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Introduction

This booklet is intended to give a flavour of some of the PhD projects available in the School of Physics & Astronomy from September 2015. 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: Velocity fields of planetary nebulae  
Supervisor: Prof Albert Zijlstra  
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Planetary nebulae are the death throes of stars like the Sun. In their final stages, these stars eject much of their mass into space, briefly ionizing their ejecta before fading as a remnant white dwarf. The nebulae can expand at 10-40 km/s. Spectroscopy can be used to measure the velocities; the line profiles broaden and shift because of the velocities. We have acquired some integral field spectra which measure the velocities at every position of the nebula. The project will use these new data to derive complete velocity fields. These will be used to study the evolution of the stars and the origin of the catastrophic mass loss.

Title: Finding all the nearby radio pulsars with the next generation of radio telescopes  
Supervisor: Prof Ben Stappers  
Contact:  ben.stappers@manchester.ac.uk

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. Amongst other things these objects can tell us about the physics of their spin and their extremely strong magnetic fields. They can also be used as tools with which to test the laws of physics including testing theories of gravity and allowing direct detection of gravitational waves. We are currently undertaking a survey for new radio pulsars using a next generation radio telescope called LOFAR. This array of telescopes, located throughout Europe but with its core in the Netherlands, operates at frequencies around 150 MHz and is giving us a completely new view of the radio pulsar population. This project would involve the student becoming involved in the search team and hunting for new pulsars. The new discoveries will be fully characterised by the student in order to understand them, thereby revealing if any of them are useful for further physical tests. The results of the survey will also be used to study the nature of the population of radio pulsars. This is possible as we expect to be able to detect all of them out to a distance of about 2 kiloparsecs. LOFAR pulsar surveys are a stepping stone on the road to searching for pulsars with the Square Kilometre Array.

Title: The Physical Nature of Maser Objects  
Supervisor: Dr Malcolm Gray  
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Astrophysical masers are generated in a variety of sources, varying in scale from comets in our own Solar System, to kiloparsec scale zones in the cores of certain active galaxies. A common feature of most maser sources is that the emitting regions are observed as a set of discrete features, some of which are resolved at VLBI resolution, that are distributed across all, or only part, of a much larger source zone. The purpose of the project is to attempt to determine, through analysis of observational data and computer modelling, what the physical nature of the maser features is. There could be several answers, depending on the type of source. Are comets the hosts of masers in star-forming regions, as they are in our Solar System, for example? What is it that makes the gas in maser features able to generate maser radiation, whilst presumably similar gas near to them apparently cannot? Recent data from space VLBI (baseline of 3 Earth diameters) has revealed structure smaller than 1 million km in water masers, helping to eliminate some possibilities.

Studying anomalous microwave emission – near and far  
Supervisor: Dr Clive Dickinson  
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Anomalous Microwave Emission (AME) is an excess of diffuse Galactic emission observed at frequencies ~10-100 GHz. It cannot be explained by the usual processes related to synchrotron, free-free, cosmic microwave background (CMB) and thermal dust emission. Initially discovered in 1997, the AME has been observed by many experiments, but yet still little is known about this enigmatic component of the interstellar medium (ISM). It is also of importance as a foreground to CMB experiments. The best explanation for the AME is electric dipole radiation from small rapidly spinning dust grains in the ISM, or "spinning dust emission". This can naturally explain the spectral shape
observed and can readily produce the required amounts of radiation. However, many mysteries still exist around AME since it is difficult to separate from the other components and high frequency (>10 GHz) are difficult to make by ground-based experiments. Jodrell Bank is a world-leader in both measuring and understanding diffuse Galactic foregrounds, including CMB component separation. We are involved in many CMB and foreground experiments including C-BASS and QUIJOTE. We also lead the Galactic science programme for the ESA Planck space mission which has led to a definitive identification of the spinning dust grains for 2 nearby molecular clouds. The student will study the AME in much more detail, using the latest instruments (e.g. AMI, GBT, JVLA, Planck, ALMA) that can image diffuse Galactic emission as well as the latest surveys such as C-BASS and QUIJOTE, which we have privileged access to. Particular areas of interest include constraining the polarisation of AME (which may have a strong impact on future CMB polarisation data), the contribution of magnetic dust emission, and detecting AME in nearby galaxies. The student will become familiar with single-dish and radio interferometry data analysis, as well multi-frequency imaging and spectral fitting. The research will be of importance for future CMB experiments as well as interstellar medium astrophysics.

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: i) The development of automated classification schemes for cataloguing different classes of variable and transient objects. ii) 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. iii) 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. iv) 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. It is also anticipated that the student will present their work both at conferences and at VVV collaboration meetings in Europe and in Chile.

Title: Design and development of very Low Noise Amplifiers with direct electron channel cooling
Supervisor: Prof Lucio Piccirillo lucio.piccirillo@manchester.ac.uk

Low noise amplifiers (LNAs) are one of the most important components to be commonly found in the radio receivers that are used in radio astronomy. Their importance comes from the fact that by providing gain and by being one of the first components in the receiver chain their performance can dominate the overall sensitivity of the receiver. Generally this performance can be improved by nearly an order of magnitude by cooling the LNA in cryostats and this was typically done to 20K. However, recent experimental research at the University of Manchester has shown that a further improvement in performance can be achieved by cooling to temperatures below 4K. However, although the relationship between noise temperature and physical temperature is almost linear above 20K, it becomes quadratic below 20K. Monte Carlo simulations at the Chalmers University of Technology (Sweden) have shown that this is due to insufficient cooling of the electron channel, which remains substantially hotter than the rest of the transistor and the LNA body. In this project the student will be involved in the design, manufacturing and testing of a new classes of LNA that hope to solve this hot electron problem. It will use physical cooling of the channel by immersing the transistor and its support components in a pool of liquid helium. The student will learn the theory and practise of low noise amplification, microwave measurements at cryogenic temperatures, very low temperature cryogenic techniques and nano-fabrication techniques. At the end of this project, the student will have acquired
many useful skills like the usage of rotary and turbo pumps, high vacuum techniques, electronics, cryogenic techniques, data handling, theory and practise of microwave engineering. These skills are quite common in a variety of experimental fields from particle physics to solid-state physics and astrophysics. There will of course also be the opportunity to travel and present work at a variety of international conferences.

Title: A polarized view of the strongest magnets in the Universe: Radio Pulsars  
Supervisor: Prof Patrick Weltevrede Patrick.weltevrede@manchester.ac.uk
The defining characteristic of radio pulsars is their periodic pulses which can be detected by radio telescopes. The stars that generate these radio pulses are neutron stars, super dense stars with a mass of ~1.5 solar masses and a radius of only ~10 km. Radio pulsars accelerate particles to relativistic speeds which then move along the field lines of their extremely strong magnetic fields. As the beam of radio emission that these particles generates sweeps across the Earth (like a "light house") we expect it to describe a specific change in polarisation which can tell us details of the geometry of the pulsar, including the location of its rotation and magnetic axes, however it turns out to be more complicated than this and is giving us a glimpse of the electrodynamics of the emission process itself. In this project you will investigate the polarization properties of pulsars. You will start with data from the Lovell radio telescope at Jodrell Bank Observatory, making full use of its new polarization capability. This will be supplemented with data from the Parkes telescope in Australia and LOFAR, a large next generation array of radio telescopes operating at very low frequencies. This project involves data analysis and building a computer model describing the physics of the pulsar magnetosphere, which will include various relativistic effects. The model will be used to provide a self-consistent picture which can describe your data, for which the currently oversimplified "standard" model fails.

Title: Design and realization of a wide-band sub quantum noise parametric amplifier (paramp) based on the linear kinetic inductance property of superconductors  
Supervisor: Prof Lucio Piccirillo lucio.piccirillo@manchester.ac.uk
Low noise amplifiers have for many years been a crucial component in many radio observatories, and our ability to further our understanding of the universe has gone hand in hand with our ability to improve the noise performance of LNAs. However, the noise performance of these transistor based LNAs is fundamentally limited by quantum mechanics, the infamous quantum noise limit, hν/k. However, the non-linear kinetic inductance of superconductors potentially allows this limit to be circumvented through a technique known as noise squeezing, which was demonstrated using a very narrow bandwidth Josephson Junction in the 1980's. More recently a paramp with a bandwidth >20% was built, thus opening up this amplification technology for use by the astronomy community. This project will cover the design, manufacturing and testing of a new parametric amplifier and as the technology is still in its infancy there will be plenty of opportunity to develop both the theoretical and practical sides of the paramp's design. For example by developing an understanding of the amplification mechanisms or investigating the most suitable material and layout for the planar circuit. Depending on the level of progress and interests of the student it is envisaged that the project will conclude by integrating the amplifier into a prototype instrument.

Title: Galactic foregrounds and their relevance to the Cosmic Microwave Background  
Supervisor: Prof Richard Davis richard.j.davis@manchester.ac.uk
As has been shown the BICEP work is controlled by our understanding of the Galactic Foregrounds and particularly in polarisation. We are currently studying the synchrotron radiation with the CBASS project and free-free emission with Hbeta off the Plane and RRLs on the Plane. Dust comes in at least two forms of thermal and anomalous forms and is studied with high frequencies for thermal dust and Ka band for the anomalous dust.
Title: Design and construction of a continuous miniature dilution refrigerator for POLARBEAR2 and SIMONS array
Supervisor: Prof Lucio Piccirillo lucio.piccirillo@manchester.ac.uk

The next frontier in Cosmic Microwave Background research is the detection of the B-modes in the CMB Polarization. Depending on the angular scale of observations, many interesting phenomena can be discovered: for example, a large angular scale detection of B-modes will constitute an observation of the primordial background of Gravitational Waves with information about the very first moments of existence of our Universe. POLARBEAR is a Cosmic Microwave Background polarization experiment sited at high altitude in the Atacama Desert. The goal is to detect CMB B-modes and use them to investigate the origin and evolution of the Universe and to understand physics and cosmology beyond our Standard Model. Inflationary theories are currently the best framework we have to explain several aspects of the Universe today. They predict that the early Universe underwent a phase of exponential expansion during which a background of gravitational waves was produced. Those gravitational waves will then produce a primordial B-mode signal at the time of recombination. An inflationary phase would have occurred at such high energy density that there is no hope of studying the phenomena in any accelerator that could be built on earth in any foreseeable future. POLARBEAR, however, will be able to see the direct signature of inflation through CMB polarization, and will potentially be able to investigate physics that occurs at energies where all the forces of nature are unified. The evolution of the universe is based on the idea of gravitational instability, whereby initial tiny fluctuations in the density of the Universe grew under the influence of gravity to form the large-scale gravitational structures we see around us today. These structures bend the trajectories of CMB photons through gravitational lensing, distorting its primordial polarization and converting E-modes into B-modes. Imaging the lensing-generated B-modes, POLARBEAR will be able to shed light on all the components of the Universe influencing structure formation, such as neutrino mass and dark energy. The student will be involved in all phases of the design and construction of the sub-K cryogenics for the POLARBEAR2 and SIMONS array receivers.

Title: Computational Models of Astrophysical Masers
Supervisor: Dr Malcolm Gray Malcolm.gray@manchester.ac.uk

New interferometric instruments such as ALMA have enabled us to produce detailed images of masers in the 100-GHz to 1-THz region for the first time. Single-dish instruments, such as the airborne SOFIA, are opening up an observing window above 1-THz. We need computational models of methanol and water masers in star-forming regions, evolved stars and external galaxies to test our understanding of these new observations. The project involves two types of modelling: The first type is parameter-space searching, where the non-LTE radiative transfer problem is solved in a fairly straightforward model many times over a wide range of physical conditions. This allows us to identify the optimum conditions for amplification in the observed maser lines, and to select transitions for new observations by SOFIA. The second type of model involves more sophisticated simulation of specific sources, for example the red supergiant star VY CMa, which has now been imaged by ALMA in the 321, 325 and 658GHz water maser lines.

Title: Detection of Baryon Acoustic Oscillations via HI intensity mapping
Supervisor: Dr Clive Dickinson clive.dickinson@manchester.ac.uk

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 using Integrated Neutral Gas Observations), that has the possibility of detecting BAOs (Battye et al. 2013). We are currently pursuing funding and site locations for the 40m dish required for BINGO. In the meantime, much preparation is required both on the instrumentation side, and on the analysis side. In particular, we need to make detailed simulations of BINGO data, taking into account the bright foregrounds and also instrumental systematic effects that could be problematic. These issues will be critical to the success of the experiment. We are also affiliated with other HI intensity mapping experiments including interferometric arrays that could be the focus of the project depending
on progress with both experiments. The student will become a key member of the BINGO team and cosmology group at Manchester. Depending on your interest, and background, you will work with the BINGO team to develop simulation tools, component separation and analysis techniques, and will be involved in the design and testing of instrumentation for BINGO (e.g. testing of receivers, programming of digital backends etc.). An important aspect will be dealing with foreground contamination from our Galaxy and extragalactic radio sources.

Title: Very High Frequency Resolution Observations of Masers
Supervisor: Dr Malcolm Gray Malcolm.gray@manchester.ac.uk

A new generation of radio interferometers, including e-MERLIN, based at Jodrell Bank, and the JVLA, has correlators that are highly flexible in the arrangement of the frequency channels, of which there are typically tens of thousands. These instruments have the capability to observe spectral lines with a resolution as fine as 1Hz, or slightly better. In the case of maser lines, such resolution offers the possibility of investigating fundamentals of maser physics. Do astrophysical masers have radiation statistics that depart from the gaussian form that holds for thermal radiation, for example? In the case of highly-evolved giant stars, the high resolution may be used to detect correlated frequency shifts between a number of separate maser features, enabling us to detect the passage of acoustic and MHD waves through the circumstellar envelope: a form of circumstellar seismology that has not been previously attempted. e-MERLIN time has already been awarded to obtain the first data for this project.

Title: Exoplanet studies through gravitational microlensing
Supervisor: Dr Eamonn Kerins eamonn.kerins@manchester.ac.uk

The gravitational microlensing effect is being used to discover low-mass exoplanets at greater host distances than possible with more familiar techniques such as the transit or radial velocity methods. Such planets are commonly referred to as cool exoplanets. Microlensing involves the transient brightening of background stars in the inner Galaxy by foreground stars or planets. A PhD project is available to work on one or more topics in this area. The topics include: i) To provide better real-time constraints on exoplanet masses inferred from exoplanet lightcurves by constructing detailed prior models of their spatial distribution and kinematics within the Galaxy. This modelling would form part of a real-time exoplanet detection system and would be used potentially to inform and update the observing strategy to ensure optimal data coverage. ii) To understand how future large microlensing datasets might help to constrain planet formation theory. Exoplanets discovered through microlensing tend to occur at host separations where formation theories such as the core-accretion model predict the bulk of planet formation to occur. Therefore their statistics can be used to constrain these theories. iii) To consider ultra-rare microlensing signals which might become discoverable through the advent of huge microlensing datasets such as now coming on line through ground-based surveys (MOA-2, OGLE-IV, KMTNet) and soon with space-based surveys (Euclid and/or WFIRST). Also to consider follow-up or simultaneous observing possibilities with next-gen facilities such as LSST and/or E-ELT.
Title: Neutron Scattering Studies of Structure and Dynamics of Water around DNA, Proteins and Biopolymers  
Supervisor: Dr Ji-Chen Li  

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  

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  

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  

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. 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: The Spatial Distribution of Transport Networks in Live Cells
Supervisors: Dr. T.A.Waigh¹, Prof. V.Allan², Prof. Philip Woodman³
Contact: Dr Tom Waigh t.a.waigh@manchester.ac.uk
¹ Biological Physics, School of Physics and Astronomy, ² Life Sciences, University of Manchester.
Live cells use a range of transport networks to move cargos around the intracellular environment that
are vital for the correct functioning of the cellular metabolism [1-6]. Predominantly the motion of
intracellular traffic is determined by the motor proteins dynein/kinesin and myosin that walk on
microtubules and actin respectively. Recent advances in optical microscopy (wave guide coupled LEDs
and fast CMOS cameras) enable the motion of intracellular cargos to be followed at sub 0.1 millisecond
time scales with nanometer resolution. Crucially, this allows the stepping behaviour of single motor
proteins to be followed inside live cells (A.Harrison et al, unpublished data, 8 nm steps with millisecond
wait times).
The information content of live cell movies is now so high that intracellular motility can be spatially
resolved across whole cells with nanometre resolution. Thousands of organelles can be followed in a
single cell concurrently, and their transport pathways inferred from a subsequent statistical analysis.
Hypotheses based on modern physical ideas of network dynamics can thus be tested. For example, do
centrosomes (the organizing centres of microtubule networks) act as network hubs through which
most of the high speed transport of organelle traffic is directed? Are there secondary hubs, and if so,
what defines them? Does the network architecture have small world properties? [2]
Live cell imaging of gold labelled endosomes and lysosomes will be performed at high speeds using
optical microscopy. Subsequently the organelles will be tracked using a version of our
PolyParticleTracker MatLab software (see figure) adapted for a parallel computer architecture [4]. A
wide range of statistical tools have been developed to analyze this data such as Kalman filters for
motor protein step sizes and waiting time distributions, mean square displacements, angular
correlations, first passage probability distributions, segmentation analysis etc [1-5]. Super resolution
fluorescence microscopy (STORM/PALM) will then be used to directly image the underlying
microtubule network in the cell with ~20 nm resolution. Statistical models will be created to describe the observed network dynamics. Finally we will investigate the transport networks of lysosomes and early endosomes to observe common features in their organization.

References

Coherent X-ray Imaging for Soft Matter and Biology
Dr. T.A.Waigh¹, Prof. C.Rau²

Contact: Dr Tom Waigh t.a.waigh@manchester.ac.uk

¹ Biological Physics, School of Physics and Astronomy, Manchester. ² Diamond Light Source, Oxford.

Often there are bottlenecks in developing new large scale facility techniques to make them accessible to a large user community. The coherence beam line ‘I13’ at the Diamond Synchrotron provides the most coherent hard X-ray radiation in the world (the transverse coherence length is currently better than that from Free Electron Lasers and it profits from being a continuous source). Such radiation is extremely useful for solving the phase problem and can provide lens-less imaging of nanostructured materials. However a current bottleneck is to provide the community with the necessary experience in the X-ray optical physics and data analysis tools to enable routine use of the new imaging methods. It is a particular problem, since the methods constitute a paradigm shift for many users. They can no longer use the reciprocal space techniques encountered with standard incoherent X-ray non-crystalline diffraction methods and new iterative phase retrieval algorithms are required instead.

We were the first user group to work on the coherence beam line at the Diamond synchrotron (November, 2011). We have made steady progress with developing the equipment and have reduced the resolution limit on images of polystyrene coated superparamagnetic spheres down to 100 nm (March, 2012) using the ptychography technique, which also provides quantitative phase imaging (allows quantitative refractive indices to be measured and thus provides rich additional structural information). We expect further improvements in resolution when improved focusing is implemented on the I13 beam line with Kirkpatrick Baez mirrors (currently no focusing was used to achieve the 100 nm limit).

The student will continue with the development of coherent X-ray imaging techniques such as ptychography on the I13 beam line [1,2]. Initial developments will focus on improving the resolution of images from superparamagnetic colloids beyond the current 100 nm resolution record. New iterative phase retrieval software based on freeware algorithms of the Keith Nugent group will be developed [3]. Improvements in such software are crucial to optimize the performance of lensless imaging systems. Additional applications for the imaging techniques will then be explored in starch (mankind’s principle foodstuff) [4], nacre (ultra-tough nano composites) and yeast cells (model radiation resistant eukaryotic cells). These systems all have important unsolved structural questions at the ~50 nm length scale e.g. starch is thought to contain lamellar super-helices [4].
References

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 electro-physiologists 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)
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/)

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.

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.
Nonlinear Physics
Research in nonlinear physics focuses on the intricate behaviour of complex systems from the dynamics of fluid flows to the deformation of elastic materials, encompassing both curiosity-driven and industrially-relevant phenomena. Our laboratory-based research into complex systems is a creative activity as it often reveals unexpected phenomena, whose 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: Electrowetting on graphite and graphene
Supervisors: Prof Anne Juel (Nonlinear Physics) and Prof Robert Dryfe (Chemistry)
Contact: anne.juel@manchester.ac.uk
Electrowetting describes the change in solid-electrolyte contact angle due to an applied potential difference between the electrolyte and the solid substrate. It has become one of the most widely used tools for manipulating tiny amounts of liquids on surfaces, with emergent applications including liquid microlenses and clinical diagnostics. To date most electrowetting applications have been developed on dielectric substrates, but considerable power savings could be achieved by overcoming the difficulties of electrowetting when the substrate is conductive.

This project will focus on electrowetting on graphite and graphene deposited electrochemically on solid substrates. Preliminary experiments suggest significant differences with electrowetting phenomena on a dielectric substrate, which will be explored by allying a quantitative experimental study of electrowetting with the development of novel theoretical models. This multi-pronged approach will enable to shed light on the role of substrate defects and surface chemistry, and hence contribute to the topical discussion of wetting on graphene.

Title: Plastic deformation of polymer ribbons
Supervisor: Prof Anne Juel anne.juel@manchester.ac.uk
Ribbons curl when stretched over a blade as will be familiar to anyone who has wrapped presents. The creation of residual curvature arises in many applications from the life sciences to advanced materials. When a ribbon that exhibits a yield stress is pulled under tension over a sharp blade, differential stretching occurs that may locally exceed plastic deformation, and thus result in the creation of residual curvature of the ribbon. The aim of the project is to investigate the mechanics of curling and plastic deformation for experimental configurations of increasing complexity. These will include chiral systems and the study of buckling cascades generated by non-uniform blade geometry.

Title: Fluidisation of yield stress droplets under vibration
Supervisor: Prof Anne Juel anne.juel@manchester.ac.uk
Vibration is commonly used to fluidise materials that may only flow above an applied yield stress, such as molten chocolate, thickening agents, mucus in the lung or dense suspensions relevant to industrial processes (such as wood fibres or multiphase plaster mixtures). By contrast with so-called simple fluids like air or water, these non-Newtonian fluids also exhibit viscosities that depend on the rate of strain applied to them. Because of their complexity, the flow behaviour under periodic excitation of these yield-stress fluids is yet to be established. Preliminary investigations suggest apparently contradictory behaviour: the vibration of thin films of dense suspensions can result in its break-up into multiple droplets, while similar excitation will allow a drop of chocolate to spread. The aim of this project is to gain insight into the effects of vertical, horizontal and orbital vibration on a variety of free-surface fluid configuration, using a combination of experimental and numerical techniques.
If you try pouring chocolate on a cake or strawberry, you will probably observe that the leading edge of the chocolate layer becomes unstable and splits into series of rivulets (see the image). This phenomenon is called viscous fingering, and it typically a nuisance in any industrial process aimed at uniform coating of surfaces. However, introducing elastic boundaries can sometimes help to control the coating process by modifying the interfacial fingering instability, for example between two coating rolls. This project will study the effects of fluid-structure interaction on the thin film flow on a sphere, including the onset of viscous fingering at the leading edge of the flow. A detailed experimental investigation of the phenomenon will be complemented with a theoretical study to explore if the fluid-structure interaction can be used to suppress the fingering instability on a spherical object.

This project will focus on wrinkling in elastic capsules, which are thin spherical elastic shells that enclose fluid volumes. Available studies suggest a wide variety of patterns, but a comprehensive description and understanding of the phenomenon is still lacking. Furthermore, it is believed that wrinkling can be used to infer the mechanical properties of the wrinkled objects. These questions will be addressed by uniquely combining a quantitative experimental study with development of novel theoretical models.

Images of wrinkling in elastic capsules: poking inflated beach ball (left hand side) and a biopolymeric capsule squeezing through a constriction in a channel (right hand side).
Liquid Crystal Physics
http://esi.ph.man.ac.uk/LC_Webpage/liquid_crystals/Liquid_Crystal_Home_Page.html

Title: Graphene oxide – liquid crystal dispersions
Supervisor: Ingo Dierking ingo.dierking@manchester.ac.uk
Graphene and related materials have generated enormous interest in recent years, due to their outstanding physical properties. Liquid crystals on the other hand are soft, self-organized, materials with tremendous impact on display applications and other devices in the field of optical materials and sensors. Furthermore, both classes of materials lend themselves not only to novel and advanced applications, but also to investigations of fundamental physical behaviour. Their research is highly multidisciplinary, covering the fields of physics, chemistry, material science, engineering, all the way to the life sciences and biology. It is thus of paramount interest to combine their extraordinary properties to significantly improve and produce novel functional materials for self-organization and self-assembly. The research program will consist of two strands, (i) the formation of lyotropic liquid crystal phases by dispersing graphene oxide (GO) in suitable isotropic solvents, and (ii) the study of the effect of graphene oxide on the electric and electro-optic properties of thermotropic liquid crystal phases.
Towards task (i), dispersions with varying GO content will be prepared, and the phase diagram determined in detail. The size distribution of the dispersed GO flakes will be determined, and their effects investigated in different size regimes, 10-500nm, 1-2µm and >10µm. The phase diagrams determined by polarizing microscopy will be confirmed via calorimetric measurements in collaboration with the Department of Chemistry. An important factor is the degree of self-organization, which will be determined as a function of GO content and temperature by wide angle x-ray scattering (WAXS). This will also confirm the nature of the observed liquid crystal phase. The material characterization will be completed by Zeta potential measurements to determine the surface charge, and dielectric spectroscopy to investigate possible rotational relaxations of the GO flakes.
For task (ii) we will employ commercial thermotropic nematic liquid crystals, such as 5CB, to determine the effects of GO flakes on phase stability and order parameter at varying concentration. Electric and electro-optic properties will be studied for the dispersions, including conductivity, response time, threshold voltage, effective viscosity and dielectric spectroscopy. This will also provide insights about possible relaxation phenomena of the GO flakes. The investigations will then be extended towards ferroelectric phases, where response times, viscosity polarization, tilt angle and dielectric spectrometry will be performed to study the influence of GO flakes.

Title: Ferrofluids in liquid crystals
Supervisor: Ingo Dierking ingo.dierking@manchester.ac.uk
Ferrofluids are dispersions of magnetic rod-like particles within an isotropic liquid, generally water. When brought into a magnetic field, ferrofluids exhibit a wealth of structural and pattern formations, such as regular arrays of spikes and the like. Liquid crystals on the other hand are organic fluids which are generally anisotropic, showing structural self-organization already at the molecular scale. Molecules that form liquid crystal phases are shape-anisotropic, most often also rod-like. Liquid crystals and water based droplets are immiscible. On the other hand, the droplets induce a defect structure in the liquid crystal molecular field, which causes the droplets to attract and self-organize in chains.
Starting the project, we will characterize the liquid crystals with respect to their phases, isotropic, nematic and fluid smectic, by polarizing microscopy. We will then attempt to produce the ferrofluid-liquid crystal dispersions, most likely by use of a surfactant at different concentration, and characterize these dispersions with respect to droplet size and shape for the different phases. One aspect will include the time development of droplet aggregates and the determination of respective scaling laws. At last, magnetic field effects will be characterized and compared between the different dispersions. Differences in pattern formation will be noted as the dispersions are systematically varied in composition.
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.

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.

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.
The introduction of the spin-orbit interaction by Maier and Jensen led to an understanding of the observed shell gaps and magic numbers in near-stable nuclei. The appearance of these ideas in undergraduate textbooks gives the impression of solidity and permanence to the well-known sequence of magic numbers. Recent observations, however, have challenged this basic assumption by suggesting that the sequence of single-particle states observed near stability is actually quite fragile; studies of nuclei far from the line of β stability have begun to indicate that the familiar shell gaps do not persist in exotic systems. Instead, shifts in the sequence of single-particle levels conspire to give gaps 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.

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...
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.

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: Limits to Nuclear Binding using Isomer Tagging  
Supervisor: Dr David Cullen Dave.Cullen@manchester.ac.uk  
This project will research the limits to nuclear binding by studying the high-K isomeric, or long-lived, states in the proton-rich mass 130-140 region of the nuclear chart. These exotic nuclei lie right at the very limits of existence and cannot be made to accept an additional proton. This research work has provided the first observation of new nuclear isotopes, $^{144}$Ho, $^{140}$Dy, all of which were found by students during their PhD work. This new information is published in leading nuclear physics journals.

The main focus of this work has been to develop a technique called “Recoil-Isomer Tagging” at the University of Jyväskylä, Finland. The technique combines two arrays of gamma-ray spectrometers arrays via a gas-filled separator RITU to study the prompt feeding and delayed decay of the isomeric states. The technique has proven very selective at picking out weakly bound nuclei near the limits of nuclear binding. We recently applied a variant of this technique at Argonne National Laboratory, USA which allowed the first information to be found for the drip-line nucleus $^{140}$Dy.

In this experiment we identified the ground-state rotational band of a proton drip-line nucleus which gave important information on its deformation. No information was known about this nucleus prior to this experiment. Since that time we have developed this technique by adding a new Multi-Wire Proportional Counter which allows the experiments to collect data at a higher rate than was previously possible, see http://personalpages.manchester.ac.uk/staff/dave.cullen/mwpc_page.pdf This means that other nuclei which are further from stability are now available to be studied for the first time.

We have just been awarded a new grant (2009-11) to develop a new detector which will allow the lifetimes of unbound nuclear states to be deduced for the first time. The development of this new detector and the first data taken with it will form part of a student PhD project which will be performed at the University of Jyväskylä, Finland. More details of this project can be found at http://personalpages.manchester.ac.uk/staff/dave.cullen/phd_proj_2009_jyv.pdf

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:
Dr Alex Oh alexander.oh@manchester.ac.uk
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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.

One of the first proton-proton collision events at an energy of 13 TeV following the 2015 restart of the Large Hadron Collider

Title: Matter-antimatter differences at LHCb
Main Contact: Dr Marco Gersabeck marco.gersabeck@manchester.ac.uk
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Prof George Laferty George.laferty@manchester.ac.uk
Dr Rob Abbleby rob.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, 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
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Dr Marco Gersabeck marco.gersabeck@manchester.ac.uk
Prof George Laferty George.laferty@manchester.ac.uk
Dr Rob Abbleby rob.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
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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.
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.
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: Using QCD to investigate new physics phenomena at the LHC  
Contact: Prof Jeff Forshaw jeff.forshaw@manchester.ac.uk  
The LHC will explore new phenomena, such as Higgs boson physics and possibly exotica associated with supersymmetry or extra dimensional theories. The key challenge will be to extract the maximum amount of physics from the data and this project is concerned with developing the theoretical understanding of QCD to such a level that it can be used as a tool to study new physics processes. QCD is ever present at the LHC - because the colliding protons interact strongly with each other - and leads to the production of quarks and gluons. Crucially the way those quarks and gluons are emitted is correlated to whatever else is happening in the collision. Manchester particle physicists are experts in understanding and exploiting these correlations. One example is the way one can measure the couplings of Higgs bosons to W/Z and gluons by looking at the associated gluon radiation (there is less radiation in events where the Higgs is produced via the fusion of two W particles than in events where it is produced via the fusion of two gluons).

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.
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.
Title: Developments of the nsFFAg  
Supervisor: Dr Hywel Owen Hywel.Owen@manchester.ac.uk

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
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.

Photograph taken with NIR illumination. The skin of the frog on the right contains pterorhodin and its reflection closely matches that of the leaf.
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/
Title: Surface properties of quantum dots for next generation solar cells  
Supervisor: Professor Wendy Flavell  
Wendy.Flavell@manchester.ac.uk

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).

The THz time domain spectrometer designed and built in the PSI in Manchester

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, we need 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. THz radiation is a very sensitive probe of these photoexcited carriers, so we will also use our THz time domain spectrometer to study a process known as ‘carrier multiplication’ – where an incident photon of sufficient energy can produce more than one electron-hole pair, potentially improving solar cell efficiency.
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 CO₂, 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 by the atoms 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 techniques can further cool atoms to temperatures only a few nK above absolute zero. These atoms make up new states of matter, which are studied for their quantum effects.

The atom cooling and trapping apparatus in Manchester, showing the source chamber (right), Zeeman slower (centre) and trapping chamber (left) where collision experiments are carried out.

In this project, atom cooling and trapping experiments are undertaken using a high intensity cold atom beam source developed in Manchester, as shown above. Experiments include electron impact collision studies from cold atoms, as well as the study of the fundamental properties of the cold atoms which
are produced. A new type of atom trap (the AC-MOT) was recently invented in Manchester that uses sound reinforcement amplifiers to drive current through the trapping coils, the polarization of the six molasses laser beams being adjusted in synchronicity with the audio signal. This new type of atom trap can be switched on and off more than 300 times faster than the more conventional DC-MOT, allowing new experiments to be conducted. These include the study of electron impact excitation and ionization, where the unique nature of cold atoms allows new high precision experiments to be conducted. We can either exploit the very low momentum of the targets to accurately define an ionizing collision, or we can use this to ensure we can laser-excite the atoms to highly excited Rydberg states prior to super-elastic scattering of an electron from these targets. These excited atoms can be placed in a highly elliptical state, where the electron orbits around the nucleus in a way similar to planets orbit around the sun. By choosing different atomic states via the laser interaction we can then precisely probe the interface between quantum and classical models of the atom. These projects are carried out in the new laboratories in the Photon Science Institute, using the state of the art laser systems located there.

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

Electron spectrometers for ionization and excitation studies of laser prepared targets. In (a), two detectors (A1, 2) are used to detect electrons from the interaction (an e, 2e) process. In (b), a Magnetic Angle Changing (MAC) device controls the direction of incident and super-elastically scattered electrons from laser prepared targets.

In these projects a laser field is used to prepare atomic or molecular targets in an excited state prior to electron impact. The incident electron of well controlled momentum ionizes the laser excited target, excites the target to a higher level or may super-elastically scatter from the target (i.e. the electron gains energy as the target relaxes back to the ground state). In each process the state of the target is controlled by the laser beam, allowing the ‘shape’ or orientation of the target to be modified prior to the collision.

In ionization experiments (as shown in figure (a)) an incident electron scatters from and ionizes the target, leading to two electrons in the final state. These electrons are detected and time-correlated so that it then becomes possible to determine the reaction from individual targets, and to measure the ionization probability as a function of the scattering angle for comparison to theory. New experiments are planned where the target is either an atom excited by a CW laser, or a molecule which is aligned adiabatically by a powerful pulsed laser. Both types of target have never been studied before, and so we work in close collaboration with theoreticians in the USA and Australia who model these complex interactions using sophisticated quantum theories.

In the excitation experiments (figure (b)) we adopt a time reversal approach to reveal highly precise information about the scattering process. In these experiments a laser defines the ‘shape’ of the electron charge cloud prior to electron impact, and we measure the rate of super-elastically scattered electrons as a function of the scattering angle and target shape. In this way experiments can be conducted many thousands of times faster than is possible using conventional coincidence techniques.
New experiments are underway which includes 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 50. In this way we will study atoms of technological and scientific importance, including Zn which is being considered as a replacement for mercury in low energy lighting, and Gold and Silver which are important due to their electronic structure. Results from these experiments will then be compared to state of the art calculations produced by theoretical groups in Canada, Australia and the USA. This work was chosen as a ‘research highlight of 2008’ by the Institute of Physics, and was also published in *Europhysics News*.

**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 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, efficiency and powerful sources of terahertz radiation and the fundamental properties of GaN semiconductors make this a tantalising possibility.

In this project the student will use the state-of-the-art laser facilities within the Photon Science Institute to reveal the physics that governs the properties of this remarkable materials system and optimise GaN-based quantum well structures for terahertz sources and detectors. This work will 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.
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 gluons, 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).

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 renormalisation 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 $^3$H and $^3$He. In combination with the results of the preceeding project, this will allow extractions of neutron polarisabilities from Compton scattering experiments on $^3$He, 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 be very useful in particle and condensed-matter physics. This suppresses 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

Baló’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.
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.
Statistical Physics and Complex Systems

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 dermization in which each pair of neighboring electrons forms a spin singlet (spin-zero valence bond) hence total spin of the systems 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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