectors to maximise the experiment's sensitivity to new physics phenomena and thus establishing the world's most sensitive search for charged-lepton flavour-violation.

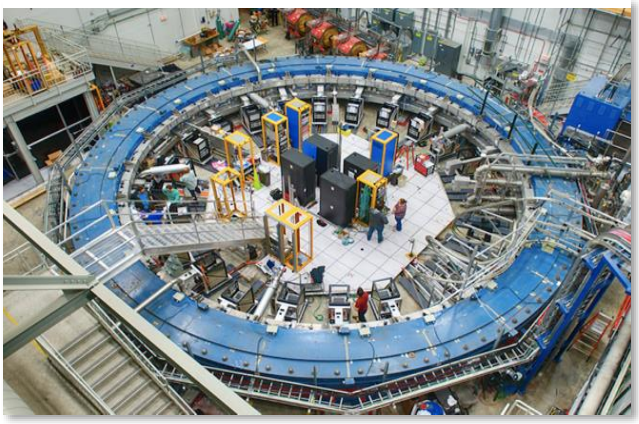
Project: g-2: The anomalous magnetic moment of the muon

Main contact:

Prof. Mark Lancaster (mark.lancaster@manchester.ac.uk)

The interaction of a muon's spin with a magnetic field defines its magnetic moment in terms of the gyromagnetic ratio, g. In the Dirac equation, g is exactly 2, but additional higher order QED, electroweak and strong interactions increase its value by ~ 0.1% such that in the Standard Model (SM),g-2 is predicted to be: 0.0023318362(9). g-2of the electron is the most accurately predicted and measured quantity in physics and g-2of the muon is the most accurately measured quantity using a particle accelerator storage ring.

The Fermilab (FNAL) Muon (g-2) experiment has recently published an analysis of less than 10% of its data and confirms a previous measurement made at the Brookhaven National Laboratory(BNL)almost 20 years ago. Together these two measurements measure g-2 to be: 0.0023318412(8):different from the SM prediction by 4.2 standard deviations. This is presently the largest difference between a SM prediction and a measurement, and is perhaps a sign of a new interaction beyond the SM. Results from the LHCb experiment that muons do not behave the same way as electrons also hint that muons are perhaps anomalous. With the data already accrued, the FNAL Muon (g-2) experiment can establish evidence for new physics with a significance of more than 5 standard deviations should the FNAL and BNL measurements be further confirmed with the higher statistics analysis.



The FNAL Muon g-2 Experiment

A student on this project will be involved in the final year of the 6-year data taking campaign at FNAL, where data with a μ-beam will be taken, and the analysis of the final, highest-statistics data from the experiment that will establish the definitive measurement of g-2 of the muon. Particular focus will be on the evaluation of the systematic uncertainties due to the harmonic motion of the beam and the variance in the beam momentum.

Neutrino Physics

Neutrinos have already taken us beyond the Standard Model of Particle Physics, and may well be ready to reveal yet more new physics beyond the Standard Model. Our group is active in several key areas of neutrino research. We are involved in the US-based liquid argon programme, which includes the Short Baseline Neutrino (SBN) Programme that is searching for the sterile neutrino -a completely new particle; and DUNE, a long-baseline experiment with a cathedral-sized detector, which aims to explain the matter-antimatter asymmetry of the University through observations of neutrino oscillations. Another important question is whether the neutrino can be its own antiparticle, a so-called Majorana fermion. In this case it should be possible to observe an extremely rare radioactive decay called neutrinoless double-beta decay, which would violate lepton number conservation -we are searching for this process with the SuperNEMO detector in France and with NEXT in Spain. We also have an active detector instrumentation efforts that aim to enhance noble element detectors for future experiments.

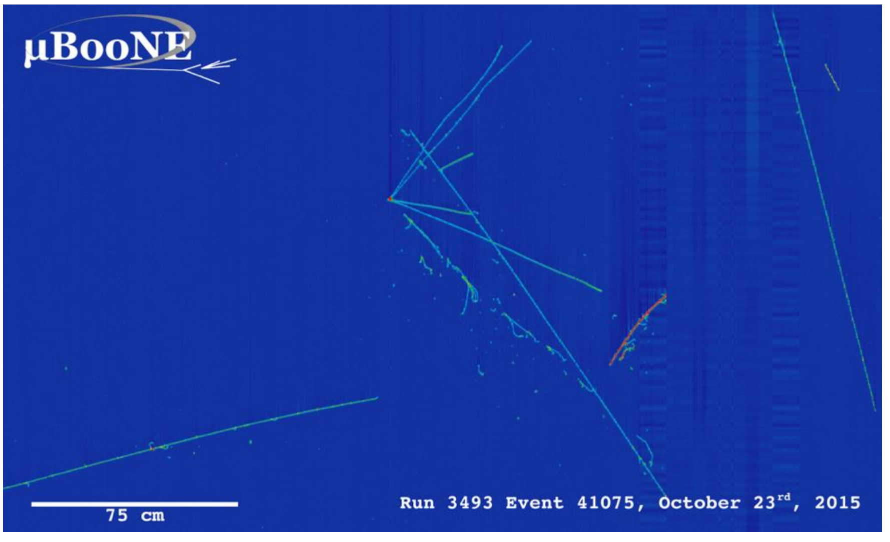
<u>Project: The SBN Programme (MicroBooNE and SBND)</u>

Main Contact:

Prof. Justin Evans(justin.evans@manchester.ac.uk)

Further Contacts:

Prof. Stefan Söldner-Rembold (stefan.soldner-rembold@manchester.ac.uk)



One of the first neutrino events observed by the MicroBooNE detector at Fermilab.

The SBN Programme will combine three international experiments in order to perform the world's most sensitive search for sterile neutrinos, using the phenomenon of neutrino oscillation. Sterile neutrinos are hypothesized, new neutrino flavours, which do not interact via the weak force; they are only observable through their oscillations. SBN aims to search for such oscillations by placing three liquid argon TPC (LArTPC) detectors (MicroBooNE, SBND, and ICARUS T600) at short baselines along the Fermilab Booster Neutrino Beam and studying how the rates of different neutrino flavours vary as a function of the neutrino travel distance. This project will involve the analysis of data from the already running MicroBooNE experiment, as well as the commissioning of the SBND experiment, which is currently being constructed. Our group's focus is on reconstructing electromagnetic showers to search for neutrino oscillations, and looking for alternative signatures of physics beyond the Standard Model. The project could also have a small hardware component through involvement in the commissioning of the SBND detector.

Project: Deep Underground Neutrino Experiment

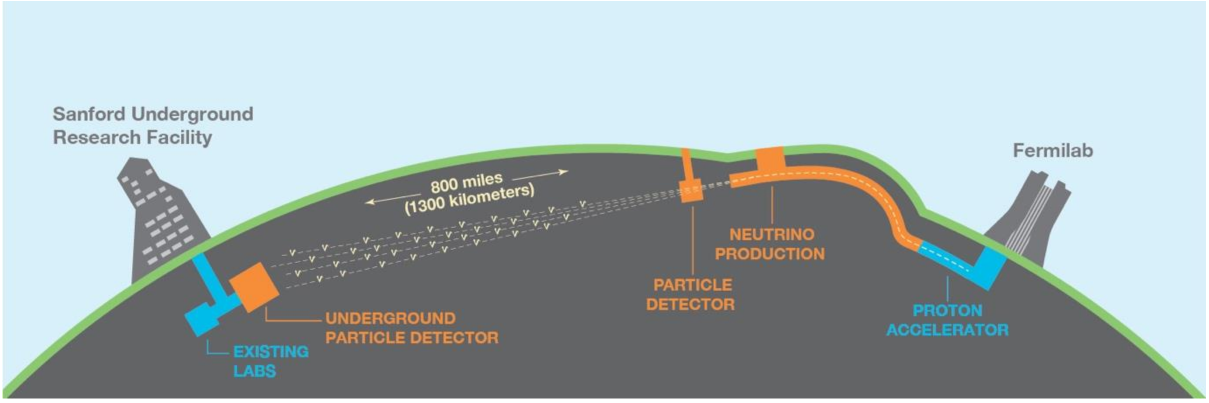
Main Contact:

Prof Stefan Söldner-Rembold (stefan.soldner-rembold@manchester.ac.uk)

Further Contacts:

Prof. Justin Evans (justin.evans@manchester.ac.uk)

Prof Roxanne Guenette (roxanne.guenette@manchester.ac.uk)



DUNE is an international, next-generation neutrino science project with the goal to discover CP violation in the lepton sector, study neutrino oscillations, and to record neutrinos from a supernova explosion. The neutrino beam produced at Fermilab near to Chicago will be measured in a Near Detector on-site and at a large underground facility in South Dakota.

The Deep Underground Neutrino Experiment (DUNE) is an international collaboration of scientists from more than 30 countries with the goal to study neutrino interaction and to discover CP violation in the lepton sector of the Standard Model, addressing the fundamental question of matter dominance in the Universe. It will also study neutrinos from supernova explosions and search for other non-standard physics phenomena, such as proton decay.

Our group plays a leading role on the project: we are responsible for building one of the largest components of the detectors, large wire planes (called Anode Plane Assemblies) that will read out the charge produced by neutrino interactions in the liquid argon of the DUNE far detectors located in South Dakota. We are also starting a programme to develop the next-generation charge readout designs, using a pixel design that will allow us to measure “true” 3D images of the interaction. Potential PhD projects could be related to the optimisation of the design of such a detector, building and testing of detector components, or the developments of algorithms for the reconstruction of the images. Another important aspect is the development of physics analyses using machine learning techniques. As we are also collaborate on the short-baseline neutrino programme (see separate section), which uses similar detector techniques, data from these detectors could be used to validate and further develop physics analyses with a focus on searches for physics beyond the Standard Model.

Project: NEXT experiment

Main Contact:

Prof. Roxanne Guenette (roxanne.guenette@manchester.ac.uk)

The NEXT high pressure xenon gas detector, located underground at Canfranc, searches for Majorana neutrinos.

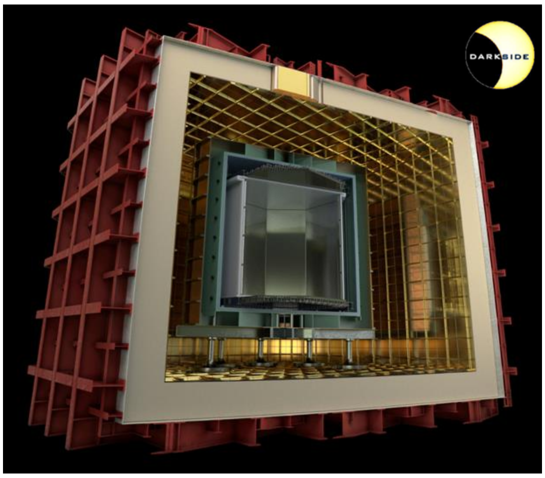
The NEXT experiment uses a high-pressure xenon gas time projection chamber to search for Majorana neutrinos. This type of detectors allows for great energy resolution and offers imaging capabilities that can help reduce background, two essential ingredients for identifying the extremely neutrinoless double beta decay process. We are currently constructing a new phase of the experiment at the Laboratorio Subterráneo de Canfranc in Spain, NEXT-100 which will take data for the next few years, providing competitive limits on the neutrinoless double beta decay half-life and demonstrating the capability of the technology at larger scale. Our group will play an active role in the detector commissioning and will perform several data analyses. We will also work on developing a new readout plane for the future ton-scale phase of the project.

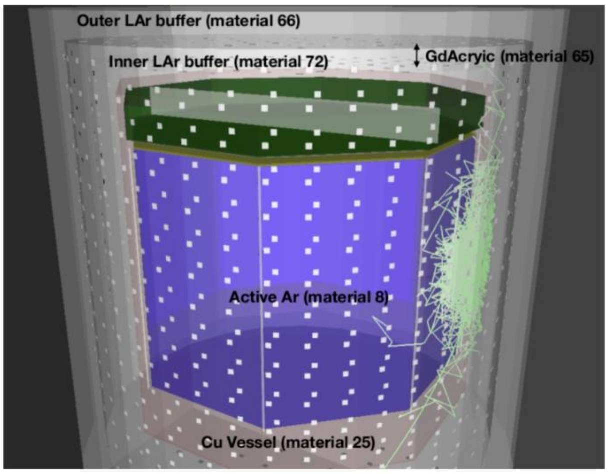
Dark matter direct detection searches

<u>Project: The search for dark matter: DarkSide-20k</u>

Main Contact:

Dr. Darren Price (darren.price@manchester.ac.uk)





A simulation of the DarkSide-20k experiment and tests of the readout of the silicon photosensors in the neutron veto

The DarkSide-20k experiment aims to discover dark matter via the elastic scattering of dark matter particles from space on argon nuclei in a 50-tonne detector instrumented with over 11,000 cutting-edge silicon photosensors operating at cryogenic temperatures.

DarkSide-20k is designed for a sensitivity reach to dark matter interaction rates more than two orders of magnitude beyond current searches at dark matter masses of 1 TeV and to have leading sensitivity to masses above the energy scale accessible at the LHC. This experiment is in the R&D phase and is expected to begin taking data at the Laboratori Nazionali del Gran Sasso in Italy in 2023.

Manchester holds key responsibilities within the experiment. These includethe construction of the high efficiency low radioactivity cryogenic silicon photosensor modules for the outer detector, and the design electrical tests and performance characterisation of these sensors, critical toenable discriminate dark matter signals from natural radioactive background processes. The Manchester group plays a central role in algorithm development, detector simulations,and the analysis of data from prototype detectors. The group plays a central role in he expansion of the science programme of DarkSide, publishing innovative studies in conjunction with theorists exploring prospects and strategies for studying non-standard dark matter models, expanding dark matter mass sensitivity down to the tens-of-MeV range,and exploration of neutrino physics opportunities with this detector.

Potential PhD project work can combine aspects of detector design/construction, computer simulations, data analysis, and physics sensitivity studies.

ATLAS Experiment

Project: The ATLAS Experiment at the Large Hadron Collider (CERN)

Main Contacts:

Dr. Alex Oh (alexander.oh@manchester.ac.uk)

Prof. Terry Wyatt (terry.wyatt@manchester.ac.uk)

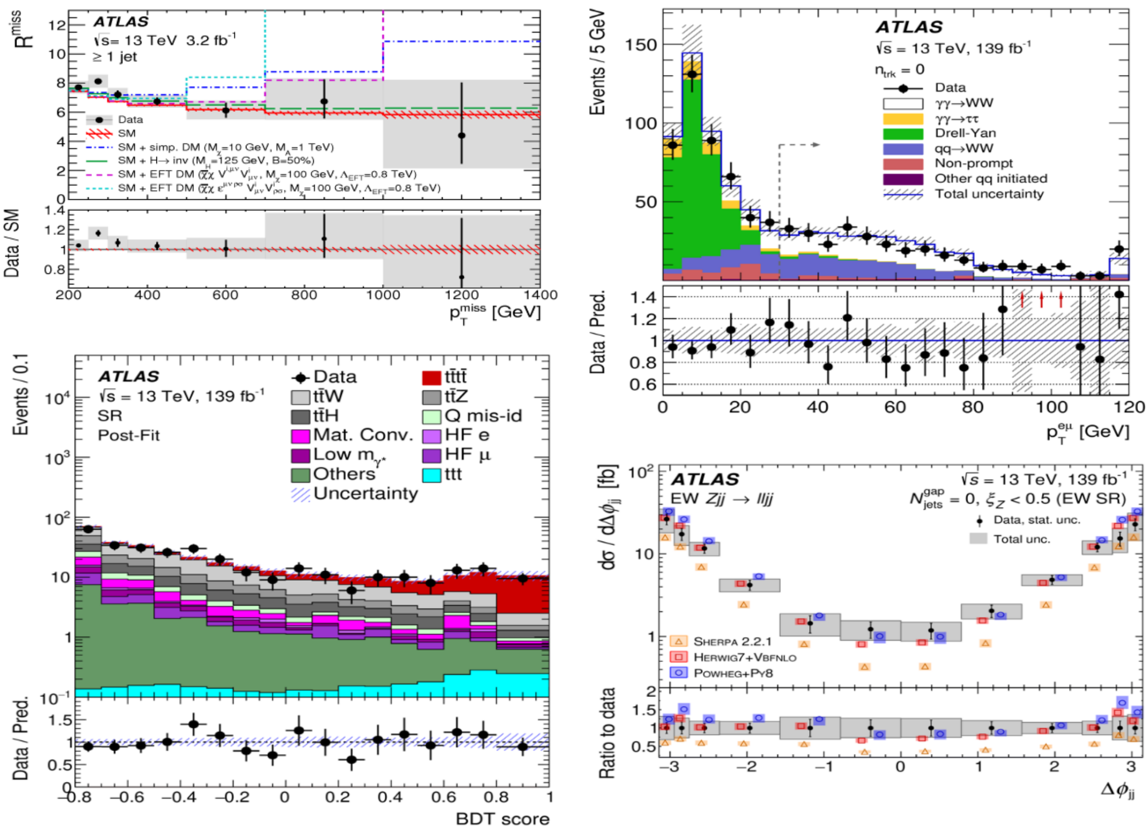
Further Contacts:

Prof. Cinzia Da Via (cinzia.davia@manchester.ac.uk)

Prof. Yvonne Peters (yvonne.peters@manchester.ac.uk)

Prof. Andrew Pilkington (andrew.pilkington@manchester.ac.uk)

Dr. Darren Price (darren.price@manchester.ac.uk)



Illustrations of some recent firsts from the ATLAS Manchester group: new methods for searching for dark matter at the LHC (top), observation of the production of W boson pairs in photon-fusion (top right), evidence for four-top production (bottom left), precision measurements of pure electroweak production of Z+2jet systems (bottom right).

ATLAS is a general-purpose particle physics experiment at the Large Hadron Collider (LHC).Manchester has played a major role in the ATLAS experiment for many years, with members taking international leadership across all areas of ATLAS operations, such as data acquisition, physics analysis, detector commissioning and detector upgrade.

ATLAS collected 140 $fb^{-1}$of proton-proton collisions at a centre of mass energy of 13 TeVin the LHC Run-2 (2015-2018). From 2022 onwards, this will be augmented with data collected during LHC Run-3. This provides a dataset that is unprecedented in both size and energy. Our goal is to provide world-leading sensitivity to dark matter, CP-violation, extra dimensions, additional Higgs bosons, heavy Majorana neutrinos, gravitons and leptoquarks. We perform this research from multiple angles. We search directly for these new physics phenomena as predicted by specific theories. We also produce model-independent measurements that test the predictions of the Standard Model, which could provide the first hints of something completely new and unexpected.In 2021, we expect to offer projects in the areas of electroweak physics, Higgs physics, and physics beyond the Standard Model.

The Manchester group has played a major role in studying the self-interactions of the weak bosons. Recent highlights include precision differential measurements of vector-boson scattering processes at a hadron collider, the first observation of photon-photon fusion processes, and the search for proton-proton collision events that contain three weak bosons. Each of these processes is sensitive to the self-interactions of electroweak bosons, which is a key prediction of the Standard Model, and deviations from the expected event rates would signify anomalous weak boson self-interactions: a smoking gun for new physics! The processes however are extremely rare and measurements are only becoming possible now, with the large datasets available from the LHC.

In the Higgs sector, we continue to develop new ways of understanding the interactions of the Higgs boson. Our group members made the first measurements of the Higgs boson differential cross sections and used these to search for anomalous Higgs boson interactions. We are also heavily involved in studying the relationship between the Higgs boson and the Top quark, with major contributions to the observation of Higgs bosons produced in association with a top-antitop pair. We currently lead measurements that probe the CP nature of the Higgs-Top interaction, which could provide the missing source of CP violation needed to explain the matter-antimatter asymmetry of the universe.

The Manchester group has been central to the development of new initiatives in the search for new physics phenomena, spearheading new approaches to the search for dark matter through precision measurements and through real-time data-analysis techniques. We lead new efforts to search for heavy Majorana neutrinos and other lepton number violating phenomena at the LHC through weak boson fusion processes, have developed novel observables to test the principle of lepton universality in W boson decays, and are the primary developers of the 'Trigger-Level Analysis' technique that dramatically improves the sensitivity to final states that are limited by the ATLAS data acquisition system. We have a broad direct search programme for new particles through two-boson and three-boson final states (searching for high mass particles like gravitons), di-tau final states (searching for particles preferentially coupling to third-generation particles, or doubly-charged Higgs bosons), bb-tau-tau final states (sensitive to leptoquark and di-Higgs production), and searches for rare low mass particles that would evade standard searches.

Very few particle physics groups in this country or the rest of Europe can boast of a close and long-standing connection between experimental and theoretical particle physicists. This provides plenty of fruitful opportunities for joint experiment-theory collaborations in LHC physics. We have had several very successful examples of PhD students developing a piece of phenomenology or a novel analysis technique in collaboration with the particle theory group, which they have then applied to the analysis of ATLAS data.

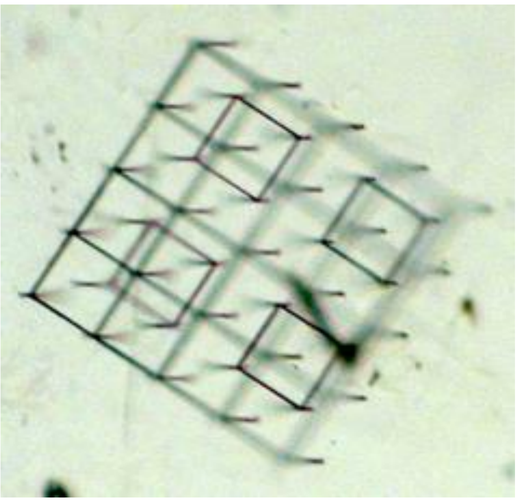
In addition to physics analysis, PhD students contribute to one of the other areas of ATLAS operations. The Manchester group has long-term involvement and leadership in developing the data acquisition system (the ‘trigger’), improving hadronic jet reconstruction and calibration (including heavy-flavour tagging), and determining the properties of hadronic tau decays. We are also strongly involved in upgrading the ATLAS pixel detector for data-taking through to 2035. The PhD projects will combine activities from any of these research areas.

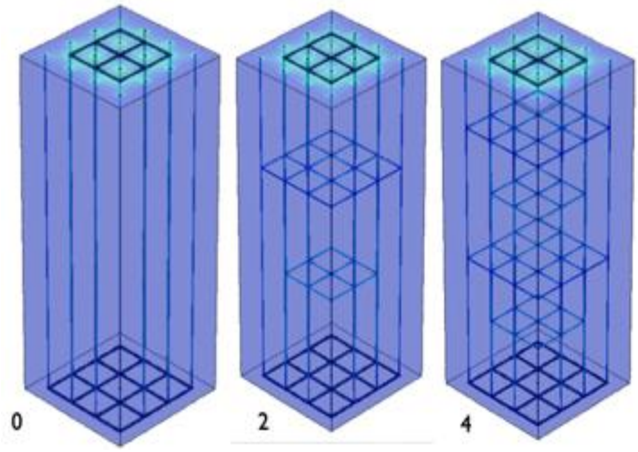
3D Diamond Detectors

Project: Development of a beam conditions monitor with 3D diamond for the ATLAS experiment

Main Contacts:

Dr. Alex Oh (alexander.oh@manchester.ac.uk)





A photograph of a 3D diamond detector with graphitic wires inside the buld diamond (left) and a simulation of the device with different wire geometries (right).

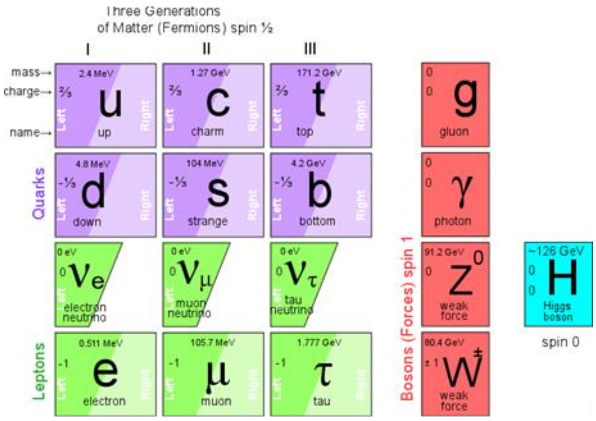
3D diamond detectors have evolved from an idea to an actual proven concept. The key point is to combine radiation hard detector material with in-bulk electrodes (called 3D). The Manchester group is leading the development of this novel technology, being the first to successfully produce the first ever prototype of such a detector in single crystalline and poly crystalline CVD diamond. For this project the Particle Physics group strongly collaborates with the Laser Processing Research Centre at the University of Manchester.

One application of this new technology would be in the field of particle physics, specifically for the Phase-2 upgrade of the detectors at the Large Hadron Collider or at a future linear collider for a beam-calorimeter application. Here a so-called Beam Conditions Monitor (BCM) will be safeguarding the inner silicon tracker against any abnormal beam conditions of the LHC. The BCM' project is developing and will commission a diamond-based detector to be installed during the long shutdown 3 of the LHC in 2024.

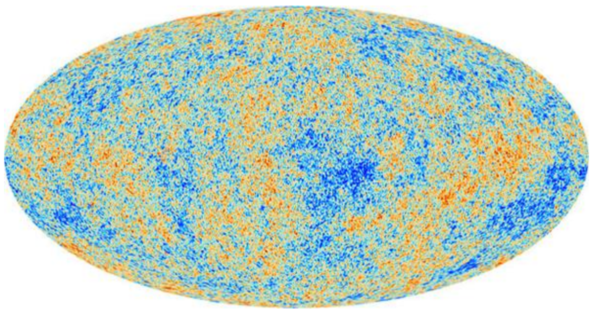
We also collaborate with The Christie Hospital to apply this technology to challenges in radiology. The objective is to use 3D diamond dosimeters for in vivo dosimetry applications for photon and proton beam therapy. More info our activities can be found here: http://alexanderoh.ch/

PARTICLE PHYSICS - THEORY

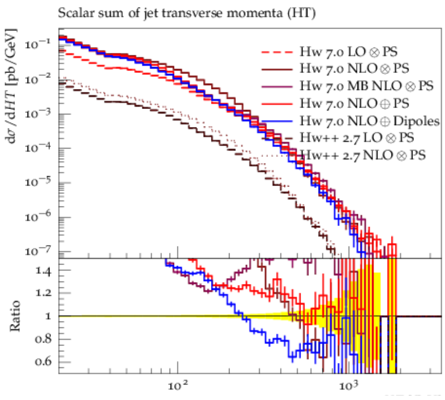
The Group has particular expertise in almost all aspects of Collider Physics phenomenology, in the Physics of the Early Universe, in Higgs and Neutrino Physics and in Physics Beyond the Standard Model. Our projects are often focused on aspects of theoretical physics that can be tested in ongoing or future experiments. Consequently we are especially interested in physics that is explored at the world's colliders, both present and future, and work closely with the experimental particle physicists both in the group and at laboratories around the world. Opportunities exist for PhD work in almost all of our research areas and projects are generally tailored to the evolving interests of individual students and their supervisors. The group's theorists regularly collaborate with each other, reflecting the fact that there is considerable overlap between the different areas of particle physics phenomenology. As a result it is usual that PhD students in this area will develop a good breadth of understanding during the course of their studies.



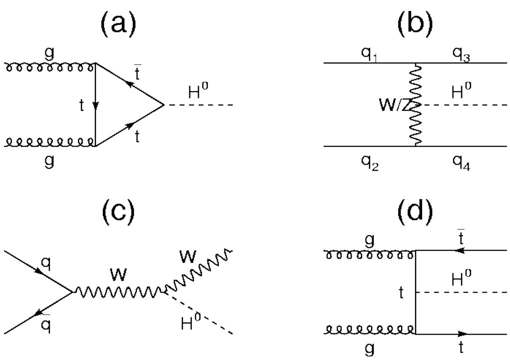
Standard Model.



PLANCK CMB image.



HERWIG 7.0 Higgs production.



Higgs production channel.

Beyond the Standard Model and Particle Cosmology
Prof. Apostolos Pilaftsis
(apostolos.pilaftsis@manchester.ac.uk)

The Standard Model of particle physics has been extremely successful in describing all current experiments, but it leaves many questions unanswered, like why particles have the masses and other quantum numbers that they do, why there are three generations of elementary particles, why there is more matter than antimatter in the universe, what the 'dark matter' of the universe is made of, whether the three fundamental forces of particle physics can be unified, and whether this can be further unified with a quantum theory of gravity. To try to answer these questions, we bring together progress in theories Beyond the Standard Model (BSM) with a phenomenological understanding of how those theories could be tested in future experiments and how we can constrain them using the existing data. A recent exciting development is the application of ideas from particle theory to cosmology, the physics of the early universe, and the realization that cosmological data are becoming precise enough to constrain the structure of BSM physics. The group has strong links with Jodrell Bank's Theoretical Astrophysics and Cosmology Group for research in this direction.

Using QCD to explore the TeV scale at the Large Hadron Collider
Dr Mrinal Dasgupta
(mrinal.dasgupta@manchester.ac.uk)

Quantum Chromodynamics (QCD) has been established at collider experiments as the theory of strong interactions, which are responsible for binding elementary quarks and gluons into nucleons. It has emerged that QCD is a remarkable theory with a split personality, possessing a friendly regime where one can do calculations using perturbative techniques (Feynman Graphs) and a more challenging non-perturbative region beyond the control of any methods that derive directly from the QCD Lagrangian,and hence still ill-understood. Additionally, while calculations in QCD perturbation theory are in principle well defined, in practice carrying out such calculations at the level of precision required by most experimental data from particle colliders is also a formidable challenge. Moreover due to the fact that non-perturbative effects are always present, devising techniques to better understand the non-perturbative region is critical to the accurate description of data from colliders such as the LHC. We have played a leading role in developing the current theoretical picture of QCD radiation and non-perturbative effects. Our present focus is on the Large Hadron Collider (LHC) experiments and the search for new physics. Since the LHC collides strongly interacting particles (protons), QCD radiation affects all LHC processes and understanding it in detail is of great importance to enable discoveries of new physics at the TeV scale. Our current research is playing a vital role in bringing a deep understanding of QCD to bear on developing precision tools to hunt for new physics such as supersymmetry, dark matter or extra dimensions, at the LHC.

Automating QCD calculations
Prof. Jeff Forshaw
(jeffrey.forshaw@manchester.ac.uk)

Almost all of the measurements at contemporary colliders, including the LHC, depend on precise theoretical calculations of the QCD "radiation" of quarks and gluons. That is because this radiation is ubiquitous in collisions involving coloured particles. The relatively strong coupling in QCD means that this physics is remarkably interesting because it cannot be captured by simple fixed-order perturbation theory. Instead "all orders" algorithms need to be developed and implemented. Here in Manchester, we are world-leading experts in all-orders QCD and this PhD project will involve joining a pre-existing team of researchers to work on the theoretical development and/or computational implementation of a new algorithm which will significantly improve upon anything that has gone before. Apart from its tremendous utility, this project involves analytic work in a problem of fundamental theoretical interest.

Monte Carlo Modelling of QCD Interactions

Prof. Michael H. Seymour
(michael.seymour@manchester.ac.uk)

In high energy physics we are usually interested in interactions between partons (quarks and gluons) with high momentum transfer, producing new particles like the Higgs boson or supersymmetric partners, or more familiar ones like the top quark. These decay to produce further partons. However, partons cannot propagate freely but are confined into hadrons, the particles that interact with the detectors around the collision region. This process by which a few hard partons evolve into a system of hundreds of hadrons is far too complicated to calculate analytically and must be modelled numerically, with Monte Carlo techniques. Any attempt to understand the data from the LHC or other high energy collider experiments would be completely impossible without Monte Carlo event generators that simulate them.

Professor Seymour is a senior author of Herwig, one of the three general purpose event generators used by the LHC experiments. He is currently working on theoretical projects to improve the formal accuracy of the approximations used in event generators, called parton shower algorithms, and on more phenomenological projects, to use current data to validate and tune the modelling in the event generators to provide LHC predictions with quantified accuracy. He also works closely with experimenters using event generators to optimize their analyses and get the maximum value out of their data.

Multiple Parton Interactions at the Large Hadron Collider and Beyond

Dr. Jonathan R. Gaunt jonathan.gaunt@manchester.ac.uk

The proton-proton collisions that occur at the Large Hadron Collider (LHC) are highly complex environments. Protons are not elementary particles, but are composed of many quarks and gluons (collectively, 'partons') bound together via the strong nuclear force. In each proton-proton collision there are typically many parton-parton collisions, and the products of these collisions can further interact with each other and with the non-colliding 'spectator' partons via the strong force. Most research work conducted so far has been focussed on the dynamics of the 'primary' highest-energy collision in the absence of other interactions. For a small set of measurements, it has been shown that the effect of the multiple additional interactions can be ignored, but in many other cases it has been assumed to be the case, or the additional interactions have been modelled in a very approximate way. However, we are entering a phase of precision physics at the LHC where we are searching for signs of new physics in small deviations between experimental measurements and precise theoretical predictions. Thus, theoretical control over the additional interaction effects is now needed. This project involves developing novel first-principles theoretical descriptions of the additional interactions, and developing numerical tools based on these descriptions to make predictions at the LHC. The project will not only be of significant utility to the LHC precision physics programme, but will also lead to new understanding of proton structure and the interactions of the proton constituents.

Effective Field for New Physics at the LHC:

Dr. Eleni Vryonidou <eleni.vryonidou@manchester.ac.uk>

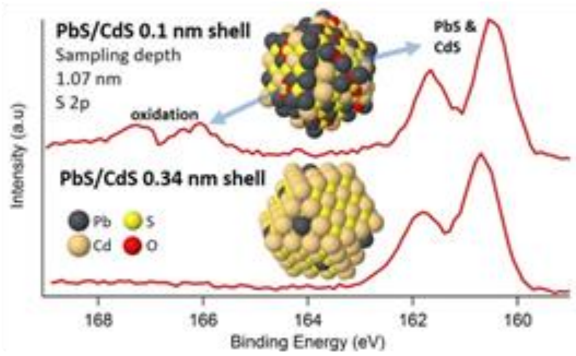
The Large Hadron Collider (LHC) is colliding protons at unprecedented energies in an exciting effort to learn more about the fundamental particles of Nature. After the Higgs discovery at the LHC, the particle physics community is pursuing a gigantic effort of determining the properties of the Higgs boson and hunting for signs of new phenomena beyond our current theoretical understanding of particle physics, the so-called Standard Model (SM). The LHC is searching for undiscovered particles and measuring the interactions of all known particles. If new particles are too heavy to be directly produced in the collisions, their effects can be detected by small modifications of the interactions of the particles that we already know exist. These small modifications can be studied within a theoretical framework that particle physicists call the SM Effective Field Theory (SMEFT). A precise determination of the interactions of the Higgs and all fundamental particles constitutes a challenge, and requires collaboration between experimental and theoretical particle physicists. My work aims at providing accurate theoretical predictions and the necessary computer codes to compute the probabilities of scattering processes occurring at the LHC within the SMEFT. Combining the predictions and data, I will then extract information on the interactions of the elementary particles such as the Higgs boson to other particles and itself. Any modification of interactions found will point to the mass scale of new particles and can provide hints to the answers of the most fundamental questions of Nature.

PHOTON PHYSICS

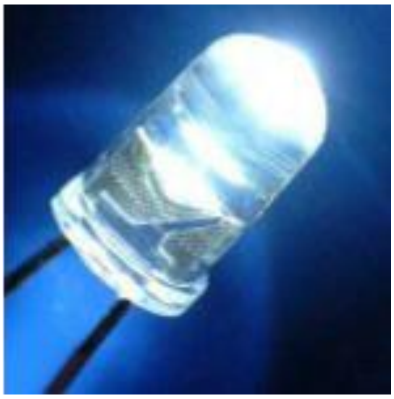
The Photon Physics group studies the interactions between light and matter and uses light to investigate a range of novel and important systems. The scope of the work ranges from improving our theoretical understanding of the quantum nature of these interactions to developing new spectroscopic and microscopic techniques for material science, medicine and biology.

Our experimental work utilises light in its broadest sense, exploiting the electromagnetic spectrum from x-rays to THz frequencies and we employ the cutting-edge facilities available in the Photon Science Institute, as well as developing new light sources ourselves. This work often studies the physical processes that underpin applications with important real-world impact, such as the development of efficient new solar cells and LEDs for low-energy lighting.

Students working with the lasers at the Photon Science Institute.



Synchrotron-excited nm-scale depth profiling used to understand passivation of the surfaces of quantum dot light harvesters.



An LED incorporating InGaN quantum wells.

Carrier dynamics in GaN films and InGaN/GaN Quantum Wells
Dr. David Binks
(david.binks@manchester.ac.uk)

LEDs based on InGaN/GaN quantum wells are revolutionising the efficiency of lighting, leading to a significant reduction in global power consumption and consequent impact on the environment. However, while these LEDs work well in the blue spectral region, they are much less efficient at other wavelengths. This necessitates the combination of a blue LED with a yellow phosphor to produce light that is sufficiently 'white' for the illumination of homes and offices, even though this involves an inherent energy loss. A much more efficient and controllable approach would be to make white light by combining the output of different coloured LEDs.

One reason why InGaN/GaN quantum wells become less efficient for emission at longer wavelengths is that obtaining LEDs that emit at these colours involves increasing the indium concentration in the quantum wells. This results in a stronger electric field across the well separates the electron and hole wavefunctions, reducing the rate at which they recombine radiatively so that it is less competitive with non-radiative processes. This electric field largely originates as a consequence of the hexagonal crystal phase of typical InGaN/GaN quantum wells.

Currently we are investigating carrier recombination processes in GaN films and InGaN/GaN quantum wells grown in the cubic crystal phase, the greater crystal symmetry of which greatly reduces the field across the quantum well. This work is supported by a recently-awarded EPSRC research grant to investigate cubic GaN material systems in collaboration with the Department of Materials and Metallurgy at the University Cambridge. We use a suite of spectroscopic techniques on cryogenically-cooled samples in well-equipped, established laboratories. In particular, photoluminescence (PL) and PL excitation spectroscopies are used to determine how carrier recombination is affected by the structure and composition of the samples, with PL decay measurements used to measure the characteristic lifetimes of the underlying processes. Raman spectroscopy is also an important technique because it yields insight in the crystal structure purity of the samples.

Research projects include:

- Investigating the cubic phase of GaN films and InGaN/GaN Quantum Wells.

Optical techniques as medical diagnosis tools

Prof. Mark Dickinson in collaboration with Dr. Andrea Murray (mark.dickinson@manchester.ac.uk and andrea.murray@manchester.ac.uk)

There is a long standing collaboration between the Photon Physics Research group at the University of Manchester and Salford Royal NHS trust, looking at mainly optical techniques for investigating Systemic Sclerosis (SSc) and Raynaud's phenomenon. Both of these conditions affect the microcirculation of the peripheral limbs, and we have been using these techniques as a window into the disease diagnosis and progression. It is anticipated that some of the projects will involve collaboration with industrial partners and may lead to CASE awards.

Research projects include:

- Advanced imaging (such as photo-acoustics).
- Using mobile devices for patient self-monitoring of disease progression.
- Functional imaging of the microvasculature using our techniques as an adjunct to MRI, microCT and biopsy.

Understanding photovoltaics and photocatalysts at the atomic scale
Prof. Wendy Flavell
(wendy.flavell@manchester.ac.uk)

There is an urgent need to make better use of the 120,000 TW of power provided by the Sun, by using it to generate power. Alternatively, we can use its energy directly to make useful chemicals (so-called 'solar fuel' - one goal is to produce the world's fertiliser through photofixing nitrogen). In my current research, I am working to develop an understanding of how photoactive junctions work at the atomic scale. The transport of charge across interfaces is fundamentally important in this, but the processes occurring immediately after the absorption of light are poorly understood. Improving our understanding will help us to answer questions such as 'how can we make solar cells cheaper and more efficient?'

How do we do this? My group uses world synchrotron facilities for surface spectroscopies (such as photoemission) to study light-harvesting quantum dots, organometal halide perovskites and heterojunctions for next-generation solar cells. Currently we are developing time-resolved measurements using laser-synchrotron pump-probe spectroscopy in order to probe the charge transport in real time at these interfaces. We also use advanced spectroscopies in the Photon Science Institute at UoM, including near-ambient pressure X-ray photoelectron spectroscopy. This helps us to understand the reactions of just the topmost few atomic layers of our nanomaterials with the atmosphere - critical to the long-term stability of solar cell devices containing them. In the last few years, we have also commissioned a world-first instrument for Hard X-ray PhotoElectron Spectroscopy (HAXPES), that allows us to probe buried interfaces in device structures.

40 PhD students of 13 nationalities have graduated under my supervision.

Some recent papers: DOI:10.1039/c7cc01538k; DOI:10.1021/acsami.1c10420 ; DOI:10.1039/c7nr00672a ; DOI:10.1063/1.4943077 ; DOI:10.1039/d1nr05436h

Research projects include:

- Understanding novel solid state photovoltaic cells.
- Surface properties of quantum dots for next generation solar cells.
- Ultrafast measurements of charge transport in nanoparticles for solar nanocells.
- Degradation and surface passivation of halide perovskite light harvesters.
- Designing new catalysts for nitrogen photofixation.

Ultrafast laser-driven sources of terahertz radiation
Dr Darren Graham
(darren.graham@manchester.ac.uk)

Terahertz radiation, which sits between infrared and microwave radiation on the electromagnetic spectrum has historically been very difficult to utilise, and yet this last unexplored region of the spectrum has the potential to transform a diverse range of fields. My group's research interests are focused primarily on the development and exploitation of novel terahertz radiation sources. I address challenges both within the fields of photon physics and accelerator physics. Within the field of photon physics, my group uses ultrafast laser spectroscopic techniques to develop novel sources of terahertz (THz) radiation utilising the state-of-the-art laser facilities at the Photon Science Institute (PSI), and working closely with industrial partners. Further information about the work of my group can be found at https://personalpages.manchester.ac.uk/staff/Darren.Graham/

PhD projects include (but not limited to):

- **Ultrafast Spintronics** – Recently, the emission of extremely broadband electromagnetic radiation, spanning from the mid- to far-infrared spectral regime and covering the so-called 'terahertz gap' in the spectrum, from ferromagnetic structures has led to an exciting new route for the generation of terahertz radiation. The ability to control the properties of the emitted THz radiation also has the potential to facilitate a wide range of diverse, technologically demanding scientific applications, from improved medical diagnosis to non-destructive testing and advanced airport security scanners. Furthermore, by understanding the fundamental emission process we will be able to establish new characterisation tools for use in developing the next generation of spintronic devices, where ultrafast spin processes are being investigated for data storage and manipulation.
- **Ultrafast Terahertz Spectroscopy of GaN Semiconductor Structures** – The 2014 Nobel prize in Physics was awarded for the invention of the efficient blue light-emitting diodes (LEDs) that have enabled the development of bright and energy-saving white light sources. This breakthrough in the blue part of the spectrum has spurred interest around the world in exploiting GaN semiconductor quantum wells, the material at the heart of blue LEDs, in other regions of the electromagnetic spectrum. One region of particular interest is the terahertz region. To realise the potential of this region we require compact, efficiency and powerful sources of terahertz radiation and the fundamental properties of GaN semiconductors make this a tantalising possibility. In this project the student will use the state-of-the-art laser facilities within the Photon Science Institute to reveal the physics that governs the properties of this remarkable materials system and optimise GaN-based quantum well structures for terahertz sources and detectors. This work will be carried out in close collaboration with the Materials Science Department at the University of Cambridge. The opportunity to work in collaboration with international renowned academics will provide training in cutting-edge experimental physics techniques. The skills gained will provide a solid foundation for a future career in industry or academia.

Atomic collision physics using combined electron and laser beams

Prof. Andrew Murray
(andrew.murray@manchester.ac.uk)

Our research combines electron and laser interactions with atomic and molecular targets to study the fundamental processes that lead to excitation and ionization. This research is important in fields ranging from understanding energy loss mechanisms in Tokomaks, through to studying how low-energy electrons cause DNA breaks in cells leading to cancer. We combine high-resolution laser and electron beams to probe these interactions. Laser beams are used to cool, trap and excite atoms before an electron beam further excites, de-excites or ionizes the target under study. In this way we precisely control their quantum state, with the results from our measurements being compared to models developed by colleagues in Europe, the USA, Australia and the UK. We are the leading group in the world in this area of research, with all experiments conducted using custom-built spectrometers in Manchester together with the laser facilities in the Photon Science Institute. We operate five different experiments that study electron-impact excitation and ionization from laser-excited atoms and molecules, the production of cold electrons from cold atoms, and the production and study of highly excited neutral Rydberg atoms (whose diameters are up to 10% that of a human hair).

Research projects include:

- Electron impact ionization and excitation of atoms and molecules

- Study of quantum interference from two-colour photoionization pathways using a toroidal spectrometer (a 'double-slit' experiment with a single atom – see Physics World, Feb 2020) (**NEW** fully funded EPSRC project)
- Production of a quantum diffraction grating using single photo-electrons emitted from a cold atom array (**NEW** fully funded EPSRC project)
- Producing & ionizing highly excited Rydberg atoms following stepwise electron impact and laser excitation (**NEW** fully funded EPSRC project)

Spectro-microscopy of nanostructured materials
Dr. Patrick Parkinson
(patrick.parkinson@manchester.ac.uk)

It is over 60 years since Richard Feynman claimed "There's plenty of room at the bottom", establishing the field of functional nanotechnology. In this field, performance depends on both the geometry and quality of a material. Optical nanotechnology is rapidly emerging as an enabling technology for the new field of on-chip photonic integrated circuitry, which provides a novel alternative for fast, low cost and energy efficiency computation.

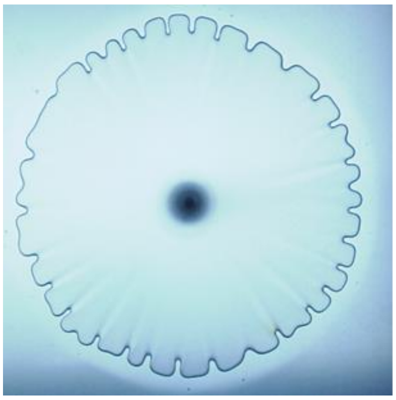
Key elements include light emitters, lasers, and sensor which must be designed and produced at the sub-wavelength scale; by exploiting advances in bottom-up fabrication, billions of single element devices can be produced in a single growth run. However, understanding the complex behaviour of material, electronics, and light within sub-micron and heterogeneous materials presents a huge challenge.

As part of a UKRI Future Leaders Fellowship "Big-Data for Nano-Electronics", our group develop an experimental and data-science framework for high-throughput functional characterisation of single-element nanotechnology. The aim of this project is to make use of existing high-throughput imaging and spectroscopy tools to measure geometrical and material properties of large ensembles (~10^6) of single devices which make use of a newly installed cutting-edge laser system. Statistical approaches including Bayesian optimization and machine-learning will be used to identify routes to control and harness disorder, to produce a framework for analysis of large correlated datasets.

Research projects include:

- Ultra-high-throughput spectroscopy and imaging to the smillion-endpoint regime
- Bayesian analysis for model development in nanoelectronics
- Single-photons and large-scale analysis; joining big-data to quantum measurements

PHYSICS OF FLUIDS AND SOFT MATTER

Research in Physics of Fluids and Soft Matter is focused on the dynamics and instabilities of complex systems, from bubble flows to soft tissues, and encompasses both curiosity-driven and industrially-relevant phenomena. Our group currently consists of 12 members including three permanent members of academic staff (Dr Draga Pihler-Puzović, Dr Finn Box and Prof Anne Juel) and a laboratory technician (Martin Quinn). Laboratory-based research into nonlinear phenomena often reveals unexpected findings, which in turn requires interpretation via mathematical modelling.

Our group houses the laboratories of the Manchester Centre for Nonlinear Dynamics (MCND, http://www.mcnd.manchester.ac.uk). Founded in 2000 by the Schools of Physics and Mathematics to ally quantitative experimental investigations, with cutting edge approaches in mathematical and numerical modelling of complex systems. MCND builds on Manchester's outstanding pedigree in fundamental fluid mechanics to provide a modern, multidisciplinary training environment of high international profile, which is unique in the UK.

Current research themes in our group where PhD projects are available include:

- Instabilities in two phase flows and fluid-structure interaction (AJ, DPP, FB).
- Biomimetic flows and microfluidics (AJ, DPP, FB).
- Instabilities of soft solids and metamaterials (DPP, FB).
- Wetting and drying (AJ).
- Yield phenomena and viscoelasticity (AJ, DPP).

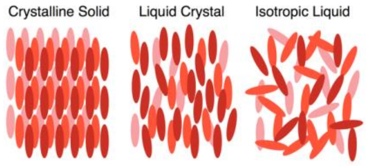
For more information, please visit our research page:
http://www.mcnd.manchester.ac.uk/

or contact anne.juel@manchester.ac.uk or draga.pihler-puzovic@manchester.ac.uk. PhD funding is available through EPSRC Doctoral Training Awards and CASE studentships.

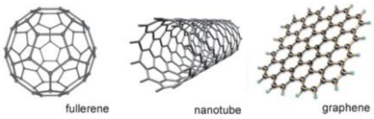
SOFT MATTER AND LIQUID CRYSTALS

Dr.Ingo Dierking (ingo.dierking@manchester.ac.uk)

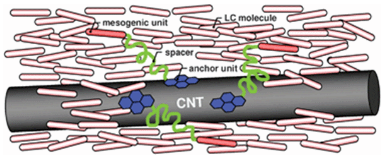
Our group primarily performs experimental research in different areas of soft condensed matter, liquid crystals, polymer modified liquid crystal composites, nanoparticle dispersions in anisotropic fluids and liquid crystal phases formed by colloidal materials, especially graphene oxide. Investigations range from fundamental physical questions to studies which are of relevance to the applications.



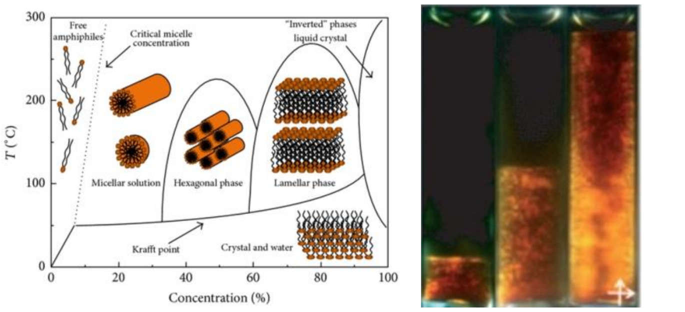
Thermotropic liquid crystal



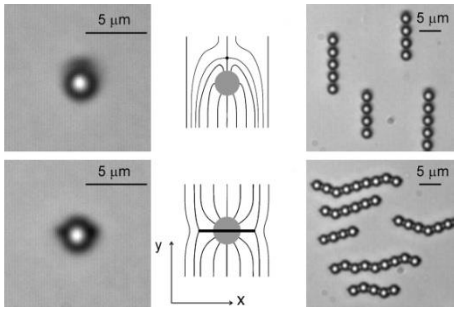
Carbon nanoparticle dopants



Novel functional materials

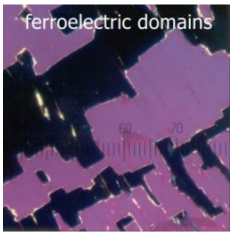


Lyotropic liquid crystals of graphene oxide and colloids

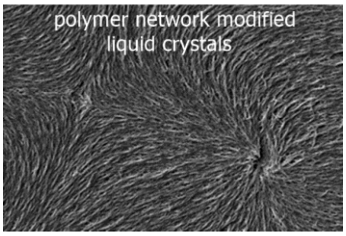


Electrophoresis and colloid chaining

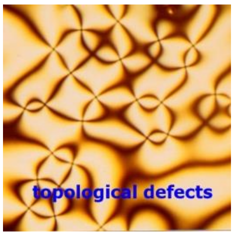
We use a range of in house experimental optic, electric and electro-optic techniques. For some specialized techniques and material synthesis, we collaborate with different groups world-wide.



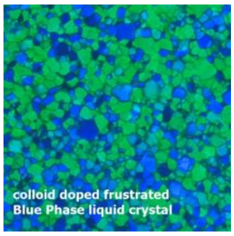
Ferroelectric LC



Polymer modification



Defect annihilation



Frustrated phases

<u>Possible projects</u>

- Defect annihilation in lyotropic chromonic liquid crystals via machine learning
- Pattern formation in hydrogen-bonded liquid crystals
- Cellulose nanocrystal and nanofibre liquid crystals
- Lyotropic liquid crystals from 2D materials
- Solitons in liquid crystals
- Functional nanoparticle dispersed liquid crystals