**Introduction**

This booklet is intended to give a flavour of some of the PhD projects available in the School of Physics & Astronomy from September 2016. The list of projects is by no means exhaustive and is aimed at giving applicants an idea of the research interests of our staff. If you would like to make contact with any of the supervisors to discuss a project in more detail, or require other information, please contact:

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Tel: +44(0)161 306 9220
Title: Magnetic reconnection and heating the solar corona  
Supervisor: Prof Philippa Browning philippa.browning@manchester.ac.uk

Research in solar plasma physics is concerned with modelling the complex interactions of magnetic field with plasma in the solar atmosphere, in the context of the wealth of new space and ground-based observations of the Sun which is transforming our understanding of our nearest star. There are many synergies with the physics of magnetically-confined fusion plasmas, and there may be opportunities for PhD projects to explore both fusion and solar applications, with potential collaborations with CCFE (Culham Centre for Fusion Energy).

A major unsolved problem is to explain why the solar corona is at a temperature of over a million degrees Kelvin (compared with a surface temperature of about 6000 K). Coronal plasma is believed to be heated by dissipation of stored magnetic energy, but the details remain controversial. A strong candidate for an efficient energy dissipation mechanism is the process of magnetic reconnection - which also operates in solar flares, and in many other space and astrophysical plasmas.

PhD projects are available to model coronal heating through reconnection, both using numerical magnetohydrodynamic simulations and through semi-analytical modelling, based on the idea that the coronal field relaxes towards a minimum energy state. Current models of energy release in unstable twisted coronal loops will be extended to more complex configurations, investigating the multi-thread nature of coronal loops and interactions between different loops. One project will be to complement results from two-fluid simulations by developing a relaxation model appropriate for Hall magnetohydrodynamics.

Title: The origin of solar flare energetic particles and their observational signatures  
Supervisor: Prof Philippa Browning philippa.browning@manchester.ac.uk

Solar flares are dramatic releases of stored magnetic energy in the solar corona. They are manifestations of the fundamental plasma physics process “magnetic reconnection”, which occurs in many other space and astrophysical contexts as well as in fusion plasmas. A challenging question is to understand how the magnetic energy is released and charged particles are accelerated to high energies in flares. We have been developing test particle models to show how particles can be accelerated in complex fields, both with fragmented current sheets and near magnetic null points. PhD projects are available to investigate particle acceleration and magnetic reconnection in solar flares, extending current models to incorporate the effect of the feedback of the accelerated charged particles on the electromagnetic fields, and investigating more realistic field configurations.

Students may use a new “reduced kinetics” approach to develop self-consistent models including energetic electrons and evolving magnetic fields. This work mainly relies on computer simulation, and may involve both the use of existing codes as well as code development.

An important aspect of this work is “forward modelling” of the observational signatures – the energetic particles may be detected both through hard X-ray and radio emission.

Towards precision mass measurements of cool exoplanets using microlensing  
Supervisor: Dr Eamonn Kerins eamonn.kerins@manchester.ac.uk
Microlensing, which employs the principles of gravitational lensing, is the only current technique able to discover cool low-mass exoplanets that lie beyond a few AU from their host. Planet formation theories suggest that low mass planets in this region may not have migrated far since their formation. Therefore, understanding the demographics of these systems can allow us to directly test planet formation theories.

Microlensing surveys are now entering a new era of high precision mass measurement thanks to the increased deployment of wide-field high-cadence surveys (OGLE, MOA, KMTNet) which can now monitor hundreds of millions of bulge stars on timescales of minutes, but also because of the simultaneous use of space-based assets (Spitzer, Kepler, and possibly Euclid and WFIRST in the future). Simultaneous observations from space allow parallax microlensing effects to be detected, which are often crucial in breaking the three-way distance-mass-velocity degeneracy in microlensing modelling.

At Manchester we have developed the Manchester-Besancon MicroLensing Simulator (MaBuLS), the most advanced simulation of Galactic microlensing currently available. This computational project will involve extending the capability of MaBuLS to allow for parallax detection of microlensing so that it can use the full range of information to help provide population statistics on detected parallax events, including cool planetary but also black hole candidate lens systems. Previous experience with the use of Python will be beneficial.

Title: Data mining the Galactic Centre: the near-infrared VVV Survey
Supervisor: Dr Eamonn Kerins eamonn.kerins@manchester.ac.uk
The Vista Variables in the Via Lactea (VVV) survey is a multi-year survey of the inner Galaxy at near-infrared wavelengths using VISTA, the World's largest infrared telescope. The VVV survey team is an international collaboration of European and Chilean astronomers. At Manchester our contribution to the project has been the development of a difference image analysis pipeline which can identify millions of variable objects from around 3 million images of around 100 million monitored stars. The key goals of the survey include:
- the identification of "standard candle" variable populations such as RR Lyrae stars, which can be used to develop a 3D reconstruction of visible stars in the inner Galaxy;
- the detection of rare gravitational microlensing events which allow us to determine the underlying mass distribution of the inner Galaxy;
- the identification of stellar motions on the sky (proper motion) which allow us to measure the kinematical properties of the inner Galaxy.
This PhD project will involve working on one or more of the following areas:
1. The development of automated classification schemes for cataloguing different classes of variable and transient objects.
2. The development of a "citizen-science" front-end to allow public users to engage in classifying objects or finding specific classes of objects of interest.
3. Mapping the underlying distribution of RR Lyrae stars, Young Stellar Objects (YSOs), novae, and/or gravitational microlensing events, including a careful assessment of detection biases.
4. Detecting stellar proper motions and using this to constrain the kinematics of the inner Galaxy.
This project will involve a significant element of computation and software development in Python. Knowledge of Python is not a prerequisite, though a willingness to learn it is, as is a keen aptitude for programming.

Title: Transmission spectroscopy of exoplanet atmospheres
Supervisor: Dr Eamonn Kerins eamonn.kerins@manchester.ac.uk
We are entering a new era of exoplanet characterisation thanks to the large numbers of hot exoplanets (those orbiting close to their hosts) which have been routinely discovered by ground and space-based transit surveys such as SuperWASP, HAT and Kepler. Transmission spectroscopy
is a highly successful technique for probing the atmospheres of hot exoplanets. This technique will be used more frequently as the samples of known nearby planets rapidly expands with the advent of surveys such as NGTS and the launch of the NASA TESS mission in 2017 and the ESA PLATO mission in 2025, both of which will detect relatively nearby exoplanets using the transit method.

Manchester has developed a transmission spectroscopy program in collaboration with colleagues at NARIT in Thailand. We have been very successful in gaining observing time on the ULTRASPEC instrument on the 2.4m Thai National Telescope (TNT) and other facilities. By observing the wavelength-dependent nature of the transit profiles we are able to constrain the atmospheric chemical composition of hot exoplanets down to the mass of Uranus.

A PhD project is available for a student to work as part of our transmission spectroscopy team. The student will be involved in the following areas:

1. selection of exoplanet targets for transmission spectroscopy observations
2. help with the preparation of observing proposals
3. data reduction and analysis of transit lightcurves using an existing pipeline developed at Manchester.
4. comparison of multi-wavelength transit curves with exoplanet atmospheric models.

Experience with Python programming will be beneficial.

Title: Intensity mapping for future radio cosmology surveys
Supervisor(s): Prof Clive Dickinson, Prof Ian Browne (emeritus), Prof Richard Battye
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Baryon Acoustic Oscillations (BAOs) are imprinted on matter throughout the Universe. They provide a key cosmological standard ruler, that can be used to measure the expansion of the Universe as a function of redshift and therefore can constrain dark energy models e.g. the equation of state. This is one of the key science drivers for the Square Kilometre Array (SKA) that will be fully operational during the next decade. However, a new technique called "HI intensity mapping" may allow them to be detected at radio wavelengths by mapping the redshifted 21cm HI line on large angular scales. Furthermore, this could be achievable within the next few years, providing complementary information and an independent test of the cosmological model.

We have proposed a single dish experiment, BINGO (BAOs through Integrated Neutral Gas Observations), that has the possibility of detecting BAOs (Battye et al. 2013). BINGO is a collaboration between Manchester and UCL in the UK, U. Sao Paolo and INPE in Brazil, U. Montevideo in Uruguay and discussions with other partners are ongoing. It will make the most sensitive large-scale HI map of atomic hydrogen ever made, covering an area of >2000 sq. deg. The project has recently received funds from FAPESP in Brazil at the level of 3M US dollars and we are ready to begin phase 1 of the project, beginning late 2016, which involves site preparations (in Uruguay) and the construction of a complete single module. Once this has been shown to work to specification, we can then proceed to phase 2 (late-2017) where a full array of ~60 horns will be constructed along with the telescopes. The final survey is scheduled to begin around late-2018 and will last for 1-2 years at least.

The student will become a key member of the BINGO team and cosmology group at Manchester. You will work with the BINGO team to develop the instrument (testing, commissioning), and to analyse data from the prototype module and eventually from the full array. An interest in hands-on/practical radio astronomy is an advantage. Depending on your particular interest, you will also work the Manchester group in developing tools for simulations and data analysis including component separation, map-making, power spectrum analysis and cosmological analysis. An important aspect will be dealing with foreground contamination from our Galaxy and extragalactic
radio sources and precise calibration, which is required to achieve the ultimate noise level. Much of the work will be in preparation for an intensity mapping survey with the SKA.

**Constraining the physics of the early Universe with CMB polarisation**

**Supervisor: Prof Michael Brown michael.brown-6@manchester.ac.uk**

The Cosmic Microwave Background (CMB) is the most powerful cosmological probe. Measurements of the temperature anisotropies have established the current cosmological model, and are now culminating with the results from the Planck satellite. However, future measurements of the polarization of the CMB promises to open a unique window into physical processes that occurred in the very early Universe. In particular, a detection of the so-called B-mode polarization signal on large angular scales would effectively prove the theory of inflation and open a unique observational window onto physics at the Grand Unified Theory (GUT) energy scale. The JBCA cosmology group is involved in several future experiments designed to search for this early Universe signal (e.g. the ground-based Simons Array and Simons Observatory, and the proposed satellites CORE and LiteBIRD).

Since the sought-after signal is so subtle, the instrument design, observation strategy and data-analysis techniques all need to be optimised very carefully. Imperfections in the instrument, or in the way the telescope scans the sky, can lead to spurious signals in the data that can mimic the B-mode signature and ruin the analysis. The aim of this project is to optimise the instrument design, scan strategy, and data analysis techniques for these future experiments. The project will make use of analytic techniques and detailed computer simulations to investigate the impact of different design and scan-strategy choices on the ability of the telescopes to detect the inflation signal. This project would suit a student with interests in early Universe and fundamental physics and who has excellent analytic skills and experience in computer coding.

**Title: Beads on a String: The formation of stars by filamentary accretion**

**Supervisor: Dr Rowan Smith rowan.smith@manchester.ac.uk**

Observations by the Herschel space telescope have shown that molecular clouds, the stellar nurseries of our galaxy, are threaded by long filaments of dense molecular gas in which stars form at regular intervals like beads on a string. Understanding this process has important implications for all of astronomy, as the number and masses of stars formed in a galaxy will affect its evolution when the massive stars explode in supernovae explosions. Moreover, as planets form around stars, it will also affect the types of planetary systems that can be formed.

This PhD project will use cutting edge numerical simulations of filamentary molecular clouds that include chemistry and magnetic fields to investigate to investigate such structures. We will investigate the formation of the filaments, and how they fragment into stars. In particular we will test how flows of mass along the filaments can lead to the formation of massive stars (greater than 8 solar masses) that will go supernovae when they die. A crucial part of the project will be to make critical comparison of the predictions of the above models with observational data in terms of observable quantities seen by instruments such as ALMA using post-process radiative transfer calculations. This means the student will learn to use both theoretical and observational techniques throughout their PhD thesis.

**Title: How do galaxies form stellar nurseries throughout cosmic time?**

**Supervisor: Dr Rowan Smith and Dr Scott Kay rowan.smith@manchester.ac.uk scott.kay@manchester.ac.uk**

Stars form in dense clouds of molecular gas in galaxies, but how the formation of these clouds and the stars within them depend on conditions within the galaxy is still unknown. In spiral galaxies, are clouds formed in the dense spiral arms more efficient at making stars, than in regions between the arms? Are molecular clouds the same in small irregular galaxies dominated by supernovae as in
spiral galaxies? How does all this change in starburst galaxies where there is more energetic feedback from the forming stars? These questions are particularly important for galaxies at earlier cosmic times which are likely to be quite different to our current Milky Way.

In this project we will use ground-breaking high-resolution simulations of how molecular gas evolves in galaxies to answer these questions, and investigate how star formation may proceed in other galaxies beyond our Milky Way. We will vary quantities such as the galactic potential, gas surface density, stellar feedback and abundance of chemical coolants in the gas, to examine how molecular clouds may differ in other environments such as those found at earlier cosmic times. For this project, previous experience of programming and running large simulations would be beneficial, but is not absolutely necessary as the student will learn the necessary techniques throughout the project.

**Title: Search and Study of the extreme neutron stars**  
**Supervisor:** Dr Rene Breton [rene.breton@manchester.ac.uk](mailto:rene.breton@manchester.ac.uk)  
Neutron stars are some of the most exotic objects populating our Universe: they have extreme densities and gravity, the largest known magnetic fields and the fastest observed rotations. For these reasons neutron stars are powerful tools to study fundamental physics. The two available PhD positions will be involved in the search and study of the most extreme neutron stars populating our Galaxy. They will focus on a particular type of neutron stars in compact binary systems called black widows and redbacks. They are nicknames after deadly spiders because they contain an energetic radio pulsar which gradually destroys a low-mass companion. In recent years these ‘spiders’ have proved to harbour some of the most massive and fastest spinning neutron stars even found. Only a handful have been discovered and properly studied so far. The PhD candidates will be part of a team searching for new ‘spiders’ using a range of multi-wavelength observations. They will perform high-precision analysis of their optical and radio light curves in order to measure the neutron star properties (e.g. mass, rotation, magnetic field) as well as to study a range of phenomena such as radio eclipses and the impact of relativistic heating on a nearby low-mass star.

**Title: The eyes of SPHERE**  
**Supervisor:** Prof Albert Zijlstra [albert.zijlstra@manchester.ac.uk](mailto:albert.zijlstra@manchester.ac.uk)  
Stars like the Sun, at the end of their lives, eject much of their mass back into space. This is the main source of dust and carbon, building blocks of planets and life: these stars drive hte evolution of the Universe. The ejected shells are briefly visible as a planetary nebula: the fantastic structures show that the ejection is a complex process. It is not thought that much of the shaping comes from interacting binary stars, but direct observations of such interaction have been too difficult. A new instrument, SPHERE, has recently been developed for the ESO 8-meter Very Large Telescope. With its extreme adaptive optics system, it provides the sharpest images ever obtained, with resolutions down to 15 milli-arcsec. Originally developed to image extra-solar planets, it has been shown to also be able to image these interacting binaries. This project will analyze the first such data taken of a number of dying stars, to see the onset of the interactions. The student will spend up to half the time at the Observatoire de Nice to work with dr. Lagadec (this long-term attachment is available to STFC-funded students). The project will train the student in the use of next generation of high angular resolution instrument, such as developed for the European 39-m telescope, and in the use of 3D radiative transfer codes, as well produce unique data on the death of stars.

**Title: MeerTRAP – Searching for Pulsars with MeerKAT**  
**Supervisor:** Prof Ben Stappers [ben.stappers@manchester.ac.uk](mailto:ben.stappers@manchester.ac.uk)  
MeerTRAP is a European Research Council funded project to use the extremely sensitive MeerKAT telescope to search for
Radio pulsars are some of the most extreme objects in the known Universe. They have masses of about 1.4 times that of our Sun, radii of about 10 km and they spin at up to 700 times per second. They are exceptionally stable clocks that provide us with excellent tools for studying matter at high densities, ultra-strong magnetic fields and even for studying gravity and spacetime itself. MeerTRAP will use commensal observing time, piggybacking on the large MeerKAT Legacy Science projects, to find new pulsars. This approach means that there will be many repeat visits to the same area of sky on a range of different timescales. This provides us with excellent sensitivity to sources that vary for any particular reason, either because they are intrinsically variable, members of relativistic binary systems or transitioning millisecond pulsars.

The applicant would become a member of a team including 3 PDRAs and 3 PhD students plus support staff and would join an international collaboration. They would be involved in developing the capabilities for searching the 400 beams that will be generated for new pulsars across the sky. They will be involved in the discovery of new pulsars and their characterisation across the electromagnetic spectrum, including using our access to the MeerLICHT telescope. The successful applicant would need to have a good background in astrophysics or physics and computing.

Title: MeerTRAP - Searching for Fast Radio Transients with MeerKAT
Supervisor: Prof Ben Stappers ben.stappers@manchester.ac.uk

MeerTRAP is a European Research Council funded project to use the extremely sensitive MeerKAT telescope to search for pulsars and fast transients. This PhD project will enable the applicant to become a member of this team and work with the team on the development of the fast radio transient search pipeline and use it to find new transients and then undertake detailed studies of the sources that are discovered.

MeerTRAP will use commensal observing time, piggybacking on the large MeerKAT Legacy Science projects, to find new fast radio transients. Using a combination of a large number of coherent beams and the incoherent summation of all the dishes the survey will probe a range of sensitivities and timescales that will reveal larger populations of known transients like fast radio bursts and classes of transients not yet known. It is expected, for example, that up to 30-40 new fast radio bursts will be discovered every year. These will be studied in detail using our transient buffers, including forming images to accurately localise them. We will also carry out multi-wavelength follow up and this will include using our access to the MeerLICHT telescope which is slaved to the positions looked at with MeerKAT. The applicant would be a member of a team including 3 PDRAs and 3 PhD students plus support staff and would join an international collaboration. They would be involved in developing the capabilities for searching for transients in all operational modes of the telescope. They will also be involved in the discovery of new transients and their characterisation across the electromagnetic spectrum and also the study of their host locations and potentially using them as cosmological probes. The successful applicant would need to have a good background in astrophysics or physics and computing.

Title: Understanding Blazar Jets – The OVRO 40-m Blazar Monitoring Program
Supervisor: Prof Keith Grainge keith.grainge@manchester.ac.uk

Active Galactic Nuclei (AGN) are powered by accretion onto rotating super-massive black holes which create relativistic jets along the spin axis, though the detailed mechanism of this process still remains elusive. In the cases where the jets are aligned at a small angle to the line of sight, relativistic beaming dramatically boosts the apparent luminosity and variability; these objects are collectively known as “blazars.” One avenue for progressing our understanding of jet production is provided by the Fermi Gamma-ray Space Telescope, which continuously monitors all gamma-ray bright blazars, allowing an unprecedented opportunity for the systematic study of blazar jets. The exact location of the gamma-ray emission region and its proximity to the central black hole remain subjects of debate, with two main competing classes of models for the GeV emission region.
Testing these models requires a multi-wavelength approach, combining the Fermi observations with supporting radio observations to search for correlations in the light curves at different frequencies.

This project is centred around the radio monitoring of 1500 blazars with the 40-m telescope at the Owens Valley Radio Observatory (OVRO, California) and then producing a joint analysis with Fermi data. The 40-m now has 8 years of intensity observations, which now offers a very powerful data set for correlation studies. In addition, a new polarisation sensitive receiver is currently being commissioned on the 40-m, and so a novel set of additional information will shortly be available for incorporation into the analysis. This project offers the possibility for the student to take a Long Term Attachment for 3+ months to Caltech, Pasadena, in order to visit the OVRO site, to contribute to the 40-m observing, and to learn about the low-level data reduction. The project will be co-supervised by the lead of the Caltech team, Prof Tony Readhead.

Title: Design and construction of a continuous miniature dilution refrigerator for POLARBEAR 2 and SIMONS array
Supervisor: Prof Lucio Piccirillo lucio.piccirillo@manchester.ac.uk
POLARBEAR and SIMONS array are two CMB polarization experiments dedicated to the detection of the B-modes sited at high altitude at the Atacama desert in Chile. The University of Manchester, ATT team, is involved in the design and construction of the sub-K refrigerators that are at the heart of the receivers. The sub-K refrigerators will cool the bolometric arrays to base temperatures as low as 100 mK where the bolometers reach maximum sensitivity.

The students will be involved in all the phases of the design, construction and testing of the refrigerators. It is also expected that he/she will participate in the observing campaigns.

Title: Design and development of very Low Noise Amplifiers with direct electron channel cooling.
Supervisor: Prof Lucio Piccirillo lucio.piccirillo@manchester.ac.uk
A new of Low Noise Amplifiers for Astronomy and Astrophysics will be designed, realized and tested. These new amplifiers will potentially be integrated in the future generation of astronomical instrumentation. This projects involves collaboration with Chalmers University of Technology in Sweden.

Title: Design and realization of a wide-band sub quantum noise parametric amplifier (paramp) based on the non linear kinetic inductance property of superconductors
Supervisor: Prof Lucio Piccirillo lucio.piccirillo@manchester.ac.uk
This project involves the design and development of an ultra low noise parametric amplifier for future radio astronomy observatories. It will consist of a superconducting thin film exhibiting highly non-linear kinetic inductance. When pumped with an external RF signal it will be driven in a state of parametric amplification with potential sub-quantum noise characteristics. This project involves a collaboration with Oxford University, Grenoble and Chalmers.

Title: Strong gravitational lens research at JBCA
Supervisor: Dr Neal Jackson neal.jackson@manchester.ac.uk
Strong lens systems, where a background galaxy or quasar is multiply imaged by the gravitational field of a foreground galaxy, are important for several reasons. First, they tell us about the mass distribution of the foreground object independent of the light it emits. Second, the lensing also magnifies, providing us with views of sources otherwise too faint to see. Third, some lenses are useful for cosmology. The group currently includes a postdoc who specialises in lens modelling and interpretation, and students involved mainly in observations. We have a number of programs in which new students may be able to get involved:
- An e-MERLIN Legacy Programme aims to look at a number of known lens systems in order to study one of their images, in each case that in the centre of the system which gives information about the central part of the gravitational potential of the lens, close to the central black hole. Due to recent upgrades this programme should be able to start in 2017.

- We are studying radio-quiet quasars using radio telescopes and exploiting lensing magnification, which allows us to measure structures and properties of objects which (as their name implies!) are otherwise difficult to study.

- We are involved in a number of development programmes aimed at lens surveys in future telescopes such as Euclid, and existing novel radio telescopes such as LOFAR. In the case of LOFAR, an interferometer based in the Netherlands, this includes technical work on calibration of high-resolution images.
Title: Neutron Scattering Studies of Structure and Dynamics of Water around DNA, Proteins and Biopolymers
Supervisor: Dr Ji-Chen Li Jichen.Li@manchester.ac.uk
Study of the interaction of water with proteins with respect to their structure and function has recently emerged as a new field. We have recently studied water around DNA, proteins and biopolymers using various neutron sources around the world. These studies have shed new light towards the understanding of the structure and dynamics of water in the biological environments. In order to make further progress in this field, we have recently concentrated our effort on the basic building block of proteins - amino acids using inelastic and quasi-elastic neutron scattering techniques and computational methods (such as molecular dynamics and ab initio quantum mechanics).

This project will involve students to participate in neutron scattering experiments at Rutherford Appleton Laboratory, Oxfordshire (a UK neutron facility), Institut Laue Langevin at Grenoble, France (a European neutron source) and IPNS at Argonne National Laboratory (a US facility). Hence frequent travels will be needed. The data obtained from the research centres will be fed into our computers linked to these sites and analysed using computational programs. The result will then be utilised for further modelling using classical molecular dynamics and possibly ab initio quantum mechanical methods.

Title: Design and Nano-Structural Aggregation of Small Peptides
Supervisor: Professor Jian Lu J.Lu@manchester.ac.uk
Nature produces some 20 amino acids. Their connections by chemical bonding form polypeptides. The peptides can self-assemble to form very intriguing secondary structures (alpha-helices and beta-sheets) and tertiary structures. This diverse range of molecular self-assembly is the basis for the current bottom-up approach of bionanotechnology. However, little is known about how to form a given 2D or 3D nano-object starting from the primary sequence. In spite of extensive international effort, we are still unable to predict protein's 3D structures from their primary sequences. This project aims to start from a few designed short peptide sequences and determine the structures of their nano-aggregates by laser and neutron scattering. In parallel, neutron reflection will be used to reveal the interfacial assembly from these peptides at optically flat surface and interface.

Title: Interfacial Adhesion of Nano-particles
Supervisor: Professor Jian Lu J.Lu@manchester.ac.uk
Surface and interfacial assembly of micellar aggregates formed by surfactants, proteins, polymers and their mixtures has been widely reported for their role in surface conditioning and detergency. It has however been reported recently that nanoparticles such as silicon oxide and titanium oxide can undertake similar tasks by promoting spreading at the oily soil-solid substrate interface (Nature 2003, 423, 156-159), thereby achieving the same goal of surface cleaning and detergency. This project aims to undertake appropriate experimental measurements to help understand the underlying physical principles. Leading techniques such as single nanoparticle fluorescence labelling (AFM, magnetic tweezer (MT), FRET and TIRF), spectroscopic ellipsometry (SE) and dual polarisation interferometry (DPI) will be deployed to study adsorption, forces and microrheology at the interface. The project will be jointly supervised by Dr Waigh and Professor Lu.

Title: Gene Complexation with Vectors
Supervisor: Professor Jian Lu J.Lu@manchester.ac.uk
Gene delivery offers great promises for curing hereditary and acquired diseases. However, naked genes (DNA, RNA, antisenses) are all negatively charged and so are cell membrane walls. It is therefore difficult to achieve efficient internalisation and external gene expression from human cells. One of the approaches is to use cationic lipids or polymers (transfecting vectors) to condense the charges on DNA before they are exposed to cells. The neutralisation leads to the formation of various sizes and shape of DNA/vector complexes. The aim of this project is to study how the selection of vectors can lead to different nano-complexes (size, shape and net charge) whose physical properties can be subsequently linked to their gene transfection and expression behaviours (efficiency and cytotoxicity) in vitro. Dynamic light scattering (DLS), small angle neutron scattering (SANS), and single particle force measurement will be used to aid the physical characterisation.

Title: Protein Adsorption and Interfacial Conformational Structure  
Supervisor: Professor Jian Lu J.Lu@manchester.ac.uk  
Protein adsorption is an interfacial molecular process underlying many modern biotechnological processes, examples including biocatalysis, immunoassays, biomaterials development and tissue engineering. It is important to tune protein-substrate interaction and protein conformational orientation to retain their globular structure and bioactivity. However, in many other cases, protein adsorption is undesired, these including reusable surgical and medical devices where protein adsorption is the source of cross-contamination. It is thus of both fundamental and practical significance to understand how biologically important proteins interact with artificial surface and interface under physiologically relevant conditions. In this project, spectroscopic ellipsometry (SE) and neutron reflection (NR) will be used to unravel structure and dynamics associated with the interfacial phenomena of a number of model proteins.

Title: Super-resolution fluorescence imaging of bacterial biofilms  
Supervisor: Dr. Tom Waigh, Prof. Ian Roberts  
Contact: Dr Tom Waigh t.a.waigh@manchester.ac.uk  
The World Health Organisation recently warned of the threat presented by anti-biotic resistant bacteria and compared the magnitude of the problem with that of global warming. Indiscriminate global use of antibiotics combined with rapid bacterial evolution has led to the creation of resistant bacterial strains. In a post-antibiotic world millions of people will die from simple infections that were once treatable. We will use a range of physical techniques to study survival strategies bacteria implement to resist treatment. Specifically we will use super-resolution fluorescence microscopy (Nobel Prize 2014) to image bacteria, bacteria capsids and bacterial biofilms with 20 nm resolution [1]. Furthermore the viscoelasticity of the films will be studied using microrheology and traction force microscopy methods. Techniques from soft-matter physics and systems biology will be used to model the activity of the bacteria.


Title: Models for the creation of bacterial biofilms  
Supervisor: Dr. Tom Waigh, Prof. Ian Roberts  
Contact: t.a.waigh@manchester.ac.uk  
Statistical models to describe the creation of bacterial biofilms will be constructed [1]. These will include ideas from agent based modelling, colloidal hydrodynamics and systems biology. A range of medically important biofilms will be studied in close collaboration with experimental physicists and microbiologists.

Title: Optical coherence tomography study of elastic turbulence in DNA
Supervisor: Dr. Tom Waigh, Dr. Mark Dickinson
Contact t.a.waigh@manchester.ac.uk

Optical coherence tomography can be used to study the fluid mechanics of opaque solutions of DNA. Concentrated (opaque) DNA has a number of novel non-linear flow phenomena such as turbulence at very low Reynolds number. This optical physics project will develop new optoelectronics equipment to study fluid mechanics based on optical fibre interferometry (we have a UK patent in the area) [1-5]. It will then apply the techniques developed to medically important areas of research such as the flow behaviour of DNA and bacteria.

Figure. Phase diagram of the different types of flow for high salt DNA solutions as a function of the Weissenberg number (proportional to the applied shear rate \(\dot{\gamma}\)) and the concentration of the DNA.


Title: The dynamics of endosomes in eukaryotic cells
Supervisors: Dr. T.A. Waigh, Prof. Philip Woodman
Contact: Dr Tom Waigh t.a.waigh@manchester.ac.uk

Super-resolution fluorescence microscopy (STORM) will be used to study the dynamics of signalling networks inside human cells with 20 nm resolution. Many crucial steps in these signalling networks are still unknown and they fulfil many important functions in cell metabolism e.g. when cancerous cells are formed. Ideas from differential geometry will be used to analyse the structures of endosomes and relate them to the underlying molecular biology. Furthermore, bright field microscopy will be used to track the dynamics of the endosomes at short times (sub-millisecond time scales) and then statistical models will be created for the underlying activity of motor proteins [1-5].
Title: Developing a Computer Model for the Human Heart  
Supervisor: Prof Henggui Zhang H.Zhang-3@manchester.ac.uk
The function of the heart is a sequence of muscle mechanical contraction that pumps blood to maintain circulation. The mechanical contraction is initiated by a sequence of electrical excitation that propagates as electrical waves in cardiac muscle. Disorder/irregularity associated with cardiac electrical excitation waves is believed to underlie the genesis of cardiac arrhythmias diseases, which are the major causes of sudden death.

Current treatments of cardiac arrhythmias are far from satisfactory as we lack understanding of their ionic mechanisms. In this project we will use approaches from modern physics, scientific computing and visualization to collaborate with world leading cardiac electrophysiologists to develop a computer model of the human heart that integrates biophysical and anatomical details. The developed model will be used to investigate the propagation pattern of cardiac excitation waves under normal and pathological conditions. The aim of the study is to explore possible ionic mechanisms underlying the genesis of cardiac arrhythmias, which can help to improve cardiac arrhythmias treatment. (http://personalpages.umist.ac.uk/staff/H.Zhang-3/)

Title: Dynamics of Artificial Gene Network  
Supervisor: Prof Henggui Zhang H.Zhang-3@manchester.ac.uk
Many fundamental cellular processes are governed by genetic programs, which are associated with regulative interactions and DNA. It is important to understand the complex behaviours of gene oscillator and its control by constructing artificial gene networks. These studies can lean towards a quantitative understanding of mechanisms underlying gene regulation and evolutionary design principles and will provide a technique towards logical cellular control. In this project we shall use non-linear dynamics approaching the complicated behaviours of artificial gene network. (http://personalpages.manchester.ac.uk/staff/H.Zhang-3/)
**Title: Development of Computer Models of Anti-arrhythmic Drugs**  
**Supervisor: Prof Henggui Zhang [H.Zhang-3@manchester.ac.uk](mailto:H.Zhang-3@manchester.ac.uk)**

Cardiac arrhythmia is the major source of premature death. Conventional treatment of cardiac arrhythmia is to use anti-arrhythmia drugs. However, many anti-arrhythmia drugs can also be proarrhythmic but the reasons for this are not fully understood. In this project we collaborate with world leading experts in pharmacology to develop biophysically detailed computer models of actions of anti-arrhythmic drugs – the interaction between drugs and drug receptors. Using the model we shall investigate the drug action on the electrical activity of cardiac systems at single cell and tissue levels. The aim of this study is to quantitatively index the safety and risks of some popularly used anti-arrhythmic drugs. ([http://personalpages.manchester.ac.uk/staff/H.Zhang-3/](http://personalpages.manchester.ac.uk/staff/H.Zhang-3/))

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**Title: Developing 3-Dimensional Anatomical Model of Human Atrium**  
**Supervisor: Prof Henggui Zhang [H.Zhang-3@manchester.ac.uk](mailto:H.Zhang-3@manchester.ac.uk)**

Anatomical structure determines the propagation pattern of excitation of the heart. Alterations in the structure play an important role in cardiac arrhythmia genesis. This project will construct a realistic model of human atrium with a biophysically detailed model for the electric activity of each individual cell and an accurate geometry. This model will be used to study the propagation pattern of the action potential in the human atrium under normal conditions. This propagation pattern will be compared with experimental recordings obtained by optical mapping. In addition, this model will be used to investigate the propagation pattern of excitation in pathological conditions, e.g. for a distortion of the myocardium induced by infarctions.

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**Title: Developing Anatomical Model of the Pacemaker of the Heart**  
**Supervisor: Prof Henggui Zhang [H.Zhang-3@manchester.ac.uk](mailto:H.Zhang-3@manchester.ac.uk)**

In collaboration with an electrophysiological group in the Faculty of Medicine led by Professor MR Boyett and Dr Ming Lei, the student will build an anatomical model of the pacemaker of the heart, the sinoatrial node. A series of thin slices of tissue will be cut from the intercaval regions of rabbit sinoatrial node. The slices of tissue will be digitized into a data set and rendered into a 3-dimensional geometry. Using single cell models developed previously by Zhang et al., an anatomic model of rabbit sinoatrial node will be constructed to investigate the initiation and propagation of excitation in the heart. Functional roles of various proteins coding the kinetics of ionic channel, gene defects and ageing processes on heart normal and abnormal rhythms will also be investigated.
Title: Physics and Technology of Two Dimensional Matter
Supervisor: Professor Andre Geim Andre.K.Geim@manchester.ac.uk
We have recently discovered a new class of materials which are only one atom thick and can be viewed as individual atomic planes extracted from common three-dimensional crystals (see, for example, http://news.bbc.co.uk/1/hi/sci/tech/3944651.stm).

Such one-atom-thick materials were pictured many times in sci-fi books and movies but previously presumed non-existent in the real world. It is for the first time they have been found experimentally and a lot of work remains to be done to investigate their properties and search for new fundamental phenomena and possible applications for this new kind of matter.

A graphene molecule of one atom thickness

One of the most urgent PhD projects we could offer is to microfabricate free-standing membranes from the discovered 2D crystals and, by using modern atomic force microscopy, to investigate their mechanical properties and transparency to gas atoms. The project is to be carried out in close collaboration and by using world-class facilities of Manchester Centre for Mesoscience & Nanotechnology www.man.ac.uk/nanotechnology

Title: Quantum turbulence in superfluid helium in the zero temperature limit
Supervisors: Prof. Andrei Golov Andrei.Golov@manchester.ac.uk, Dr. Paul Walmsley Paul.Walmsley@manchester.ac.uk
At very low temperatures, liquid helium is a pure superfluid with zero viscosity. Turbulent flows in this fluid consist of a tangle of identical quantized vortex filaments, making it an ideal laboratory system for experimental and computational investigations of complex turbulent phenomena. Our previous experimental work has shown that different types of turbulence are possible depending on how the vortices are arranged. At large length scales, correlations between vortex lines can mimic classical fluid eddies, but it is also possible to create a random tangle of vortices which has no classical analogue. At small scales, the quantized nature of vorticity dominates, and in this fundamentally important regime the dynamics is controlled by reconnections (where vortices swap their heads and tails) and waves on vortex lines.

Several new experiments to investigate quantum turbulence across a broad range of temperatures (including near zero temperature) are planned. One will involve trapping particles (helium excimer molecules, fluorescent spheres) on the cores of vortices, allowing the exciting possibility of direct visualization of vortex tangles through laser-induced fluorescence. The trapping of electrons on vortex lines will be used as a complementary technique as they can slide along vortex lines under the influence of an applied electric field, allowing the small-scale structure and dynamics of vortices (such as Kelvin wave excitations) to be probed. Secondly, we plan to develop new probes to allow measurements of the velocity and pressure of superfluid turbulence inside a recently constructed bellows driven flow channel (a superfluid analogue of a classical wind tunnel). The aim is to develop a better understanding of quasiclassical flows and how vortices interact with container boundaries at different temperatures. The projects will be carried out using
a state-of-the-art rotating cryostats, the only facilities of their type in the UK, and complemented by numerical simulations.

**Title:** Electrical and electromechanical properties of two-dimensional materials at the nanoscale  
**Supervisors:** Dr Laura Fumagalli, Prof Konstantin Novoselov  
**Contact:** Dr Laura Fumagalli, [laura.fumagali@manchester.ac.uk](mailto:laura.fumagali@manchester.ac.uk)

Graphene and other two-dimensional (2D) materials have shown unique electronic/mechanical/optical properties, motivating the current 2D technology revolution in physics, engineering and materials science [1,2]. In particular, a pivotal role is played by electrical and electro-mechanical properties of these layers and how they vary when 2D layers are combined into novel heterostructures. However, in many cases the experimental determination of these properties is challenging as they are inherently linked to the structure/mechanics of the layers on the nano- and atomic scale, requiring to use and develop advanced local probes to access them.

This project aims at probing electrical and electromechanical properties of novel 2D materials and devices with advanced scanning probe microscopy [3-5] such as electrostatic force microscopy (EFM), piezoelectric force microscopy (PFM) and Kelvin Probe Force microscopy (KPFM). By using a nanometric tip attached to a probe scanning over the surface as a nano-finger, we will access fundamental electrical properties such as conductivity, polarizability and contact potential differences on the nanometer scale and we will visualize how they change with the local structure/mechanics of the devices in different environments (air and liquid). This research will contribute to determine fundamental properties of new 2D materials and how to assemble them to create new functionalities.

The student will focus on the fabrication of the devices, learning a variety of microfabrication and characterization techniques using the state-of-the-art facilities of the National Graphene Institute, and on the use of advanced scanning probe microscopy to study novel 2D materials/devices on the nanometer scale.

**References**
1. K. S. Novoselov, A. Mishchenko, A. Carvalho, A. H. Castro Neto '2D materials and van der Waals heterostructures' Science 2016, 353, 561  
2. A. K. Geim. and I. V. Grigorieva 'Van der Waals heterostructures' Nature 2013, 499, 419  

**Title:** Probing molecular systems confined between two-dimensional materials at the nanoscale  
**Supervisors:** Dr Laura Fumagalli, Prof Andrei Geim  
**Contact:** [laura.fumagalli@manchester.ac.uk](mailto:laura.fumagalli@manchester.ac.uk)

Abstract: Graphene and other two-dimensional (2D) materials have recently shown the unprecedented ability of isolating molecular fluids at the nanoscale [1,2]. This has opened up exciting opportunities in physics, chemistry and biology to study and control properties/reactions of confined molecules. They are ubiquitous in nature and play a crucial role in many processes - e.g. molecular transport in synthetic nanochannels and biological nanopores, molecular structure of macromolecules such as DNA and their interaction with other molecules, etc. Yet, they have remained practically unexplored so far because measurements under confinement are extremely challenging.
This project aims at probing properties of molecular systems entrapped in 2D cells by using advanced scanning probe microscopy (SPM) [3,4] - last-generation microscopes that can access structural/electrical/mechanical/chemical properties on the molecular scale by using an atomically sharp tip as a scanning probe. We will explore the possibility of directly probing confined molecules by taking advantage of 2D materials to confine them and of scanning probe microscopes to measure their properties, with particular interest in their electrical properties. The ultimate goal of this research is to unravel fundamental properties of molecular systems remained unknown so far and to develop novel 2D nanofluidic devices for new technological breakthroughs.

The student will focus on the fabrication of 2D devices, learning a variety of microfabrication and characterization techniques using the state-of-the-art facilities of the National Graphene Institute, and on the use of advanced scanning probe microscopy to study them at the nanoscale.

References

Nonlinear Physics

Research in nonlinear physics focuses on the intricate behaviour of complex systems including fluids, soft matter and granular materials, which encompass both curiosity-driven and industrially-relevant phenomena. Fundamental advances in this area are best achieved through a dual approach of detailed quantitative experimental investigations and cutting edge mathematical and computational modelling. Our laboratory-based research into complex systems often reveals unexpected phenomena, which understanding and interpretation in turn requires mathematical modelling. We offer a wide range of PhD projects, with experimental and/or theoretical components. Please look up http://www.mcnd.manchester.ac.uk and/or email anne.juel@manchester.ac.uk for further information.

Title: Transition to disordered front propagation
Supervisor: A. Juel (Nonlinear Physics)
anne.juel@manchester.ac.uk

The aim of this project is to explore whether the nonlinear dynamics ideas developed for shear flow transition to turbulence (a, b) in the last twenty years can be extended to shed light on the transition to disorder in another canonical flow: Saffman–Taylor fingering in a confined channel, an archetype for front propagation and pattern formation (c, d). This system exhibits striking similarities with shear flow transition in that: (1) the single propagating finger solution of a depth-averaged model is known to be linearly stable up to very large values of the driving parameter, and (2) the threshold value of the driving parameter has been found experimentally to be sensitive to the level of perturbations in the system. This project will combine quantitative experiments and numerical simulations of a depth-averaged model to establish whether disordered front propagation can be characterised by chaotic meandering between weakly unstable solutions, as hypothesised in shear flow transition.

Title: Spreading and drying of suspension droplets on topography
Supervisor: A. Juel (Nonlinear Physics)
anne.juel@manchester.ac.uk

Controlled spreading of small amounts of liquid is a crucial requirement in many applications such as microfluidic ('lab-on-a-chip') devices and inkjet-printing-based manufacture of displays. Several techniques including electro-wetting, surface energy patterning of substrates and thermo-capillary pumping have been proposed to drive small volumes of liquid. We have recently shown that spreading can be enhanced or prevented near a gradient in topography depending on whether it slopes uphill or downhill, respectively. In inkjet printing applications, the liquid is a suspension of solid particles in a solvent that evaporates to leave a material film. On a flat substrate the well-known coffee stain effect is associated with Marangoni currents in the droplet which result in the inhomogeneous deposition of the particles upon drying. The aim of this project is to establish how topography can be used to control the homogeneity of the material film.
Pattern switching under compression appears on all length scales, ranging from the buckling of DNA to wrinkling of engineering components in the aerospace industry. Advances in experimental and mathematical techniques have recently sparked further interest in these phenomena and their utilisation in novel engineering applications, such as soft robotics and flexible electronics. Crucially, the soft systems in question are capable of significant deformation but can still recover their original configurations if the compressive load is removed.

One such system is an elastic column with an array of regular holes [see the image on the left]. Its solid counterpart, the classical Euler column, buckles laterally when compressed uniaxially [the left column of the left image]. However, the holey column under compression stays straight overall while the holes deform into an array of mutually orthogonal ellipses [the central column of the left image]. Another example is the compression of a soft granular column, which comprises a regular array of cylindrical particles of two types with different softnesses and sizes [see the image on the right]. Under compression the initial uncompressed checkerboard-like pattern rearranges until a new pattern with vertical triplets of harder particles is formed.

The aim of this project is to develop a comprehensive experimental and theoretical description of these phenomena by conducting a detailed quantitative comparison between the two. We will also exploit potential applications of these tunable metamaterials.

Title: Forming Patterns Using Fluid-Structure Interaction.
Supervisor: D. Pihler-Puzovic (Nonlinear Physics)
draga.pihler-puzovic@manchester.ac.uk

One of the most iconic problems of pattern formation is growth of complex dendritic fingers at the interface of air and a viscous fluid in the narrow gap between two parallel plates. However, this system becomes even more exiting when one of the plates is replaced with an elastic membrane. The resulting fluid-structure interaction fundamentally alters the interfacial patterns that develop, resulting for example in concurrent existence of both fingering and wrinkling in elastic sheet (see the image).

These flow-induced elastic deformations underpin a wide variety of natural processes, from the geophysics of laccolith to the physiology of pulmonary airway reopening. Similar fluid-structure interactions arise in industrial applications, where elastic boundaries are introduced to control processes such as roll coating. The purpose of this project is to develop benchtop experiments that study formation of these patterns. Pattern formation will be addressed by uniquely combining a quantitative experimental study with development of novel theoretical models.
Top view of the experimental fingering pattern under a polypropylene sheet

Location: Fluid Dynamics Group, School of Mathematics, University of Manchester

Title: Convective mass transfer for cleaning and decontamination

Supervisor: Julien Landel (julien.landel@manchester.ac.uk)

Description

Cleaning and decontamination processes can rely on different mechanisms to remove a patch of alien substance attached to a substrate. A shear flow covering the substrate can remove the substance through mechanical forces, potentially combined with chemical surfactant agent decreasing the adhesion of the substance onto the surface. However, this project is concerned with a second type of mechanism which is based on the dissolution of the substance into the cleaning fluid flow covering the substrate.

This second type of cleaning process establishes a convective mass transfer between the alien phase and the cleaning phase. Several applications rely on this process, particularly when the dispersion of the substance is unwanted, such as in the decontamination process of toxic chemical spills. In our daily life, the cleaning mechanism more and more favoured in dishwashers relies also on a convective mass transfer as it has been shown empirically to reduce energy and water consumption.

This project will focus on the case of a film flow covering a single droplet containing several substances. Many fundamental questions are still unresolved in this multiphase convective mass transfer problem. In particular, we will study how advection processes inside the drop can influence the convective mass transfer. Effect of solubility and surface tension on the overall mass transfer can also be analysed. The project will explore these questions using a combination of experimentation, numerical simulations and theoretical analysis.

The project is suitable for an enthusiastic and creative candidate who has good knowledge in fluid mechanics and some experience in experimentation and numerical simulations.


Location: Fluid Dynamics Group, School of Mathematics, University of Manchester

Title: Turbulent particle-laden jets

Supervisor: Julien Landel (julien.landel@manchester.ac.uk)
Turbulent particle-laden jets are relevant to many geophysical and industrial applications: from volcanic eruptions, to sediment resuspension, fluidisation processes and chemical reactors. Much work has been done on the dilute regime of these two-phase flows, where the particles have a small impact on the fluid and can often be considered as passive tracers. In this experimental project, we focus on the poorly understood dense regime, where the coupling between the solid particles and the fluid is more complex.

Many fundamental questions, of high relevance to the applications mentioned above, are still unresolved. This project will explore the impact of the particle density on turbulent entrainment processes. Entrainment processes during an explosive volcanic eruption have a considerable impact on the extent of the damages. They determine whether the eruption will collapse and form a pyroclastic flow, with local implications, or whether the eruption column will rise and form an ash cloud spreading over extended regions, such as in the case of the 2010 eruption of the Icelandic volcano Eyjafjallajökul. This project will also explore the effect on mixing processes, which are very important for instance in chemical reactors where the efficiency of the reaction depends strongly on the efficiency of the mixing.

These dense particle-laden jets are still poorly understood due to the considerable challenges faced analytically and numerically. Technical difficulties have also prevented progress on the experimental side for a long time. New experimental techniques, based on novel experimental design and imaging techniques, recently developed in the laboratory have allowed to probe much further into the complex dynamics of these dense particle laden jet. The main goal of this project is to pursue the development of these techniques in order to address the questions on entrainment and mixing described above.

The project is suitable for an enthusiastic and creative candidate who has some experience in experimentation and good knowledge in fluid mechanics. Some knowledge in imaging analysis technique is desired but not necessary. The motivation and readiness of the candidate to learn new techniques and develop them to explore fundamental scientific questions will be key to the success of this project.
Liquid Crystal Physics
http://esi.ph.man.ac.uk/LC_Webpage/liquid_crystals/Liquid_Crystal_Home_Page.html

Title: Carbon nanomaterials in liquid crystal phases
Supervisor: Ingo Dierking ingo.dierking@manchester.ac.uk

Liquid crystals are primarily known for their applications in flat panel displays, but more recently also in non-display applications, such as optical elements, or sensors. Carbon nanomaterials, such as fullerenes, nanotubes and graphene, on the other hand have generated applications in the fields of lubricants, one dimensional conductors and nanowires, and organic, molecular electronics, not to talk about several Nobel Prizes.

We will combine these two fields of research to produce modern hybrid materials by mixtures of liquid crystals with zero-, one- and two-dimensional colloids and exploit their self-assembly through the liquid crystal mediated self-organization. Fullerenes can be added at varying concentrations to Blue Phases, in order to stabilize the phase over wide temperature intervals, which is needed to exploit them in novel fast switching display applications without the need of alignment layers. Nanotubes can be dispersed in Twist Grain Boundary phases for the same reason and to produce regular arrays of molecular nanowires. Similarly, they can be mixed into discotic liquid crystals for increased conductivity of materials for organic electronics. Graphene or graphene oxide can be dispersed at varying concentration in a range of liquid crystal phases to tune the properties, such as response times, threshold voltage, viscosity or elastic constants.

In this project we will investigate a range of different possibilities of carbon nanomaterial-liquid crystal hybrid systems and their influence on phase behaviour and properties. This will be done by several different experimental techniques, such as polarized optical microscopy, electro-optic and electric techniques, as well as dielectric spectroscopy and specialized sample cell production. Other techniques, such as differential scanning calorimetry or x-ray diffraction will be available in collaboration with other groups.

Title: Photo-responsive ferroelectric liquid crystals
Supervisor: Ingo Dierking ingo.dierking@manchester.ac.uk

Liquid crystals with an azo-group in their molecular structure can show photo-responsive properties due to cis-trans isomerisation when illuminated with light of a certain wavelength. At the same time, molecules that are chiral and for the smectic C* phase, can be ferroelectric, i.e. exhibit a spontaneous polarization in the absence of an outside applied electric field. Such materials also may exhibit a frustrated phase, called twist grain boundary (TGB) phase between the paraelectric and the ferroelectric phase. This TGB phase is quite complicated in structure and represents the analogue to the Abrikosov flux lattice phase in type II superconductors in a magnetic field. The structure of these phases will further be studied through polymer stabilization, which provides a template of the phase structure and stabilizes phases that polymer networks were formed in.

We will systematically characterize such novel materials, first of all with respect to their phase sequence without and with illumination at varying wavelength and applied electric field, and secondly with respect to their electro-optic, electric and dielectric behaviour. This includes temperature dependent measurements of the tilt angle, spontaneous polarization, threshold fields, response times and viscosity, as well as dielectric spectroscopy over a wide frequency range to study different collective modes, again in cis and trans conformation of the molecules. The investigations will provide information about a class of novel materials, which may be used in new applications in the field of sensors and light controlled optical elements.
Title: Dispersions of liquid crystals with magnetic nanoparticles and ferrofluids
Supervisor: Ingo Dierking  ingo.dierking@manchester.ac.uk
In recent years the dispersion of nanoparticles in liquid crystals has attracted increasing interest and attention, due to the possibility to tune physical properties of the liquid crystal phases on the one hand, and to exploit the self-assembly of the liquid crystal to induce self-assembly of nanomaterials, on the other. In most cases dielectric nanoparticles of spherical or cylindrical shape were used in nematic liquid crystals, or ferroelectric nanoparticles in nematic and ferroelectric liquid crystal phases. In this project we will investigate the influence of magnetic particles as well as ferrofluids dispersed within the liquid crystal. This allows the steering of the material by two independent applied fields, addressing the nanoparticles by the magnetic field and the liquid crystal mainly by an electric field. We will study in how far magnetic nanoparticles can be aligned by the self-organization of the liquid crystal itself, as well as an additionally imposed magnetic field, and what influence a superimposed electric field exerts. Similarly, we will use ferrofluids, dispersions of magnetic particles in an isotropic liquid, with droplets then dispersed in a liquid crystal matrix, to determine the viscosities (and their anisotropy and temperature dependence) of the liquid crystal on a microscopic scale. For the latter, nematic, fluid smectic as well as lyotropic phases can be employed. An experimental setup for the application of a magnetic field at varying amplitude will be constructed, and otherwise standard methods of liquid crystal electro-optics and simple fluid dynamics be employed.

Title: Graphene oxide in lyotropic liquid crystals
Supervisor: Ingo Dierking  ingo.dierking@manchester.ac.uk
It is known that graphene oxide, when dispersed in an isotropic polar solvent such as water, can form a lyotropic nematic phase, depending on concentration and size of the graphene oxide flakes. Similarly, it has recently been demonstrated that dispersing graphene oxide in a standard thermotropic nematic liquid crystal can drastically change its physical properties. This project aims to establish the influence of graphene oxide at varying concentration and size on an already formed standard lyotropic liquid crystal. In this case, not only the concentration and size of the graphene oxide can be varied, but the interaction with the liquid crystal can further be tuned by changing the concentration and chain length of the surfactant forming the lyotropic liquid crystal, as well as the solvent. Comparisons between pure solvent with graphene oxide and lyotropic solvent with graphene oxide at the same concentration can then provide insight about the effects of the liquid crystallinity of the dispersing phase on the properties of the whole system, while at the same time concentration and size effects can be separated independently. In a further step the dispersing lyotropic phase can be varied, for example by choosing a concentration in the lamellar or the hexagonal regime of the phase diagram. It will then be interesting to investigate the additional effect of the graphene oxide, which is strongly favouring a nematic structure. Furthermore, the surfactant induced lyotropic phase may additionally be varied to include chroomic phases.
This project relies quite extensively on specialized sample preparation and polarized optical microscopy. Also electro-optic techniques and dielectric spectroscopy will be involved, together with x-ray diffraction in collaboration with other groups.

Title: Motion of spherical and elongated microparticles in liquid crystals
Supervisor: Ingo Dierking  ingo.dierking@manchester.ac.uk
The motion of particles in a liquid, caused by the application of an electric field, i.e. electrophoresis, is a topic of long standing interest, fueled by the possible applications of such systems. The use of liquid crystals as the fluid matrix on the other hand is only very recently generating massive interest. This is due to two complementing aspects, (i) the realization that modes of particle motion in liquid crystals are drastically different from those observed in standard liquids, and (ii) the possibility of realizing a variety of different displays with less complicated production processes, such as Blue Phase devices and electrophoretic paper-like screens. A feature of both aspects is the urgent need to develop a fundamental understanding of the underlying physics of particle motion in self-organized anisotropic fluids. This is precisely the aim of the proposed application, to experimentally investigate in detail the motion of micrometer sized particles in liquid crystals as a function of systematically varied applied parameters, and to develop a consistent description of the latter, also aided by computer simulations. The present project will significantly enhance the fundamental understanding of liquid crystal-particle dispersions and their properties, as well as the interaction between liquid crystal molecules and
particles. From theoretical descriptions, conclusions can be drawn towards nano-particles via the experimental investigation of micro-particles. Particularly, the project will provide a major contribution in understanding the interaction between applied fields with particles in anisotropic liquid crystal hosts. This will carry further the development of descriptions in electrophoresis to novel fluids and shape anisotropic particles, and will thus also be of importance to researchers outside the liquid crystal community. It is necessary to develop such an understanding in order to be able to conceive novel applications and to push materials development into new directions.

If you are interested in any of these projects, please do not hesitate to contact me (ingo.dierking@manchester.ac.uk) to discuss details, or just find me in my office G.13 on the ground floor of the Schuster building.
A laser experiment at CERN and PhD student working on their project.

The University of Manchester has a long and well established history in nuclear physics research, starting with the pioneering experiments of Ernest Rutherford in the early years of the 20th Century. It was at Manchester that Rutherford demonstrated the existence of the atomic nucleus using alpha-particle scattering experiments and performed the first demonstration of nuclear transmutation.

The nuclear physics research group at the University of Manchester is one of the largest in the UK. The group consists of six academic staff with a variety of research interests, such as:

- laser spectroscopy of Exotic Nuclei (Professor Jonathan Billowes, Dr Paul Campbell and Dr Kieran Flanagan)
- spectroscopy of neutron-rich nuclei and the study of transfer reactions (Professor Sean Freeman)
- spectroscopy and electromagnetic properties of fission fragments (Dr Gavin Smith)
- properties of nuclear isomers (Dr Dave Cullen)

Most of our current research is carried out by performing experiments at major international facilities, such as at CERN (Switzerland), Argonne National Laboratory (USA), Jyvaskyla (Finland), GANIL (France), GSI (Germany), and ILL reactor at Grenoble.
Title: Exploring the Changing Shell Structure of Nuclei  
Supervisor: Professor Sean J Freeman sean.freeman@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 \( \beta \) 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 which 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 to measure the single-particle energies of particular single-particle orbitals along chains of isotopes and isotones in order to track the evolution of single-particle structure. This may involve making measurements on stable targets as well as using radioactive beams in order to track single-particle structure away from stability. This work utilises novel devices such as the HELIOS spectrometer at Argonne National Laboratory, Chicago, USA. HELIOS has been designed for the study of transfer reactions using radioactive beams.

Title: Nuclear observables relevant to neutrinoless double beta decay  
Supervisor: Professor Sean J Freeman sean.freeman@manchester.ac.uk

In order to have confidence in any neutrino mass determined via the observation of neutrinoless double-beta decay it is important to validate the calculated nuclear matrix elements. Observation of \( 0\nu\beta\beta \) would allow the absolute neutrino masses to be determined if the associated matrix elements can be determined. No other physical process samples these directly and so complex calculations must be used to determine them. Different methods (QRPA, shell models, IBM etc.) have yet to reach satisfactory consistency. It is clear that the initial/final

HELIOS Spectrometer, ANL, Chicago, USA

Q3D spectrometer, MLL, Munich, Germany
nuclear wave functions are important and transfer reactions are able to provide useful tests by benchmarking the relative occupation of valence orbitals. Some calculations use the BCS approximation, the validity of which can be assessed by pair transfer. Phd projects in this area would involve using single-nucleon transfer reactions to measure the neutron and proton occupancies of neutrinoless double-beta decay candidates. These results can then be compared to theoretical predictions in order to validate the nuclear matrix element calculations relevant to neutrinoless double-beta decay. Additionally the measurement of pair-transfer can be used to validate the BCS approximation in these nuclei. These measurements are made at the Maier-Leibnitz Laboratorium, Munich, Germany using a tandem accelerator and the Q3D spectrometer as well as at RCNP, Osaka, Japan using coupled cyclotron accelerators and the Grand Raiden spectrometer.

Title: Laser Spectroscopy of Exotic Nuclei: 
Supervisor: Dr Kieran Flanagan, kieran.flanagan-2@manchester.ac.uk
Measurements of optical isotope shifts and hyperfine structures by laser techniques provide some of the most basic properties of radioactive nuclei. This type of measurement is particularly powerful since it does not rely on any assumptions of a particular nuclear model and therefore can be used to rigorously test theoretical predictions. Even more fundamentally, an optical resonance can confirm the simple fact of existence of a nuclide ground state or isomer.

![Theoretical model for two step Resonance Ionization of a radioactive atom and the experimental setup at CERN ISOLDE.](image)

The research theme of this project is the study of short-lived exotic nuclei with laser spectroscopy. The PhD will study the role of three-nucleon forces and their associated influence on nuclear structure and the limits of nuclear existence. This work will also investigate the interplay between tensor and central forces and the associated effect on quantum shells in exotic nuclear systems. This proposal will study how the shape of the nucleus is modified at the limits of nuclear existence. We will use innovative laser spectroscopy methods to achieve these goals. The project will be carried out at the ISOLDE facility, CERN, which is the premier radioactive beam facility at the precision frontier. The wider scientific impact of this research will influence modelling explosive stellar processes and nuclear synthesis, understanding the structure of astrophysical compact-objects such as neutron stars and predicting regions of enhanced stability in the super heavy elements. The PhD project will develop ultra-sensitive methodologies that set a new paradigm in laser spectroscopy. It will build on the cutting edge technology of collinear resonance ionization spectroscopy (CRIS) that has been developed by the Manchester group. The CRIS technique combines the high resolution nature of collinear laser spectroscopy with the high sensitivity of resonance ionization spectroscopy.
Title: Improved Identification of illicit materials using an X-ray Backscattering technique.
Supervisor: Dr David Cullen Dave.Cullen@manchester.ac.uk

The aim of this research is to demonstrate the potential improvements that can be made in X-ray backscattering techniques to better identify illicitly smuggled material in cargo / baggage. The possibilities of this project will be achieved by combining a detailed understanding of the X-ray scattering processes and Monte-Carlo modelling with experimental results from poly-energetic X-ray sources and new high-efficiency, high-resolution CZT detectors.

Current state-of-the-art commercial X-ray backscatter cargo scanning systems make use of the increased scatter that results from low-Z (atomic number) organic materials to identify contraband items. The detectors used in current systems are only capable of measuring the intensity of scattered X-rays. However, areas of high-backscatter intensity, typically associated with contraband (drugs, tobacco, plastic explosives & currency), can be established as brighter regions in an X-ray image. Figure 1 shows a typical X-ray backscatter image of a car being driven through a scanner with contraband items hidden within the body panels.

This rather basic level of organic/inorganic separation is usually the only information available. To date, this has been considered sufficient to identify crates which don’t meet their manifest and require human inspection. This process creates delays and some crates are unnecessarily opened.

Working together, Manchester University and Rapiscan systems (Cheshire) recently demonstrated that more information relating to the material composition of the inspected object was available within backscattered X-ray data. By measuring both the intensity and energy of the backscattered X-rays simultaneously it was possible to increase the level of material separation beyond that of simple inorganic/organic. The key aspects of this project were the unique combination of new high-resolution, high-efficiency, CZT detectors coupled with validation and comparison of the experimental measurements with theoretical simulations using the Geant IV (Monte-Carlo) code. In this project, the original setup will be scaled up to evaluate whether this approach can be a realistic option for an improved large-scale industrial cargo security screening device. A new CZT multi-detector setup will be used with higher-intensity poly-energetic X-ray sources, first with a pulsed 50-keV tabletop X-ray source at The University of Manchester and later with a larger 200-keV X-ray source at Rapiscan systems in Cheshire.

A fully-funded STFC-CASE 3.5 year PhD studentship is currently available for this project which includes an additional stipend and 1 year based at Rapiscan systems in Cheshire.

Title: Exposing subtle details of the nuclear force through lifetime measurements.
Supervisor: Dr D. M. Cullen, dave.cullen@manchester.ac.uk

The lifetime of a nuclear state is a fundamental observable which gives a direct probe of the nuclear force. Classically, the lifetime, $T$, is given by the quantum mechanical Fermi-Golden rule,

$$T = \frac{2\pi}{\hbar} \langle \psi_f | \hat{H} | \psi_i \rangle \rho(E) dE$$
where $H$ is the nuclear Hamiltonian, $\psi_i$ and $\psi_f$ are the initial and final nuclear states involved in the process and $\rho(E)dE$ is the density of final states. For nuclei, the transition between the initial and final states usually takes place with the emission of an electromagnetic gamma-ray which conserves angular momentum, parity and energy. Measurements of the nuclear state lifetimes in exotic nuclei allow subtle details of the nuclear force to be examined far from stability where weak but important parts of the nuclear force are often revealed. Lifetime measurements remain the best way to deduce the presence or absence of nuclear collectivity necessary to determine the exact location of new shell closures in exotic nuclei.

With STFC support we have developed and built a highly efficient Differential Plunger for Unbound Nuclear States (DPUNS) [1], see Figure 1.

DPUNS has allowed progress to be made in the understanding of excited state lifetimes in exotic nuclei beyond the proton drip line. Several experimental campaigns have been performed in Finland with over 30 publications over a three-year period with 3-completed and 2-current PhD theses. The PhD students are expected to lead the research analysis and are first authors on all of the published papers. The next DPUNS campaign of 4 experiments will take place in Finland in May 2017.

Our recent research focus has been on:

1. **Defining the location of closed shells:**

The lifetime of the nuclear states directly defines the nuclear collectivity. This gives information on how a quantum-mechanical ensemble of $\sim$200-300 strongly interacting nucleons acts together to produce very large transition rates, orders of magnitude greater than the single-particle values. The determination of nuclear collectivity is extremely important around closed shells where collectivity must fall to zero and single-particle transition rates should be observed.

**The N=Z=50 Closed Shell:** We have studied this effect around the doubly magic N=Z=50 closed shell by measuring lifetimes in $^{109}$I and $^{112}$Te. These nuclei appear to show anomalies in the trend of decreasing collectivity as the doubly-magic closed shell is approached [2]. This may constitute evidence for an isospin dependence of the effective charges predicted by Bohr and Mottelson in 1975. We are currently testing these ideas with new lifetime data on $^{113}$Te and $^{114}$I.

**The Z~114 Closed Shell:** In order to radically understand the role of spin-orbit interaction in the stabilisation of super-heavy nuclei, and to determine the location of the highest N,Z shell closures, we have modified DPUNS to be used as a charge-plunger. This will allow a determination the lifetimes and collectivity of nuclear states

![Figure 1. The DPUNS differential plunger for unbound nuclear states installed at the University of Jyväskylä in central Finland. The picture shows the degrader foil through which the recoiling nuclei of interest pass before and after they decay. Full details of DPUNS can be found in reference [1].](image-url)
in the super-heavy nuclei for the first time and thereby, define the location of the next proton shell gap after Z=82. Current state-of-the-art theoretical models currently predict very different values. Microscopic-macroscopic models predict Z=114 and mean-field approaches predict Z=120, 124 & 126. The main reason for these discrepancies is that the models rely on large extrapolations from regions where the interactions are experimentally verified. Our lifetime measurements of these nuclei will help validate the various theoretical models through a series of experiments on the nuclei above and around $^{252}$No (Z=102). DPUNS charge plunger will be commissioned in Finland late in 2017 and the main experiments performed in 2017-2019. A PhD student starting in September 2017 is ideally placed to lead the analysis of this project.

2. A simultaneous understanding of proton- and gamma-ray emission in exotic nuclei beyond the proton drip line:

Over the last four years, we have used DPUNS to measure the lifetimes of unbound nuclear states in proton-emitting nuclei. With these measurements, we have developed a new theoretical framework which simultaneously treats proton emission and electromagnetic emission with a common set of wave functions [3]. The wave functions for the unbound states, $\Psi_i$ and $\Psi_f$ are derived from a Woods-Saxon model which considers the odd-proton to be orbiting a core which is effectively given by the wave function of the daughter nucleus, $\Psi_d$. For a given deformation (deduced from our lifetime measurements) the code therefore, simultaneously predicts both the parent and daughter wave functions, $\psi_p$ and $\psi_d$, which are then fixed and used in Fermi-Golden rule expressions with Hamiltonians for both particle-emission with

$$T_{proton} = \frac{2\pi}{\hbar} \langle \psi_d | \hat{H} | \psi_p \rangle \rho(E) dE$$

and electromagnetic transition rates

$$T_{EM} = \frac{2\pi}{\hbar} \langle \psi_f | \hat{H} | \psi_i \rangle \rho(E) dE .$$

We have used this theoretical approach to understand proton emission across a range of nuclei with very different deformations where the proton is coupled both adiabatically and non-adiabatically to the core. This approach has allowed a better description of proton emission process. We have used this approach for the mildly deformed oblate proton emitter $^{151}$Lu. Not only was this the best evidence to date for proton emission from an oblate nucleus, it also settled a long-standing 30-year theoretical debate on the shape of this nucleus [3,4]. This year, we finalised lifetime measurements for the deformed $^{113}$Cs. These results were used within the theoretical framework to simultaneously determine that both proton emission and gamma-emission from $^{113}$Cs are best described with a relatively large quadrupole deformation [5]. We are currently expanding this programme with STFC funding to be able to study more exotic nuclei with the development of a new triple-foil plunger for exotic nuclei (TPEN), see Figure 2.
This device will allow lifetimes to be measured in more exotic nuclei with smaller production cross sections for the first time. TPEN will be commissioned in May 2017 in Finland. A PhD student will lead the data analysis of this commissioning experiment in 2017 and TPEN will later (2018-20) be used with radioactive beam developments at CERN, RIKEN (Japan) and FAIR (Germany).

References:


Nuclear medicine: Molecular Radiotherapy Dosimetry
Supervisor: Dr D. M. Cullen, dave.cullen@manchester.ac.uk

Molecular Radiotherapy (MRT) is a cancer therapy technique in which radioactive pharmaceuticals are administered inside the body to deliver a lethal radiation dose to malignant cells whilst sparing surrounding healthy tissue. There is now an extensive clinical portfolio of MRT procedures which has been significantly enhanced with the introduction of new radiopharmaceuticals. MRT treatment is generally minimally invasive, incurs few side effects and can achieve impressive results.
When delivering MRT, the radiation doses to the tumour and normal tissue should be accurately determined for each patient using nuclear-medicine imaging - an essential component in the diagnosis, staging and management of many oncological conditions. Due to the inherent complexity of measuring radiation doses from in vivo decays current MRT dose calculations are still non-optimised generic averages based on theoretical organ dimensions without regard for individual patient size and weight. Ultimately because of the uncertainty in determining doses for radiation sensitive organs, a significant proportion of patients do not receive critical tumour doses and therefore, the greatest therapeutic benefit, see Figure 1.

Our collaboration between the Manchester nuclear-physics group and the nuclear-medicine group at The Christie NHS Foundation Trust has established a fruitful interdisciplinary research program which seeks to address the complex and interconnected problem of providing accurate patient specific dosimetry for MRT.

Our research focuses on two key aspects of MRT dosimetry:

1. The application of Monte-Carlo simulation techniques to improve activity quantification and dosimetry calculations for a variety of MRT treatments.
2. The validation of dosimetry calculations using realistic patient analogues.

By using a detailed Monte-Carlo simulation of a GE Infinia Hawkeye 4 SPECT/CT camera (as used at The Christie) we can fully track gamma rays and beta particles interactions from the initial decay within a patient body until detection in the SPECT camera. Figure 2 shows our simulation which has been used to model SPECT scan acquisitions of simple water filled phantoms (approximating the human body), more complex anthropomorphic human shaped phantoms and CT images of patient therapies. By characterising the scattering of gamma rays in the SPECT camera system we have been able to significantly improve the image quality and accuracy of activity quantification.

Our research is focused on the development of 3D printing techniques to produce organ models to facilitate the validation of MRT dosimetry for realistic patient morphologies. These models allow many of the underlying systemic sources of error in MRT dosimetry calculations to addressed and provide a major step towards providing individualised patient-specific MRT treatment plans. The knowledge exchange and output [1-2] from this project has had direct impact at The Christie. We have been awarded several STFC-IPS grants over the past
6 years and the collaboration has been extended with a commercial partner HERMES Medical Solutions Ltd. This leading supplier of cross platform nuclear medicine software provides a pathway to translate our research into a commercial product. The group currently has three PhD students (two funded by an STFC CASE awards) and a postdoctoral researcher.

Publications:

Title: Laser Preparation of Cooled Radioactive Atoms
Supervisor: Dr Paul Campbell Paul.Campbell-3@manchester.ac.uk
Our group works in a collaboration that performs laser spectroscopic studies of the nucleus. Experimental work is based at an international laboratory (JYFL) in Finland. Thesis studies undertaken in the laser collaboration at JYFL will concentrate on the effects of, and experimental opportunities afforded by, optical pumping in an on-line ion trap (that captures and holds short-lived radioactive ions). The studies will aim to provide experimental techniques for the manipulation of state and sub-state populations in ionic ensembles and will use the manipulated ionic populations to study new nuclear phenomena.

Optical pumping effects in radioactive ion traps have only recently been demonstrated to be significantly strong and a novel experimental technique awaits development and exploitation. In detail, the student will develop laser techniques capable of manipulating the ground and metastable state populations in ionic ensembles and use this technique to enable the on-line spectroscopic study of previously inaccessible nuclear species. The student will also develop techniques for the manipulation of magnetic substate populations in radioactive ionic ensembles and use these techniques for the study of polarised radioactive ion beams.

Title: Probing the Origin of Fission-Fragment Angular Momentum
Supervisor: Dr Gavin Smith Gavin.Smith@manchester.ac.uk
It is well known that the angular momentum vectors of fission fragments are aligned roughly perpendicular to the fission axis. This alignment means that gamma rays emitted from a fission fragment are correlated with the fragment direction. In addition, in spontaneous fission of an even-even nucleus, the initial angular momentum is zero which means that the fragment spins are correlated leading to anisotropy in the emission of inter-fragment gamma rays. Our measurements suggest that this correlation is not as strong as one might expect. Is this because of the role of relative angular momentum or is it because the spin vectors are tilted at scission? This project uses measurements of fragment-gamma and inter-fragment gamma-gamma correlations using data collected at GAMMASPHERE to try to answer these questions.

Title: Pulse-shape Analysis with a Bragg-Curve Spectrometer
Supervisor: Dr Gavin Smith Gavin.Smith@manchester.ac.uk
Bragg-curve spectrometers are heavy-ion gas detectors that have an electric field applied along the trajectory of the ion. The gas is ionized along the ion track and drifts towards the anode. The anode signal contains information on the energy and atomic number of the ion. For fission fragments, the velocity is such that the previous crude method of fast/slow integration of the anode pulse is not adequate. We have now available fast electronics which allows the digitization of the signal. The current research project involves taking data with this system at Manchester, developing the algorithms to determine Z and E in real time and then using the system to do gamma-spectroscopy on highly exotic fragments of neutron-induced fission at the ILL High-flux Reactor facility in Grenoble, France.
Particle Physics

The Particle Physics Group at Manchester offers projects in both experiment and theory. It is also possible to combine these two areas, and students can choose joint projects supervised by both an experimentalist and a theorist from the group. Projects are also available in detector development.

Further details about all Particle Physics areas of research and contact information of all group members can be found at our website: http://www.hep.manchester.ac.uk/research.html

General enquiries about postgraduate opportunities in Experimental Particle Physics should be addressed to Yvonne.Peters@manchester.ac.uk, and those for Theoretical Particle Physics should be addressed to Mrinal.Dasgupta@manchester.ac.uk.

Experimental Particle Physics

The experimental particle physics group is involved in activities at the LHC, in particular the ATLAS and LHCb experiments, and neutrino physics, covering SuperNEMO, PINGU, the SND programme and LArTPC detector development. The group works on data analysis and detector developments. Details of the projects and the involved academic members of staff are given below.

Title: The ATLAS Experiment (LHC)
Main Contacts:
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Prof Terry Wyatt terry.wyatt@manchester.ac.uk
Further Contacts:
Prof Cinzia Da Via cinzia.davia@manchester.ac.uk
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Dr Andrew Pilkington andrew.pilkington@manchester.ac.uk
Dr Darren Price darren.price@manchester.ac.uk

Manchester group members play leading roles in the ATLAS experiment, the largest particle physics experiment at the Large Hadron Collider (LHC) in Geneva, Switzerland. They coordinate international research teams in data analysis and in the development of new detectors and algorithms. With the restart of the upgraded LHC this year, new data are becoming available for study at a record-breaking energy of 13 TeV.

Our goals with these data include the search for dark matter, extra dimensions, additional Higgs bosons, heavy Majorana neutrinos, supersymmetry, new TeV-scale particles such as gravitons, and measurements of the properties of the newly-discovered Higgs boson. We perform this research from multiple angles: directly searching for these new physics phenomena as predicted by specific theories, but also through precision tests of the Standard Model with the aim to measure differences that could provide the first hints of something completely new and unexpected.

The Manchester group offers a broad range of projects, making precision measurements and searching for new phenomena through the study of vector bosons, the Higgs boson, top, beauty and charm quarks, and hadronic jets.

Manchester has one of the few groups in the country that can boast close connections between the experimental and theoretical particle physicists. This provides plenty of fruitful opportunities for joint experiment-theory collaborations in LHC physics.
In addition to data analysis, the Manchester group has long-term involvement and leadership of the development of triggers and data acquisition algorithms, measurement of the luminosity, calibration of the detector response, and we are strongly involved in upgrading the ATLAS pixel detector for data-taking through to 2025+. Detector research and development include cutting-edge semi-conductor technologies like 3D silicon and 3D diamond. Manchester led the qualification and industrialisation of 3D silicon for the first ATLAS detector upgrade.

Possible PhD projects can combine activities from multiple of the above research areas.

Title: Matter-antimatter differences at LHCb
Main Contact: Dr Marco Gersabeck marco.gersabeck@manchester.ac.uk
Further Contacts:
Prof Chris Parkes christopher.parkes@manchester.ac.uk
Prof George Lafferty George.lafferty@manchester.ac.uk
Dr Rob Appleby robert.appleby@manchester.ac.uk

First Data from LHC Run II
Manchester is one of the larger university groups working on the LHCb 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 are 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.

There are research projects in both of our main areas of focus: matter anti-matter asymmetries (CP violation) 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. In bottom hadrons we are involved in measurements using semi-leptonic B meson decays, which tackle one of the largest discrepancies with the Standard Model of particle physics. Among rare decays our general focus is on lepton-flavour violating processes, which we study in tau lepton decays as well as in bottom and charm hadron decays to a mixture of electrons and muons.

Many different measurements can be made in the rich field of quark and lepton flavour physics, and it is important to establish whether they can all be explained by the Standard Model or whether the hints of small differences turn out to be the first signs of some new physics. In addition to data analysis the group has major responsibilities in the operation of the LHCb Vertex Locator, in particular its spatial alignment and data quality monitoring. New projects will focus on the analysis of data taken in Run-2 of the LHC. The figure shows one of the first collisions as recorded by the LHCb experiment in 2015.

**Title:** Next generation LHC Experiment - LHCb Upgrade

**Main Contact:** Prof Chris Parkes christopher.parkes@manchester.ac.uk

**Further Contacts:**
- Dr Marco Gersabeck marco.gersabeck@manchester.ac.uk
- Prof George Lafferty George.lafferty@manchester.ac.uk
- Dr Rob Appleby robert.appleby@manchester.ac.uk

Manchester is one of the larger university groups working on the LHCb 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 are involved in running the vertex detector of the experiment and in the design and construction of an upgraded detector for much higher luminosity.

The LHCb experiment will be upgraded to a new detector for higher luminosity operation in 2018. One of our key work areas over the coming years will be the design, construction, commissioning, and operation of the upgraded LHCb vertex detector. Our group will carry 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 CO₂. Research projects in this area span the full range of high-technology detector work. This includes the assembly and related testing systems to ensure spatial accuracy at the micron level, stability under temperature and pressure variations, and functioning of the electronic elements.
The second area of our involvement is readout electronics performed with dedicated configurable integrated circuits (FPGAs). Research projects cover the design of the algorithms, their tests with test-beam experiments, and their emulation in software. In the long run, these algorithms will be tuned based on data taken with the upgraded LHCb detector. The third area that our group contributes to is the software of the vertex detector where we hold responsibilities for the reconstruction, simulation and data quality monitoring. Research projects focus in particular on an accurate simulation of radiation damage effects and on the monitoring of their impact on data acquisition. All LHCb upgrade projects can be either completely hardware based or they can be combined with data analyses of the current LHCb experiment.

Title: The SuperNEMO Project
Main Contact: Prof Stefan Soldner-Rembold stefan.soldner-rembold@manchester.ac.uk
Further Contact: Dr Justin Evans justin.evans@manchester.ac.uk

SuperNEMO is a new international experiment proposed as a successor to the current NEMO-3. It will search for neutrinoless double-beta decay, a process that is only possible if neutrinos have mass and are their own anti-particles. Discovery of neutrinoless double-beta decay would be groundbreaking, and would require modifications to the Standard Model of Particle Physics. The SuperNEMO detector will begin taking data in 2016, at the Modane Laboratory on the French-Italian border. This PhD project will involve the analysis of the very first data from SuperNEMO, making a world-leading search for neutrinoless double beta decay. This is a challenging rare-event search, requiring detailed understanding of the various radioactive backgrounds that can mimic a double beta decay. The data obtained will be sensitive to a wide range of beyond-the-standard-model physics, including lepton flavour violation, right-handed W bosons, and Majoron exchange.
The PINGU experiment is a proposed new phase in the next phase of the exiting IceCube experiment, which will turn the Antarctic ice shelf into a precision neutrino detector. PINGU will be able to measure the oscillations of atmospheric neutrinos with unprecedented precision, resolving a long-standing question: the neutrino mass hierarchy. This is the question of which of the neutrino mass states is the heaviest, which is a vital input to probing the matter-antimatter asymmetry in the neutrino sector. This project would give the student the chance to develop the design and physics programme of the PINGU experiment, as well as analyzing data from the existing DeepCore experiment, a prototype for PINGU that is currently taking data at the South Pole.
The SBN Programme will combine three international experiments in order to perform the world’s most sensitive search for sterile neutrino oscillations. 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 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 forthcoming data from the MicroBooNE experiment; detector development, construction, and commissioning for SBND; and simulations for SBN.
The LArIAT detector Light Readout Module

Current and future neutrino experiments propose to employ liquid argon time projection chambers (LArTPCs) to probe neutrino properties with unprecedented precision. Several small-scale LArTPC experiments are currently under construction or operating in neutrino beams, providing opportunities for physics measurements. At the same time, they are leading R&D for future-generation experiments, such as DUNE, which aims to search for CP violation in the neutrino sector, and determine the neutrino mass hierarchy.

Light collection systems for LArTPCs are the most rapidly developing component of this technology. In addition to providing triggering for the experiment, and allowing for the identification of beam neutrino events from cosmic ray backgrounds, their applications are quickly expanding to include energy reconstruction and particle identification. This can enable new opportunities for physics measurements, e.g. supernova core collapse neutrino measurements and understanding of nuclear effects in neutrino interactions. This project will involve development of light collection systems for LArTPC’s as well as simulations and analysis of data provided by the Fermilab SBN experiments.
Theoretical Particle Physics

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.

Title: Beyond the Standard Model and Particle Cosmology
Contact: 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.

Title: Using QCD to explore the TeV scale at the Large Hadron Collider Contact: 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.

Title: Automating QCD calculations
Contact: Prof Jeff Forshaw jeff.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.

**Title: Monte Carlo Modelling of QCD Interactions**  
**Contact: 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. He offers PhD opportunities in all of these areas, and also frequently co-supervises students in the ATLAS sub-group to provide a more theoretical strand to their experimental activities. In 2017, Prof. Seymour will host a Marie Skłodowska-Curie Early Stage Researcher position on the development of parton shower algorithms beyond the leading colour approximation, funded by the Horizon 2020 European Training Network MCnetTN3.

**Title: Early Universe and Particle Physics**  
**Contact Dr Fedor Bezrukov** fedor.bezruk@manchester.ac.uk

Modern physics has an excellent and precisely tested theory, Standard Model (SM) of particle physics, which explains all the modern laboratory experiments. With addition of the general theory of relativity the model allows also to describe the evolution of our Universe. However, here comes the problems-- several observations that are part of the Standard Cosmological Model, LambdaCDM, can not be explained within the SM of Particle physics, making cosmology now the main reason to search for physics beyond the SM. The major tasks are to explain are the inflation, Dark Matter, and Baryon asymmetry of the Universe.

We are focusing on the study the inflationary models and relation to the properties of particle physics. The interesting questions include models with modified coupling of fields and gravity, scale invariant theories. At the same time, the models studied are relevant for Dark Matter generation, provide predictions for new physics searches in the laboratory. Collaboration with other groups within the School of Physics and Astronomy is crucial for the project.
Particle Accelerator Physics
Manchester plays a major role at the Cockcroft Accelerator Institute, based at Daresbury. Our activities cover a range from the lowest (EMMA 18 MeV) to the highest (the LHC at 7 TeV) energies. We list four projects here, but the field is wide and many others are available.

To the left is shown a computer simulation of wakefields excited in the main linacs of the International Linear Collider (ILC) superconducting cavities. Rightmost is a prototype section of the 20 km high gradient linac for the Compact Linear Collider (CLIC).

Title: The luminosity upgrade of the LHC
Supervisor: Dr Rob Appleby robert.appleby@manchester.ac.uk
The LHC has now been successfully commissioned at CERN, is providing proton and heavy ion collisions to the experiments and there is now a significant accelerator physics challenge in upgrading the delivered luminosity through machine upgrades. This upgrade requires a detailed understanding of the dynamics of protons in the LHC, often in new and novel regimes. One important aspect of this is the formation of new proton beam optics, which deliver the required luminosity and permits exploitation of recent advances such as RF crab cavities and novel halo collimation schemes. In this PhD project you will address these issues both theoretically, numerically and experimentally on the LHC, working with the existing LHC accelerator physics team in Manchester and with the LHC team at CERN to proton beam dynamics, develop new LHC charged particle optics and develop novel solutions to issues such as halo collimation.

Title: VHEE Applications for Radiotherapy Studies
Supervisor: Prof. Roger Jones roger.jones@manchester.ac.uk
Proton therapy has potential benefits over x-ray therapy. However, recent albeit limited in extent, research conducted at SLAC and other laboratories have indicated the potential to use high energy electrons (VHEE) for radiotherapy. SLAC have utilized their existing x-band linacs which are able to supply 70 MeV beams to sample specimens. The research in this area is quite limited at present however and there is an opportunity to explore higher energies with greater depth penetration and potentially less scattering. There may be indeed be advantages of this technique over extant methods –such as more precise and rapid delivery to tumors with reduced fractionation.

This project will explore the fundamental delivery to target specimens using the 150 MeV facility at Daresbury Laboratory (DL), and later on the 250 MeV CLARA facility. In the initial part of the project
the student will have the unique opportunity to collaborate with the ASTeC team in designing and commissioning the S-band linacs and overall machine operation. The student will be based a significant fraction of her or his time at DL. Many aspects can be explored with the facilities at DL. One aspect that may be studied is target and organ motion—which results from many sources including musculoskeletal, breathing, cardiac, organ filling, peristalsis, etc. Currently 15-90 minutes per fraction for state-of-the-art high-dose radiotherapy. To this end, means of rapid delivery of electrons to the sample specimens will be explored. Whilst the student participates in commissioning work on the S-band linacs, simulations will also be conducted in parallel, on the dose delivery potential of VHEE (using GEANT4 or similar codes).

Title: Electromagnetic wakefields and beam dynamics in Accelerator structures
Supervisor: Dr Roger M. Jones Roger.Jones@manchester.ac.uk
The accelerator physics group in the school of physics at Manchester places particular emphasis on complex particle motion, optical design and the effects of beam-excited wakefields. We study wakefield effects of beam collimators, and Higher Order Modes (HOMs) in superconducting and normal conducting cavities; this entails understanding their excitation and suppression, and how to use them as an intrinsic beam-based diagnostic. We work on the main high gradient accelerating linac, crab cavities, beam delivery system, interaction region and extraction line dynamics for the ILC and CLIC projects, the study of the dynamics for EMMA and the ATF, the ATLASFP project for the LHC, the HIE-ISOLDE nuclear accelerator upgrade, computational beam dynamics, photocathode beam dynamics, high intensity and high energy nuclear isotope accelerators, and particle beam dumps. Opportunities exist for PhD work in these areas with students developing and using theoretical, computational and experimental skills. Students will have the opportunity to participate in research at major international facilities. Ongoing collaborations exist with the ALICE at Daresbury, CLIC, LHC/ATLASFP and HIE-ISOLDE at CERN, ILCTA at FNAL and the ATF2 at KEK. A developing activity is focused on an analysis of electromagnetic wakefields and beam dynamics in spoke and elliptical cavities for the European Spallation Source (ESS) in Lund, Sweden. ESS will become 10 times more powerful than facilities in the US and Japan. The main accelerating cavities of ESS will be required to cope with beam-excited higher order modes which have the potential to dilute the beam emittance and in the worst case scenario, to excite a beam break up instability.

Title: Charged Particle Collimation with Wakefields
Supervisor: Dr Roger M. Jones Roger.Jones@manchester.ac.uk
We propose to develop a suitable formalism and simultaneously simulate the effect of particle scattering in collimators and the effect of wakefields on relativistic particle beams. These dynamical effects are conventionally treated separately, and this project will use a unified approach to study the impact on high energy and low Emittance beams. The formalism shall be included in the code MERLIN, with many resulting applications. For example, we will study the impact of the wakes and re-scattering in the LHC collimation system upon the dynamics and absorption of the stored particles. To date, only a single code platform has been used to perform collimation simulations on the LHC, using SixTrack with FLUKA to model scattering, loss, and subsequent particle shower generation. Wakefields imparted by the collimators will modify the passing bunches significantly, but this is presently modelled separately to the collimation process. This work necessarily entails a strong collaboration with colleagues at CERN and at the SLAC National Accelerator Laboratory where collimator beam-based experiments are conducted.
The world's first non scaling Fixed Field Alternating Gradient accelerator, EMMA, is being built as a Manchester-led project at the Daresbury Laboratory. Its commissioning and early operation will enable machine studies to be done of this new type of accelerator. Students will assist with experiments and later be able to devise their own. Understanding of nsFFAg principles should open the door to FFAg proton accelerators; simpler and more compact than synchrotrons and capable of producing much higher currents. These have been proposed as machines for cancer therapy, and also for 'sustainable' Thorium powered ADSR reactors. Students can look in detail at either of these applications.

Title: Proton Beam Delivery for Radiotherapy
Supervisor: Dr Hywel Owen Hywel.Owen@manchester.ac.uk

Christie Hospital is presently constructing the UK’s first full energy proton beam therapy facility, which improves on current X-ray based radiotherapy techniques by providing a much more specific dose distribution that targets cancerous tumours whilst sparing surrounding tissues. However, to make best use of this technology requires better imaging of the tumour location, a task best done with the protons themselves imaging techniques that can be carried out simultaneously. One important project is to design a suitable proton beam delivery system that can take protons from a cyclotron or synchrotron, and deliver them accurately to a patient without being unduly large. In this project you will incorporate a novel arrangement of magnetic elements, and determine the usefulness of superconducting magnets in the final delivery.

Title: Plasma Wakefield Acceleration (PWFA)
Supervisor: Dr. Guoxing Xia guoxing.xia@manchester.ac.uk

With the recent discovery of the Higgs Boson-like particles at the Large Hadron Collider (LHC) at CERN, the physicists are looking forward to constructing another electron-positron linear collider or electron-proton collider for precise measurement of the properties of the Higgs particles, e.g., its mass, spin, the couplings, self-coupling with other particles and the new physics beyond standard Model etc. However, any proposed energy frontier (TeV, or 10^{12} electron-volts) collider is more than 30 km long and cost over billion pounds. The obvious question is: can we make the future machine more compact and cost effective?

The development of the plasma accelerator has achieved significant breakthroughs in the last decade. The laser wakefield accelerator can routinely produce several GeV electron beam with percentage energy spread within only a few centimeter plasma cell and the accelerating gradient (~100 GeV/m) is over three orders of magnitude higher than the fields in conventional RF based structures (in general less than 100 MeV/m). The charged particle beam driven plasma wakefield acceleration has successfully demonstrated the energy doubling of the electron beam from the Stanford Linear Collider-SLC within an 85 cm plasma. These significant breakthroughs show great promise to make the future machine more compact and cheaper.
Proton-driven plasma wakefield acceleration (PDPWA) has been recently proposed as a means to bring a bunch of electrons to the energy frontier (TeV) in a single stage of acceleration. The idea is to couple the huge amount of energies stored at the current proton synchrotron to an externally injected witness beam (electrons) through the plasmas. Particle-in-cell simulation has shown that a 1 TeV LHC-like proton bunch can be used to excite the plasma wakefield and accelerate a bunch of electrons to 600 GeV in a single stage through a 500 meter plasma cell. Compared to laser and electron beam driven plasma wakefield accelerator-based collider design, this will greatly reduce the stringent requirement on the alignment and synchronization of the multistage accelerator modules. If the PDPWA scheme can be demonstrated, this will lead to a much cheaper TeV electron-positron linear collider based at the current CERN accelerators infrastructure. A brand new experiment AWAKE at CERN will test this scheme by using the CERN SPS beam.

In addition, the electron beam driven plasma wakefield acceleration is now also being planned and investigated. The idea is to utilize the local research facility VELA and CLARA at the Daresbury lab to study the interactions between the electrons and the plasmas experimentally. This experiment will be the first UK based beam driven plasma wakefield acceleration experiment.

There are many interesting issues that the student can work on, e.g., the collider design based on proton driven plasma wakefield acceleration and the related issues, the simulation study of interactions between proton/electron beam and the plasmas, the plasma channel for reducing the electron-plasma scattering etc.

As a multidisciplinary research topic. Studies will involve theoretical work (classical electrodynamics, plasma physics, accelerator physics, etc.) and also computer skill (particle-in-cell, parallel computing).

References

Title: Ultra Compact Dielectric Laser Accelerator, an Accelerator on a Chip!
Supervisor: Dr. Guoxing Xia guoxing.xia@manchester.ac.uk

Nowadays, the energy frontier particle accelerators (e.g. Tevatron at Fermilab, LHC at CERN) are enormous and costly. One of the main limiting factors is the RF breakdown from the metallic based RF cavities (the main acceleration element).

On the other hand, the dielectric materials (e.g. silica, quartz, etc.) have larger breakdown voltages. Dielectric laser-driven accelerators (DLA) are strong potential candidates for ultra-compact electron accelerators and might even open up new avenues for future high energy physics accelerators and free-electron lasers. Due to a much higher damage threshold (0.2-2 J/cm²) than metals, these dielectric microstructures can support accelerating fields that are orders of magnitude higher than what can be achieved in conventional radio-frequency cavity-based accelerators. This can boost the acceleration gradients up to several GV/m. A proof-of-principle experiment has successfully demonstrated acceleration of relativistic electrons with an accelerating gradient of 250 MeV/m in a fused silica double grating structure and the acceleration of non-relativistic 28 keV electrons through a single grating structure was also observed. These two experiments demonstrate the possibility of an all-optical DLA for full energy acceleration in the future.

This is a new European research project. We are working on optimization of various dielectric structures to achieve the high acceleration efficiency. The proposed dielectric laser acceleration experiment at the Daresbury laboratory will complement to the detailed theoretical and numerical investigation of the DLA schemes.

This research involves laser physics, accelerator physics and high performance computing (particle-in-cell).
References

Further details about all Particle Physics areas of research can be found at our website: www.hep.manchester.ac.uk/research.html

Enquiries about postgraduate opportunities in Experimental Particle Physics should be addressed to terry.wyatt@manchester.ac.uk, those for Theoretical Particle Physics should be addressed to Mrinal.Dasgupta@manchester.ac.uk, and those for Accelerator Physics should be addressed to Roger.Jones@manchester.ac.uk

Title: Terahertz driven linac: Shrinking the size and cost of particle accelerators
Supervisors: Dr Darren Graham (Manchester), Dr Steven Jamison (Daresbury Laboratory)
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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 a PhD student to work on terahertz driven particle beam acceleration, joining a collaborative project at the Cockcroft Institute (www.cockcroft.ac.uk). 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 breakthrough the 100 MV/m accelerating gradient limit of conventional radio-frequency accelerating cavities, thereby enabling a new generation of table-top particle accelerators.

Left: Recent development of a sub-relativistic THz accelerator. Right: Ultrafast lasers system in Dr Graham’s lab at the PSI.
Below: the VELA accelerator at STFC Daresbury Laboratory.
The Cockcroft Institute 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 UK’s participation in flagship international experiments. 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 new facility is able to deliver a capability for the cutting edge development and qualification of advanced accelerator systems and techniques. 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.

For further information contact Darren.Graham@manchester.ac.uk

Photon Physics
http://www.physics.manchester.ac.uk/research/groups/photon

The Photon Physics Group in the School of Physics and Astronomy has relocated all research projects to the new Photon Science Institute laboratories. These laboratories are located in a new 4-storey building located next to the Schuster laboratory and incorporate state of the art facilities to allow new science to be carried out. The Photon Science Institute houses researchers from many different disciplines in a research environment unique to the University, and to the UK. By bringing together scientists and engineers from disciplines ranging from physics through to the biological and medical sciences, opportunities arise to engage in novel research programmes and collaborations which are both cross and multi-disciplinary. The descriptions of projects given here reflect only a small part of current research programmes in the School of Physics and Astronomy, and there are many opportunities to carry out new research at the Institute.

Title: Thermoregulation in Neo-tropical Tree Frogs
Supervisor: Dr Mark Dickinson Mark.Dickinson@manchester.ac.uk
Most frogs avoid prolonged exposure to high light levels and the associated risk of dehydration. Phyllomedusine and some litorine tree frogs, however, show unusual basking behaviour and have a novel NIR reflective pigment (pterorhodin) in their skin. This pigment may help the frogs camouflage themselves from predators by matching the NIR reflectance of the leaves on which they bask. Pterorhodin may also aid in thermoregulation by reducing absorption of solar radiation. In addition, while basking these frogs sometimes undergo a visible change in skin texture which could result in changes to the absorption and hence changes in the skin temperature. This ability to change the temperature of the skin while body temperature remains near ambient may also aid in resistance to infections acquired through the skin such as chytridiomycosis. This project is to investigate the role of pterorhodin and the effects of the change in skin texture using a combined laboratory and field approach, refining the approach in the lab before venturing into the field. In addition novel imaging techniques will be used to quantify the previously observed visual and NIR change in frog skin.
The project will have three elements:

1) compare thermoregulatory and the near-infrared (NIR) reflective properties of two tree frog species containing the NIR reflective pigment pterorhodin with two species that lack this pigment across a natural range of light and temperature;

2) obtain field collected measurements of NIR reflectance of frogs and their resting substrates. This will allow us to relate laboratory findings to the life history and ecology of the frogs;

3) compare optical coherence tomographic (OCT) images of frog species with and without NIR reflective pigments, and record structural changes in the skin associated with changes in NIR reflectance.

Modelling open quantum systems beyond weak-coupling regimes

Supervisor: Dr Ahsan Nazir ahsan.nazir@manchester.ac.uk

The thermodynamics and nonequilibrium dynamics of quantum systems in contact with environmental degrees of freedom is a topic of primary importance in physics and chemistry, and is becoming increasingly relevant in biology as well. In a wide range of quantum systems the interactions with the environment are non-trivial, and cannot be treated by the standard weak-coupling approximations often used in the existing literature.

This project will develop new theoretical techniques to study such systems, and apply these approaches to quantum systems whose behaviour is not fully understood. In a departure from conventional open systems methods, the student will explore the role of highly non-classical environmental states in faithfully representing system-environment (and intra-environment) correlations in the strong-coupling regime. Particular applications include quantum dot and superconducting qubits for quantum computation, as well as the recently discovered coherent motion of excitons in natural and artificial molecular nanosystems.

The successful applicant will join a new and dynamic theoretical team within the Photon Physics group working on a variety of topics related to the physics of open quantum systems. For further details and publications please see http://personalpages.manchester.ac.uk/staff/ahsan.nazir/
There is an urgent requirement to make better use of the 120,000 TW of power provided by the Sun. In order to make solar power generation economically viable, the next generation of solar cells must be cheaper and less costly in energy terms to produce. The development of wet-chemistry synthetic routes for the fabrication of high-quality nanoparticles or ‘quantum dots’ has created an opportunity for the exploitation of these quantum dots as the light-harvesting elements in future solar cells. In principle they offer a cheap and green solution to providing solar power.

Example of a prototype solar cell. Incoming sunlight is absorbed by a quantum dot, creating an electron hole pair (or exciton) which must then be rapidly separated, the electron travelling to the photoanode via metal oxide nanorods, and the hole being transported to the photocathode via a conducting polymer.

At the heart of the nanocell device is a semiconductor quantum dot that harvests the incident light, creating an electron-hole pair, which is separated to produce a photocurrent. A potential obstacle to widespread exploitation is the limited chemical and photochemical stability of these quantum dots – in particular to oxidation of their surfaces, which affects the properties of the dot, and can impair the extraction of charge carriers from it. It is vitally important that we understand how the energy levels in the dot match up with the materials surrounding it, how charge is transported from it, and how this is affected by its surface properties – and this is the task of this PhD project. This project will use X-ray photoelectron spectroscopy (XPS) to understand the surface properties of the dot (including its stability, the effect of new surface passivation techniques and the bonding of other cell components to it.) In addition a number of synchrotron and laser spectroscopies will be used to understand the electronic structure of the dot, and how charge is transferred from it when sunlight is absorbed. Synchrotron work will be carried out European synchrotron radiation sources such as SOLEIL near Paris, or Elettra in Trieste, Italy.

Title: Ultrafast Measurements of Charge Transport in Nanoparticles for Solar Nanocells
Supervisor: Professor Wendy Flavell Wendy.Flavell@manchester.ac.uk

Semiconducting and insulating nanoparticles have a huge range of applications. These include nanoparticulate solar cell and photocatalyst materials, additives to stop polymers from degrading in sunlight, security tags, fuel additives and even sun screens. In all these cases, it is important to understand what happens after the nanoparticle absorbs light (e.g. sunlight) of sufficient energy to excite a carrier across the band gap and create an electron-hole pair in the system. The outcomes can include radiative recombination or, if a voltage is applied, the separation of the electron and hole to create and external current (e.g. in a solar cell). The desired outcome can be thwarted by a whole range of processes – for example trapping at defects at the surface of the nanoparticle or inefficient transfer of charge to the material surrounding it. These processes typically occur quite fast – on timescales varying between fs and ns.
Synchronised pump-probe experiments which exploit ultra-short pulses to study sample dynamics

One way in which to study these processes is by ‘pump-probe’ experiments, where a short pulse of light from a laser is used to create the initial electron-hole pair, which is then studied by another pulse of light, synchronised to the first. In a series of experiments, the time delay between the two is adjusted, allowing the time evolution of the system to be studied. In this project we will use a 90 fs high power laser pulse as the probe, and, as the probe, either a pulse of synchrotron radiation (from a European synchrotron radiation source such as SOLEIL, near Paris), or a very low energy ‘terahertz’ pulse generated from the laser system itself (time-resolved THz spectroscopy, or THz time domain spectroscopy).

Image of the laser pump beam overlapping the synchrotron X-ray probe beam on a sample taken at the TEMPO beamline, SOLEIL, near Paris.

We will study a number of semiconductor quantum dots that form part of a number of ‘next generation’ solar cells under development in the PSI in Manchester. Here, the aim is to understand how the electron-hole pair created in the dot by the absorption of sunlight may be rapidly separated and the charges transported to the interfaces of the device, and whether ‘charge-injection’ of the carriers is taking place at the interfaces between one component and another.
Title: Mechanism of light-induced degradation in organo-metal halide perovskite solar cells
Supervisor: Professor Wendy Flavell wendy.flavell@manchester.ac.uk
In the search for cost-effective materials for harvesting solar power, organic-inorganic hybrid perovskites are particularly promising. The efficiency of solar cells made using perovskites has increased from only 3% to more than 20% within the last 5-6 years. However, very poor stability of these solar cells in environmental conditions under continuous long-term illumination remains a critical concern that restricts the practical applications of this technology.

The NAP XPS spectrometer in the PSI at the University of Manchester

In this project, we will use two photoemission techniques to understand this problem. The first is near-ambient-pressure X-ray photoelectron spectroscopy (NAPXPS) which allows us to determine the chemical and electronic structure of a material in the first few atomic layers, while simultaneously exposing the surface to realistic pressures of atmospheric gases, and illuminating it. The PSI at UoM is one of very few labs in the world able to undertake these measurements. We will match this with results from synchrotron-excited depth-profiling XPS, which allows us to determine the composition layer by layer as we probe from the surface deeper into the bulk. Synchrotron work will be carried out European synchrotron radiation sources such as SOLEIL near Paris, or Elettra in Trieste, Italy. The aim is to understand how the chemical and electronic structure of the perovskite surfaces is changed by the atmosphere and by light, so that we can help develop strategies to passivate the surfaces against atmospheric degradation.

Title: Spintronics with Semiconductors
Supervisor: Professor Elaine Seddon; contact Professor Wendy Flavell Wendy.Flavell@manchester.ac.uk
Spintronics is a rapidly developing field in which the charge and the spin of electrons are utilised in electronic devices. Whilst magnetic materials and multilayers (which have aligned electron spins) have found extensive use in data storage and retrieval, a major research thrust now is the broad integration of magnetic and semiconductor technologies in devices. Our aim is to improve device function by a detailed understanding of the electronic structure of the individual materials and the interfaces between them.
The main spectroscopic techniques that are utilised are spin resolved photoemission and spin resolved Auger Electron Spectroscopy. The former, for which we utilise either synchrotron radiation or a DC discharge as light sources, is the most direct probe of spin resolved electronic structure. For Auger Electron Spectroscopy we utilise an energetic electron beam. This latter technique has the advantage that - with spin resolution - it is an element specific magnetic probe. The work will be undertaken using the spin polarised spectroscopy apparatus, shown below, currently based at the Cockcroft Institute adjacent to Daresbury Laboratory.

The principal aim of this project is to understand and develop the properties of systems that bring together magnetic alloys (for spin injection and spin detection) and semiconductors in spintronics devices. Building on our work in the past which focused on systems such as Fe on GaAs and magnetically soft alloys such as Fe$_{80}$B$_{20}$ we now intend to work with silicon and magnetic alloys such as nickel iron and cobalt iron.
Title: Quantum Semiconductors for Lighting for the 21st Century  
Supervisor: Dr Peter Mitchell Peter.Mitchell@manchester.ac.uk

The production of semiconductor quantum well structures based on the GaN materials system has opened up the development of light emitting diodes (LEDs) and lasers covering the region of the spectrum from the green to the deep blue part of the spectrum. The widespread use of high efficiency LEDs to replace incandescent light bulbs and compact fluorescent bulbs for use in the home and office promises to have a significant impact on the global energy crisis. If this aim is fulfilled for this application alone it may be possible to reduce the global amount of electricity used for lighting by 50%. In the US alone this would alleviate the need for 133 new power stations (1 GW each), eliminate 255 million tons of CO$_2$, and save $115 billion of electricity costs (“The Promise of Solid State Lighting for General Illumination”, OIDA Report for the US Department of Energy, 2000).

Light emitting diodes (LEDs) based on InGaN/GaN quantum well (QW) active regions are now widely used when emission in the blue and green regions of the visible spectrum is desired. Despite their widespread use some fundamental issues remain unsolved; for instance the external quantum efficiency of devices designed to emit at green wavelengths is considerably lower than that which can be achieved at blue wavelengths. The maximum external quantum efficiency is 30 % for green LEDs compared to 55 % for blue LEDs. This lower efficiency as the emission wavelength is increased in InGaN/GaN devices is commonly referred to as the ‘green gap’.

In this project the student will undertake laser spectroscopy of a range of QW structures whose properties will be targeted at enabling the production of high efficiency green LEDs. This work is part of an EPSRC funded collaborative effort involving the group in Manchester, the Materials Science Department at the University of Cambridge and Plessey Semiconductors. The student will be based in the Photon Science Institute in Manchester and will liaise with the groups in Cambridge and gain experience of growth and detailed electron microscopy undertaken in Cambridge.

Title: Laser cooling and manipulation of atoms  
Supervisor: Professor Andrew Murray Andrew.Murray@manchester.ac.uk

It is possible to control atomic motion using laser beams of well defined energy, since the selective absorption and emission of photons must be accompanied by a change in momentum of both the laser field and atom. Spontaneous emission allows atoms to be cooled to temperatures less than 1mK, whereas evaporative cooling can further cool atoms to temperatures only a few nK above absolute zero. These atoms make up new collective states of matter, which are studied for their quantum effects. In this project, atom cooling and trapping experiments are undertaken using a high intensity cold atom beam source developed in Manchester, as shown below. Experiments include electron impact collision studies from cold atoms, production of ultra-cold electrons beams, studies of highly excited cold Rydberg atoms, and the study of the fundamental properties of the cold atoms that are produced. A new type of atom trap (the AC-MOT) was invented in Manchester. This uses high power audio amplifiers to drive current through the trapping coils, the polarization of the cooling laser beams being adjusted in synchronicity with the audio signal. This new type of trap can be switched on and off more than 300 times faster than a more conventional DC-MOT, allowing new experiments to be conducted. These include the study of electron impact and laser excitation and ionization, where the unique nature of cold atoms allows new high precision measurements to be made. We can exploit the very low momentum of the targets to accurately define an ionizing collision, we can laser-excite the atoms to highly excited Rydberg states prior to studies from these targets, or we can photo-ionize the targets and study the ion and electrons that emerge.
One of two atom cooling and trapping instruments in Manchester, showing the source chamber (right), Zeeman slower (centre) and trapping chamber (left) where collision and ionization experiments are carried out.

A second project using cold atoms is developing a new source of ultra-cold electrons from laser-cooled Rb atoms (see project entitled: Research and development of an ultra-cold high brightness electron source) below. These projects are carried out in the state of the art laboratories located in the Photon Science Institute, using the very high finesse laser systems located there.


Title: Ionization & Excitation of Atoms Prepared by Laser Radiation (3 spectrometers)
Supervisor: Professor Andrew Murray Andrew.Murray@manchester.ac.uk

In these projects atomic targets are prepared in a laser-excited state prior to electron impact. The incident electron of well controlled momentum either ionizes the target, excites the target to a higher level or may super-elastically scatter from the atom (i.e. the electron gains energy as the target relaxes back to the ground state). In each process the target state is controlled by the laser beam, which allows the ‘shape’ of the atom to be modified prior to the collision. In our ionization experiments (an example of one of the spectrometers is shown in figure (a) below), an incident electron scatters from and ionizes the target, leading to two electrons emerging from the interaction. These electrons are detected and time correlated with sub-ns accuracy. It then becomes possible to determine the reaction from individual atoms, and to measure the ionization probability as a function of the scattering angle for comparison to quantum theories developed by colleagues throughout the world. New experiments are now being carried out where the target atom is excited and aligned by a CW laser, the atom then being ionized by an electron beam. This type of interaction has not been studied before our initial work in Manchester1,2, and we closely collaborate with colleagues in the USA, UK, Canada and Australia who model these interactions using sophisticated new quantum theories. A new research grant (2017-2020) has now been obtained to continue this work, in particular to study the effects of un-natural parity contributions to the measurements. This has importance in understanding energy losses in Tokomaks, since current theories have been shown to be incorrect when modelling these processes. Our work will hence allow theoreticians to develop new models of these interactions for future energy generation using fusion reactors.
In our excitation experiments (figure (b)) we adopt time reversal methods to reveal highly precise information about the scattering process. In these experiments a laser again defines the ‘shape’ of the electron charge cloud prior to electron impact, and we measure the rate of super-elasitically scattered electrons as a function of the scattering angle and target structure. In this way experiments can be conducted thousands of times faster than is possible using conventional ‘coincidence’ methods. New experiments are being conducted which adopt a resonant enhancement optical cavity around the interaction region so that the intensity of the incident laser radiation can be increased by up to a factor of 2003. In this way we study atoms of technological and scientific interest, which are important due to their electronic structure4. Results from these experiments are then compared to quantum calculations produced by theoretical groups throughout the world, so that our understanding of excitation processes can be refined.

Two of the electron spectrometers for ionization and excitation studies of laser-prepared targets developed in Manchester. In (a), two detectors (A1,2) are used to detect electrons arising from the interaction (an e,2e) process. In (b), a Magnetic Angle Changing (MAC) device controls the direction of incident and super-elasitically scattered electrons from laser prepared targets, excited in a resonance enhancement cavity (Mirrors 1 & 2).


Title: Development of an ultra-cold high brightness electron source for new accelerators, free electron lasers & high-resolution electron diffraction studies

Supervisors: Professor Andrew Murray, Dr Guoxing Xia, Dr Will Bertsche, Dr Rob Appleby

Development of an ultra-cold, high-brightness electron source is a new initiative at the University of Manchester. This source offers unique opportunities to address a range of topics from fundamental research on ultra-cold plasmas and electron microscopes, through to technology applications ranging from vastly improved accelerators to novel materials characterization.

This is a rapidly expanding topic internationally1-4, and our work will contribute significant new ideas to this emerging field. In these experiments (see figure below), laser-atom cooling and trapping methods prepare a high density ensemble of cold rubidium atoms in a conventional Magneto Optical Trap, before being injected into a new type of trap invented in Manchester5, the AC-MOT (not shown - see project entitled Laser Cooling and Manipulation of Atoms for details). Cold atoms stored in the DC-MOT are transferred using a steering laser to the AC-MOT, where experiments take place. Several high-resolution continuous wave and pulsed tuneable laser beams trap the atoms, cool them to micro-Kelvin temperatures, manipulate them into an excited state and then photo-ionize the excited ensemble. This creates an ultra-cold high-density plasma consisting of Rb$^+$ ions and cold electrons. The electrons are then rapidly extracted from the plasma using electrostatic optics, before acceleration to high energy for injection as a focused beam into different experiments6.
The new cooling and trapping source in Manchester designed to produce an ultra-cold electron beam for injection into new types of accelerators, Free Electron Lasers and for materials characterisation using electron diffraction. The source will produce an electron beam with an energy resolution several orders of magnitude better than conventional sources.

This is a multidisciplinary project involving atomic and laser physics, plasma physics and accelerator physics. Research currently is investigating the preparation and optimisation of the cold electron source, as well as on the electron acceleration, transportation and injection of the cold electron beam into different experiments. Once the electron beam has been fully characterised, it will be used as a source in new types of accelerators, as well as for probing materials using electron diffraction techniques. In each study an increase in resolution of several orders of magnitude is expected, compared to conventional sources used today. This new cold electron source will hence deliver a step-change in accelerator science, in X-ray laser production and in materials characterisation.


Title: Nanowire-enabled optoelectronic devices
Supervisor: Dr Patrick Parkinson patrick.parkinson@manchester.ac.uk

Semiconductors play a key role throughout the field of optoelectronics, providing the active material for photodetectors, light-emitting diodes, and diode lasers. Whilst materials such as silicon are commonly used, a push towards higher speed, lower cost and more tightly integrated devices have led researchers to consider novel material systems with more tunable material properties. Of particular interest are semiconductor nanowires based on III-V materials such as GaAs, InP or InAs. Nanowires inherently feature nanoscale dimensions, bottom-up fabrication routes and tuneable material parameters through surface or heterostructure engineering, and have been identified as key
components for future nanotechnology-enabled optoelectronic devices. However, nanowire-based optoelectronics are a new field, and significant challenges remain for both material characterisation and optoelectronic-relevant testing.

This project builds on recent research at the University of Oxford and a collaboration with the nanowire growth group at the Australian National University and University College London, and has three main goals:

1) To design and establish a protocol for contacting and creating nanowire based devices.

2) To investigate key material parameters using an integrated range of ultrafast optical techniques, including photocurrent microscopy, photoluminescence microscopy, terahertz photoconductivity, and non-linear optical approaches.

3) To implement the best performing nanowire devices based upon the material parameters determined earlier in the project.

Key applications are in nanolasers, highly efficient photovoltaics and ultrasmall LEDs.

This project will involve clean-room work, ultrafast laser spectroscopy and may also include computational studies for interpreting nanowire dynamics. It will be carried out in collaboration with both the University of Oxford and the Australian National University.

Title: Multimodal energy dynamics study of nano- and meso-structured photovoltaic materials
Supervisor: Dr Patrick Parkinson patrick.parkinson@manchester.ac.uk

There is a rapidly growing requirement for clean, scalable and cheap energy sources to meet global demand. It is now clear that a number of device and material approaches are required to address a variety of large and small scale applications, each with unique requirements; for instance cost, weight, longevity, appearance or ultimate efficiency.

Third-generation photovoltaics promise high efficiency, low cost and easily produced solar cells based upon low-temperature or roll-to-roll preparation methods. Key examples include dye-sensitised solar cells, nanowire-based photovoltaics and the rapidly emerging field of perovskite-based devices. These materials meet are promising due to their use of novel materials or nano/meso-structuring to control the light absorption, charge generation and charge collection processes.

A key aspect of nano or meso-structured devices is the inhomogeneity inherent to such structuring, with critical energy processes occurring at spatially separated positions in three dimensions. Investigation can be hindered by the material in a full device performing differently from the active material alone; we therefore require a non-contact, in-situ probe of photon absorption, charge generation and charge migration processes that is sensitive on the shortest length scales and fastest time scales.

This project will address this challenge by use of recently developed and proof-of-concept techniques in time-resolved microscopy and nanoscopy, utilising visible and terahertz radiation to probe the ultrafast energy dynamics in next generation solar cells. This project will focus on establishing cutting
edge optoelectronic techniques for investigating energy materials, with the goal of building a framework for understanding all energy processes in this new class of photovoltaic materials. Next-generation photovoltaic materials will be developed with collaborators at the Australian National University (nanowire photovoltaics) and the University of Oxford (perovskite photovoltaics).

Title: Ultrafast terahertz spectroscopy of GaN semiconductor structures
Supervisor: Dr Darren Graham Darren.graham@manchester.ac.uk

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, the region between infrared and microwave radiation, due to its potential exploitation in security screening, medical diagnostics and high-speed wireless data communication. To realise the potential of this region we require compact, efficient 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 involve using a range of laser spectroscopic techniques including using femtosecond laser systems to perform ultrafast terahertz spectroscopy.
The ultrafast lasers systems in Dr Graham’s lab at the Photon Science Institute will be used to perform sophisticated femtosecond time-resolved spectroscopic measurements.

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.
Theoretical Physics
http://www.physics.manchester.ac.uk/research/theoretical-physics/

Following the restructuring of Theoretical Physics activities in the School, many theoretical projects take place within the following research groups: Astrophysics; Biological Physics; Condensed Matter; Particle Physics; Statistical Physics and Complex Systems and Theoretical Nuclear Physics. In the case of the first four areas, please consult the relevant section of this booklet for project descriptions. Projects in the last two groups are described below.

Theoretical Nuclear Physics

Title: Aspects of Nucleon Structure and Chiral Perturbation Theory
Supervisor: Dr Judith McGovern Judith.McGovern@manchester.ac.uk

Although QCD is firmly established as the correct theory which describes the behaviour of quarks and gluon, and has been well tested at high energies, it is much harder to apply it to ordinary matter such as protons and neutrons at low energies. The reason is that, unlike the Coulomb force, the interactions between coloured objects gets stronger at larger distances, so that they never exist on their own but always in combinations (called hadrons). Barring intensive computer simulations (which have their own problems of interpretation), the most promising approach to understanding the structure and interactions of matter involves so-called ‘effective field theories’ which respect the symmetries of QCD but are formulated in terms of observable particles – protons, photons, pions etc. and this is called ‘Chiral perturbation theory’. Such theories have taught us, for instance, that the degree to which protons and neutrons are electrically polarised by a background field is almost exclusively due to the pion cloud which surrounds them.

Projects in this field could take a number of forms, depending on the student’s interest. Although the field is more than fifteen years old there are some unresolved theoretical issues, concerned for instance with the agreement (or lack of it) between relativistic and non-relativistic formulations, and with whether and how to include heavier hadrons such as excited protons (Deltas). There are also more practical projects which involve using the established theory to calculate cross sections for observable processes, then comparing the results with the modern, high-precision data which is being generated at an number of labs round the world. For many years the properties of the constituents of ‘ordinary’ matter were neglected as experimentalists sought to reach higher and higher energies; happily these days this situation is being rectified. Extensions to simple nuclei are also of current interest, partly because only that way can we probe the properties of the neutron. (See also ‘Effective theories of few-nucleon systems’, Dr M Birse).

http://theory.ph.man.ac.uk/~judith/

Title: Effective Theories of Few-Nucleon Systems
Supervisor: Professor Mike Birse Mike.Birse@manchester.ac.uk

Developments at the borderline between particle and nuclear physics are leading to model-independent descriptions of the forces between nucleons. These make use of chiral perturbation theory to describe the long-range parts of the nuclear forces. Recent work at Manchester has used the renomalisation group to elucidate the importance of short-range terms in the nucleon-nucleon force and in the interaction among three nucleons. This project will extend the approach to include long-range interactions in three-body systems and will apply the results to the properties of 3H and 3He. In combination with the results of the preceeding project, this will allow extractions of neutron polarisabilities from Compton scattering experiments on 3He, as are planned at MAXLab and HIGS.
Title: The Coupled-cluster Approach in Nuclear Physics
Supervisor: Professor Niels Walet Niels.Walet@manchester.ac.uk
Quantum Many-Body Physics is a well-established area of research, where the Manchester group plays an important role. Historically, we have worked on the “coupled cluster method” (CCM), which started its life in nuclear physics, but was then applied in areas ranging from quantum chemistry to particle physics. Recently, interest in applications of the method in nuclear physics has resurfaced, and there is a real push to obtain new results, and look at the method again. In this project the student will be expected to extend and apply a recently developed numerical code for the study of nuclei using the coupled cluster method. Collaborations could involve our colleagues in Oak Ridge and Oslo. There is also ample room for formal developments, depending on the interest of the candidate.

Title: Renormalisation Group for Nuclear Matter
Supervisors: Professor Mike Birse Mike.Birse@manchester.ac.uk (with Professor Niels Walet)
The renormalisation group (RG) equation for the Legendre effective action has proved to very useful in particle and condensed-matter physics. This supresses high-momentum modes by adding a scale-dependent regulator to the kinetic energy. As this scale is lowered the bare action, which can be expanded using point-like interactions, runs to the effective action with physical scattering amplitudes. We have recently applied this to pairing in nuclear matter. This project will extend that work to more realistic interactions, by including the effective range and three-body forces. The first step will be to solve the exact RG equation in vacuum to determine the couplings in the bare action. This is closely related to our work on the RG for nuclear forces in ChPT. It will provide the initial conditions on the evolution for a finite density of nucleons. The results will be used to study the properties of nuclear matter.

Title: Improved Mean-Field techniques in two-dimensional materials
Supervisor: Professor Niels Walet Niels.Walet@manchester.ac.uk
QH Skyrmions. One of the most exciting areas in condensed matter physics are the wonderful phenomena occurring in low-dimensional materials. These are often described by simplified mean field techniques that break some of the symmetries. This is fine if we can use periodic boundary conditions, but when a magnetic field is applied to such a system, we have to study a finite portion of these materials, where the physics is rather different. We shall study the fractional quantum Hall effect in the 2D electron gas, and the same effect in graphene, using a family of many body techniques borrowed from nuclear physics and other areas.

Title: Hamiltonian Quantum Field Theory
Supervisor: Professor Niels Walet Niels.Walet@manchester.ac.uk
The techniques of quantum many-body physics have been applied directly to simple quantum field theories, and can be very useful when we try to study excited states in such systems, where many of the current methods based on simulating the imaginary-time action, are less successful. As a challenge, we would like to apply such techniques to real-life field theories, such as quantum chromo-dynamics, combining our work and that of our Australian colleagues who are working on similar problems. Since this problem is rather challenging, it would require a student with a good background in quantum field theory, and a good mathematical ability.

Title: The Dynamics of Multiple Sclerosis
Supervisor: Professor Niels Walet Niels.Walet@manchester.ac.uk
Balo’s sclerosis Multiple sclerosis (MS) is a progressive degenerative disease of central nervous system (CNS), often characterised by short attacks (relapses), with a gradual improvement (remittance) in between. The disease, which involves an autoimmune response where the immune system attacks the myelin sheath protecting nerves, is relatively poorly understood. A few mathematical models have been introduced, especially one for Balo’s sclerosis. Such models take a simplified view of the underlying chemical evolution of the diseased CNS, as well the structure of the CNS.

In this project we shall build further models, with an equally simplified view of the factors playing a role in the disease, but a more realistic structure of the CNS. We shall especially concentrate on modelling the temporal evolution of the disease.
Title: Exact Renormalisation Group and Bose-Einstein Condensates
Supervisor: Professor Niels Walet Niels.Walet@manchester.ac.uk (With Professor Mike Birse)

We have recently applied a new technique, the exact renormalisation group, to the pairing problem that plays such a crucial role in Bose-Einstein condensation. We would like to extend this work to describe better what happens in real BECs. This could take various forms, but we could for instance study simplified models in a trap, or study our calculations with some truncations lifted. The hope would be to gain a better understanding of the many-body phenomena underlying this problem, and the nature of the excitations of such a field that could well be accessible experimentally.
Title: Stochastic dynamics in evolutionary game theory
Supervisor: Dr Tobias Galla Tobias.Galla@manchester.ac.uk

Traditionally the theory of games has revolved around the concept of a Nash equilibrium, these are strategies played by ‘infinitely rational’ players. In the context of biological systems an evolutionary process is more appropriate, individuals are born, compete and interact with others, and they reproduce according to the fitness (payoff) they acquire. In the language of statistical physics these are birth-death processes, subject to intrinsic noise. They can be described with the tools of (advanced) statistical mechanics, such as master and Fokker-Planck equations, path integrals, and even tools from semi-classical physics such as the WKB method.

In this project you will work on several topics in game theory, with a focus on developing a mathematical theory of stochastic evolutionary processes. This will involve analytical calculations and numerical simulations (e.g. using kinetic Monte Carlo methods). This is a fast moving field, and specific questions would have to be agreed in due course. Examples of recent work include fixation and extinction dynamics in switching environments, or the calculation of so-called ‘mixing times’ in mutation-selection systems.

As with all my projects you would read around the project in the first few weeks, and be given 2-3 initial suggestions for potential work. We then pick what excites you most. This could be tuned to your preferences (numerical work/analytical work). Ideally this then leads to a piece of concluded work and a publication roughly 9-12 months into the PhD. Typically, follow-on projects develop from this – these are often ideas that cannot be foreseen from the beginning, they just ‘come up’ along the way. At that point you may also decide to work on a completely different topic in statistical physics and complex systems (past students have done this) – or entirely unexpected new topics come up. Once a second piece of work is concluded we could then try to tackle more risky and exciting projects in the third year! Some of these may not work out, but others will, this is the nature of research and part of the fun after all! Come to talk to me, or send us your application!

Title: Models of cancer evolution
Supervisor: Dr Tobias Galla Tobias.Galla@manchester.ac.uk

Cancer can be interpreted as an evolutionary disease, in the sense that a population of non-cancerous cells develops into a tumor by the acquisition of a series of mutations. This is known as Knudsen’s multi-hit hypothesis. Models of cancer initiation describe populations of cells, which can have different numbers and types of mutations, and who interact with each other in a birth-death or branching process. This defines a stochastic population dynamics. These can be studied with tools from statistical physics, including master equations, generating functions, etc, and by simulations. In recent work with colleagues from the Dana Faber cancer institute in Boston has focused on computing the time it takes an initially healthy population of cells to reach fixation at a stage with multiple mutations. This involves a phenomenon known as ‘stochastic tunnelling’, which we have studied in detail using path-integrals, and the WKB method from semi-classical physics.

You would continue this work, focusing on models with multiple mutations and several parallel reaction pathways. Some of your work could focus on simulating different possible treatment strategies. Other aspects may include the systematic derivation of transport equations in the space of mutations. You may also contribute to an ongoing £1.5 million pound project on uncertainty quantification and mathematical modeling in healthcare.

As with all my projects you would read around the project in the first few weeks, and be given 2-3 initial suggestions for potential work. We then pick what excites you most. This could be tuned to your preferences (numerical work/analytical work). Ideally this then leads to a piece of concluded work and a publication roughly 9-12 months into the PhD. Typically, follow-on projects develop from this – these are often ideas that cannot be foreseen from the beginning, they just ‘come up’ along the way. At that point you may also decide to work on a completely different topic in statistical physics and complex systems (past students have done this) – or entirely unexpected new topics come up. Once a second piece of work is concluded we could then try to tackle more risky and exciting projects in the third year! Some of these may not work out, but others will, this is the nature of research and part of the fun after all! Come to talk to me, or send us your application!
Title: Delay equations and non-Markovian processes in epidemiology and gene regulation
Supervisor: Dr Tobias Galla Tobias.Galla@manchester.ac.uk

Traditionally, many systems in non-equilibrium statistical physics are described in terms of Markov processes. The Markov property indicates that the future evolution of the system only depends on its current state, but not how it got there. This is to say, there is no memory in the system. Many processes in the real world are not of this type, an epidemic is a good example. Recovery is not a Markovian (exponential) process, but happens after a typical recovery time. We have recently developed a theory for effective Gaussian descriptions of such dynamics, based on path integrals and generating functionals. The idea of this project is to investigate this further, and to construct and analyse delay models in the context of epidemics and of gene regulation. Specifically we have a collaboration with colleagues in developmental neuroscience, looking at decision making of cells, and the timing of cell differentiation. In this project you would combine mathematical methods, computer simulations and the modeling of biological processes. You could either work on the more theoretical end (e.g. functional integrals), or in collaboration with biologists, modeling the outcome of real-world lab experiments and/or epidemiological data.

As with all my projects you would read around the project in the first few weeks, and be given 2-3 initial suggestions for potential work. We then pick what excites you most. This could be tuned to your preferences (numerical work/analytical work). Ideally this then leads to a piece of concluded work and a publication roughly 9-12 months into the PhD. Typically, follow-on projects develop from this – these are often ideas that cannot be foreseen from the beginning, they just ‘come up’ along the way. At that point you may also decide to work on a completely different topic in statistical physics and complex systems (past students have done this) – or entirely unexpected new topics come up. Once a second piece of work is concluded we could then try to tackle more risky and exciting projects in the third year! Some of these may not work out, but others will, this is the nature of research and part of the fun after all! Come to talk to me, or send us your application!

Title: Stochastic thermodynamics and information theory in individual-based models
Supervisor: Dr Tobias Galla Tobias.Galla@manchester.ac.uk

In macroscopic systems we never observe violations of the second law of thermodynamics – this is mostly a matter of statistics, we almost always see the ‘mean’ behavior. In small systems statistical fluctuations become relevant, and individual trajectories may show unexpected properties. A systematic theory of this has been developed – the theory of stochastic thermodynamics, defining quantities such as work, heat and entropy not only for ensembles but for individual realisations of stochastic processes out of equilibrium. In particular fluctuation theorems have been derived, re-writing inequalities such as the second law as equalities. A close connection to information theory has been established.

In this project you would apply these ideas to discrete individual-based models, for example in the context of population dynamics, game learning or networked dynamics. You would construct measures of entropy production, deviation from reversibility and complexity. We will study the connection to information theory, in particular in the context of feedback and control. With colleagues in Germany we may explore parallels to quantum information theory, and to exponential families and information geometry in quantum systems.

As with all my projects you would read around the project in the first few weeks, and be given 2-3 initial suggestions for potential work. We then pick what excites you most. This could be tuned to your preferences (numerical work/analytical work). Ideally this then leads to a piece of concluded work and a publication roughly 9-12 months into the PhD. Typically, follow-on projects develop from this – these are often ideas that cannot be foreseen from the beginning, they just ‘come up’ along the way. At that point you may also decide to work on a completely different topic in statistical physics and complex systems (past students have done this) – or entirely unexpected new topics come up. Once a second piece of work is concluded we could then try to tackle more risky and exciting projects in the third year! Some of these may not work out, but others will, this is the nature of research and part of the fun after all! Come to talk to me, or send us your application!

For further information please email: tobias.galla@manchester.ac.uk, visit http://theory.phy.umist.ac.uk/~galla, or come by for a chat (Schuster Building 7.16).
Title: Variational Coupled-cluster Method and its Extension  
Supervisor: Dr Yang Xian Yang.Xian@manchester.ac.uk  
Many interesting physical phenomena are often the results of a combination of dynamic interaction between particles and their quantum mechanical nature. Magnetism, superfluidity and superconductivity are such examples. Quantum many-body theories are techniques physicists developed for calculating such physical properties of the quantum interacting systems from microscopic point of view.

Over the last half century, several quantum many-body theories have been established as most practical, accurate, and widely used. The coupled-cluster method (CCM) is one such technique. The CCM is particularly useful when accurate calculation of the correlation energy is needed. Typical such quantum systems are atoms, small molecules, electron gas, and quantum spin lattice models with classical long-ranged order. However, the CCM has proved to be poor in dealing with strongly correlated quantum systems such as Helium-4 superfluid and high-temperature superconductors.

The variational coupled-cluster method (VCCM) is an extension of the CCM to a variational formalism. Its recent development at Manchester, including its combination with the well-established method of correlated basis functions (CBF), has made it not only a general, practical tool for study of quantum interacting systems but also a technique with potential to deal with strong correlations of many bosons/fermions in liquid phase, thus overcoming the obstacles in the traditional CCM. A PhD program in this area is to further develop the VCCM and its extension, to investigate its relation with other many-body techniques, and to combine the advantages of different techniques for the ultimate unification of several well-established many-body theories.

Title: Microscopic Theory of Dimerised Quantum Spin Systems  
Supervisor: Dr Yang Xian Yang.Xian@manchester.ac.uk  
Quantum antiferromagnetic spin lattices are the direct results of strong Coulomb interaction between localised, spin-half electrons on a lattice and Pauli exclusion principle. These strongly correlated systems often exhibit interesting properties such as dimerization in which each pair of neighboring electrons forms a singlet (spin-zero valence bond) hence total spin of the system is zero. However, such perfect dimerization is often weakened in real systems by the couplings between different such neighboring spin pairs, thus producing configurations with long spin-zero bonds. A loose term, resonating valence bonds (RVB), is often used to describe these different spin configurations due to such couplings.

At Manchester, we have developed a formalism in which composite operators constructed from each spin pairs are used to generate different RVB configurations in a straightforward manner, while remaining in the zero spin sector. A PhD program in this area is to combine this formalism with our expertise in quantum many-body techniques such as the CCM or VCCM as described in the above Program I for accurate calculations of the various physical quantities of the dimerised spin systems, including ground- and excited-state energies, order parameters, etc. This program also involves investigation in real dimerised systems and comparing theoretical calculations with experimental results.

Title: Microscopic Analysis of Gossamer Superconductivity  
Supervisor: Dr Yang Xian Yang.Xian@manchester.ac.uk  
Recently Laughlin at Stanford University has proposed Gossamer superconductivity for the theory of high-temperature superconductors. In particular, his many-electron wave function is a simple product of a correlation factor with the well-known BCS state, similar to our general representation of a many-body wavefunction in our unification of the variational coupled-cluster method (VCCM) and the method of correlated basis functions (CBF) as described in the above Program I.

This PhD program has several objectives. Firstly, by microscopic calculations we determine the density (charge and spin) distribution functions of the many-body wavefunctions as proposed by Laughlin and discuss their physical implications. Secondly, we examine several model Hamiltonians (e.g., with on-site repulsion/attraction etc.) by calculating the ground- and excited-state energies and other physical properties using the Laughlin’s wave function and explore the most likely scenarios. Thirdly, we also use this application as a test ground for our unification of the VCCM and CBF.
If you wish to arrange to meet the research group coordinators below, please contact them directly:

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**Complex Systems and Statistical Physics (Theory)**
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