School of Physics and Astronomy

Postgraduate Project Booklet 2018/19

Contents

ASTROPHYSICS

(THE JODRELL BANK CENTRE FOR ASTROPHYSICS)

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

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

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

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

Research themes

Cosmology:

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

Sun, stars and galaxies:

- Solar plasmas, including understanding solar corona heating, magnetic reconnection, and the origin of high-energy charged particles in solar flares;
- Astrophysical magnetism, masers and radiative transfer;
- Star and planet formation, stellar evolution, circumstellar and interstellar

processes;

- Galactic interactions and clusters;
- Galaxies and active galactic nuclei;
- Multi-wavelength surveys.

Pulsars and time-domain astrophysics:

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

Project areas

Below are some examples of research areas and projects on offer for PhD study at JBCA in 2018. This is a non-exhaustive list and you are encouraged to look at the JBCA PhD projects webpage for further examples: . http://www.jodrellbank.manchester.ac.uk/study/postgraduate/phd-projects/ Please also feel free to make direct contact with members of JBCA staff to find out about projects they may be offering.

Cosmic Microwave Background (CMB) and weak gravitational lensing observations

Prof. Michael Brown (m.l.brown@manchester.ac.uk)

Prof. Brown's group works in the areas of Cosmic Microwave Background (CMB) and weak gravitational lensing observations. They are heavily involved with The Simons Observatory, a next generation CMB telescope to be located in Chile. The Simons Observatory's primary goal is to detect a very specific pattern in the polarisation of the CMB radiation (termed "B-modes") which will provide a unique observational window into the very early Universe and physics at GUT-scale energies. The JBCA cosmology group is also leading the SuperCLASS survey on the e-MERLIN and Lovell telescopes located at Jodrell Bank. The primary goal of SuperCLASS is to develop the emerging field of weak lensing using radio telescopes and Brown's group are leading this work for SuperCLASS. In particular, we are pioneering new weak lensing analysis techniques for radio interferometers and for measuring optical-radio cross-correlation weak lensing signals. Ultimately these techniques will be used to help understand the physics of Dark Energy using data from the Square Kilometre Array, both on its own and in cross-correlation with future optical surveys using the LSST and Euclid satellite.

Projects:

- Constraining the physics of the early Universe with the Simons Observatory
- Understanding Dark Energy with the SuperCLASS and SKA weak lensing surveys.

Modelling and simulation of magnetic reconnection, flares and coronal heating

Prof. Philippa Browning (philippa.browning@manchester.ac.uk)

Research in solar plasma physics is concerned with modelling the complex interactions of magnetic field with plasma in the solar atmosphere, in the context of transformational new space and ground-based observations of our nearest star. There are synergies with magnetically-confined fusion plasmas, and there are opportunities for PhDs exploring both fusion and solar applications, in collaboration with Culham Centre for Fusion Energy. We are also investigating physical processes underlying variable radio emission in young stars, building on understanding of solar flares.

A major unsolved problem is to explain why the solar coronal temperature is over a million degrees Kelvin. Coronal heating likely results from dissipation of stored magnetic energy, but the details remain controversial. A strong candidate for energy dissipation is the process of *magnetic reconnection* - which also operates in solar flares, and in many other space and astrophysical plasmas. One of the biggest challenges in flare physics is to explain the origin of the large numbers of high-energy electrons and ions, requiring integration of small-scale plasma kinetic models with large-scale fluid models.

PhD projects will apply magnetohydrodynamic simulations, relaxation theory, and kinetic plasma models to gain an understanding of the heating of the solar corona, and of energy release and particle acceleration mechanisms in solar flares. This will include application of new “reduced kinetics” approaches to develop self-consistent models including energetic electrons, and “forward modelling” of observational signatures, exploring the detection of energetic particles through hard X-ray and radio emission.

Projects:

- Coronal heating in unstable twisted coronal loops and interacting magnetic flux ropes.
- Particle transport and acceleration in reconnecting current sheets in solar flares.

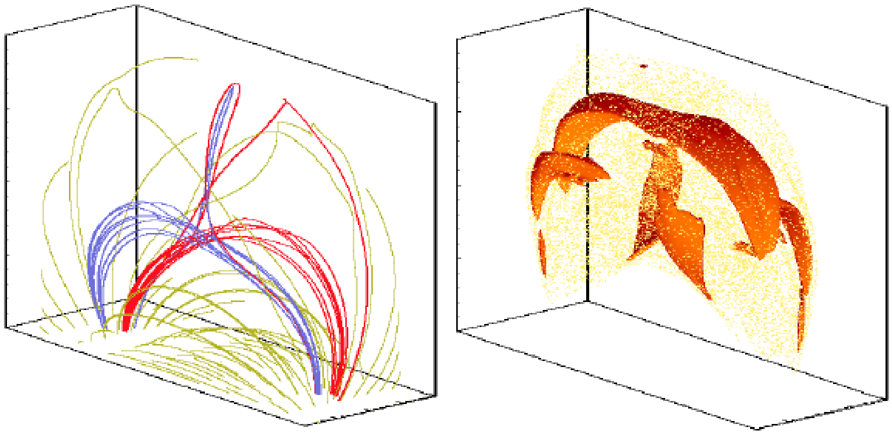


Figure: Magnetic fields and currents in magnetohydrodynamic simulation of twisted coronal loop (Gordovskyy et al, Astron Astrophys 589, A104, 2016)

Foregrounds and observational cosmology

Prof. Clive Dickinson (clive.dickinson@manchester.ac.uk)

I am a radio astronomer, working on projects to study cosmology (the Universe on the largest scales) and Galactic/extragalactic astrophysics. My main work is on understanding foreground radiation, particularly from the Galaxy, which contaminates precise measurements of the cosmic microwave background (CMB) and other cosmological surveys. I am the Manchester PI of the C-Band All-Sky Survey (C-BASS) project, which is mapping the Galactic synchrotron radiation at 5 GHz. This survey will be crucial for all CMB experiments include satellite missions such as LiteBIRD. I am an expert in diffuse Galactic emission from the interstellar medium and work on understanding the emission mechanisms involved and how they can probe the Galactic environment. I also work cosmology projects that use the novel “intensity mapping” tecehnique, using the HI and CO lines, which will map in 3-D the large-scale structure of the Universe, allowing tests of cosmology and dark energy. Experiments include BINGO, COMAP, and, ultimately, the Square Kilometre Array (SKA) which will be operational by 2025.

Projects:

- Mapping the diffuse Galactic emission at 5 GHz with the C-Band All-Sky Survey (C-BASS).
- Detecting large-scale CO emission at high redshifts using the CO Mapping Array Prototype (COMAP)

Extra-solar planets

Dr. Eamonn Kerins (eamonn.kerins@manchester.ac.uk)

JBCA research on exoplanets involves the study of the atmospheres of hot jupiters and neptunes through transmission spectroscopy, as well as the detection of cool, low-mass planets using the technique of gravitational microlensing.

Over 3,700 exoplanets have been discovered to date, mostly through the transit and radial velocity detection methods. These methods are very sensitive to large planets close in to their hosts (so-called hot jupiters and neptunes). The atmospheres of some planets detected by the transit method can also be probed using the technique of transmission spectroscopy, where we look for variations in the transit depth as a function of wavelength as a signature of atmospheric opacity variation. Observations at optical and near-infrared wavelengths have uncovered a wealth of signatures, including evidence for Rayleigh scattering, clouds, hazes, as well as spectral signatures of alkali metals, methane and water. At JBCA we have instigated SPEARNET – the Spectroscopy and Photometry of Exoplanetary Atmospheres NETwork. SPEARNET is an observational programme that is using a global telescope network to gather a large sample of transmission spectra from hot jupiters and neptunes in order to better understand the origin of the diversity of atmospheric composition within these hot planets.

Whilst we have detected very large numbers of hot and warm planets close to their host star, we still know relatively little about the demographics of cool planets at greater host distance. Planet formation theories predict that many planets form at large host distance, with more massive planets undergoing migration and moving away from their orbit of formation. Lower mass planets, on the other hand, are predicted to remain close to where they formed and so the detection of cool low-mass planets provides one of the most direct tests of planet formation theories. Gravitational microlensing, which involves the magnification and distortion of background starlight by foreground stars and planets, is the only method currently able to detect cool low-mass planets. At JBCA we have developed world-leading simulations of microlensing which are being used to develop potential exoplanet detection programmes on future space missions such as NASA WFIRST and the ESA Euclid mission. These missions should also shed light on the mystery of free-floating planets - the contested detection by microlensing of a potentially large population of planets throughout the Galaxy that are not bound to a host star.

Projects:

- Transmission spectroscopy observations and modelling of hot exoplanetary atmospheres.
- Galactic modelling of exoplanetary microlensing events and free-floating planets.

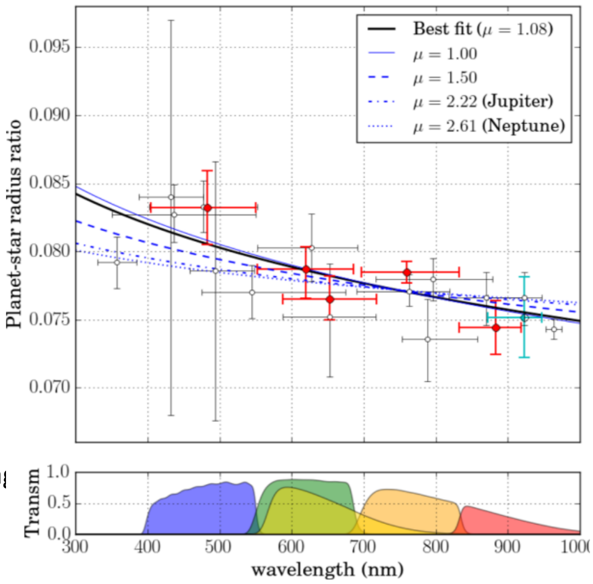


Figure shows the variation of the apparent size of the hot neptune GJ3470b with wavelength due to the effects of Rayleigh scattering in its atmosphere. Observations and analysis by Awiphan, Kerins et al. (2016, MNRAS, 463, 257).

Astrophysical Masers

Dr. Malcolm Gray (malcolm.gray@manchester.ac.uk)

My research is based on solving the combined radiation transfer and statistical equilibrium equations in a variety of complicated astrophysical environments. I have a particular interest in modelling molecular transitions from some common astrophysical molecules in the sub-mm to radio regions of the electromagnetic spectrum. Transitions in these regions can be observed with a variety of instruments, including the e-MERLIN radio array, based at Jodrell Bank Observatory, the Atacama Large Millimetre Array (ALMA), and, at the highest frequencies, the aircraft-based SOFIA.

In some conditions, population inversions can be generated in some transitions, leading to natural masers from sources that include star-forming regions, evolved stars and the nuclei of some external galaxies. Masers are very bright and often point-like sources that enable them to be used as tools for, among other purposes, kinematic analysis and distance determination.

All of my projects involve a considerable computational element, but otherwise include various amounts of data analysis from observations and of theoretical modelling.

Projects:

- The Origin of Astrophysical Maser Flares
- Understanding Full-Polarization Observations of Astrophysical Masers in Star-Forming Regions and Evolved Stars
- Identification of the Physical Objects that Support Astrophysical Masers
- Computer Modelling of non-LTE Molecular Energy-Level Populations in H_2O, CH_3OH and H_2CO

Late stages of stellar evolution: death of a star

Prof Albert Zijlstra (albert.zijlstra@manchester.ac.uk)

Stars end their working lives by ejecting much of their mass into space. For high mass stars, this happens explosively, and low mass stars, such as the Sun, eject their envelopes in a so-called superwind. The wind forms a dense shell, surrounding a star which rapidly evolves from a red giant to a hot white dwarf, while the shell becomes a planetary nebula. Planetary nebulae are among the prettiest objects in the sky, with a wide range of structures and morphologies. The explanation for these morphologies is still unclear. In Manchester, there is a world-leading group working on the stellar superwinds, what causes them, and the origin and evolution of the shells and their intricate structures. Projects typically involve observations, combined with a modelling component.

Projects:

- The study of the wind structures using the extreme-angular-resolution instrument Sphere;
- Infrared spectroscopy of planetary nebulae;
- GAIA and the galactic distribution of red giants.

Radio Observations accretion and star-formation in Galaxies across cosmic time.

Dr. Rob Beswick (robert.beswick@manchester.ac.uk)

Two of the most important processes in the evolution of our Universe are star formation and accretion; how they interact and affect galaxy evolution over cosmic time remains a critical question in astrophysics. Radio observations provide a superb diagnostic of these two processes, allowing a direct view of star-formation and the measurement of AGN accretion rates at bolometric luminosities far below anything detectable at higher energies. This group (Beswick et al) uses observations high resolution radio interferometers such as *e*-MERLIN, the jVLA, MeerKAT, LOFAR and VLBI, alongside many multi-wavelength probes, to spatially resolve distant galaxies and provide a *direct* separation of the contributions and co-evolution of AGN and SF activity in galaxies in both the local and distant Universe. In nearby galaxies high resolution radio observations can decompose an individual galaxy into its constituents (supernovae, their remnants, HII regions, and AGN activity) at a uniform distance and luminosity limit. Whilst in the high redshift Universe we use the instruments to survey the faintest galaxy population in the radio and characterise the rates of star-formation and AGN activity throughout the history of the Universe. This group lead and are involved with many of the large survey projects with SKA-pathfinder instruments, as well as playing key roles in defining the science objectives and technical work shaping the SKA. The MScR and PhD projects within this theme are primarily focussed around the use of high-sensitivity, high-resolution radio observations to investigate the interplay between SF and accretion processes in galaxies. These include the two largest *e*-MERLIN legacy programmes, investigating SF and accretion in the distant (*e*-MERGE – 1000hr guaranteed time project) and local Universe (LeMMINGs – 800hr guaranteed time project), as well as a number of key complementary programmes with other facilities.

Projects:

- High resolution radio studies of local star-forming galaxies - The Legacy Multi-band eMERLIN Nearby Galaxie Survey (LeMMINGs)
- Molecular gas observations of nearby galaxies - *fuelling the star-formation*
- Star-formation through cosmic time – *the e-MERGE galaxy census*

Spectral distortions of the cosmic microwave background and cosmology

Dr. Jens Chluba (jens.chluba@manchester.ac.uk)

My group studies what we can learn about cosmology and particle physics using observations of the cosmic microwave background (CMB). In particular, we are interested in CMB spectral distortions – tiny departures of the CMB energy spectrum from that of a perfect blackbody. These signals can tell us about energy release processes in the early Universe and are one of the main future targets in CMB cosmology. One exciting source of spectral distortions is due to the so-called Sunyaev-Zeldovich (SZ) effect. The SZ effect is caused by the up-scattering of CMB photons by the hot electron plasma residing inside galaxy clusters. Hundreds of clusters have already been detected this way (e.g., with the Planck satellite), but in the future, thousands of SZ (e.g., using CCAT-prime and Stage-IV CMB) and X-ray (e.g., e-Rosita and Athena) cluster observations will become available. This will open many opportunities for studies of large cluster samples but also individual systems. Utilizing the SZ and X-ray signals for cosmological purposes requires understanding the relations of the signal to the underlying structure of the medium, one of the focuses of my research.

Project:

- The modelling of Sunyaev-Zeldovich and X-ray cluster signals and what this can teach us about cosmology and cluster physics

How is dense gas transformed to stars in galaxies?

Dr. Rowan Smith (rowan.smith@manchester.ac.uk)

Stars are the building blocks of our Universe. They synthesise elements, control the structure and evolution of galaxies, and are the sites of planet formation. Star formation determines the number of supernovae in a galaxy, which drives the physical and chemical structure of the gas. However, it is still unclear to what extent star formation depends on local conditions within a host galaxy, and what physical processes determine the mass of stars and their rate of formation. Is star formation in the Milky Way a good analogue compared to that in other galaxies such as those found in the early universe? Under what conditions are the most massive stars, whose feedback shapes the surrounding interstellar medium, formed?

My work seeks to address these fundamental questions by performing numerical simulations using the magnetohydrodynamic AREPO code. Using this tool we can build models of where dense gas clouds are formed in galaxies, and how such clouds will fragment and collapse. Crucially by including information on the gas chemistry we can make synthetic images that can be compared to real observations from facilities such as ALMA to test the relative importance of the physical mechanism that we include in our models. This means that while my work uses a theoretical approach I also work closely with observers to interpret observations e.g.

my membership of the THOR (The HI OH and Recombination line survey of the Milky Way) collaboration.

Projects:

- Beads on a String: The formation of massive stars by filamentary accretion.
- How do galaxies form stellar nurseries throughout cosmic time?

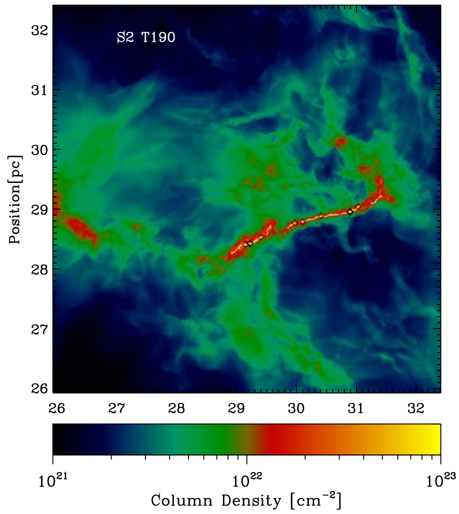


Figure: A turbulent dense molecular gas cloud simulated using AREPO with time-dependent chemistry, UV heating, sink particles, and gas self-gravity. A long filament forms within the cloud due to a combination of large-scale turbulent modes and gravitational infall. Star particles form at regular intervals in the filament and gas is channelled along the filament network to form the most massive stars.

Numerical Simulations of Galaxies and Galaxy Clusters

Dr. Scott Kay (scott.kay@manchester.ac.uk)

Understanding how the Universe went from an almost perfectly smooth state, 400,000 years after the Big Bang, to the "cosmic web² of galaxies and dark matter structure at the present day, is a major goal in modern cosmology. Over the next 5-10 years, new surveys will come online (e.g. with Euclid and the Square Kilometre Array) that will be used to map much larger volumes in the Universe. These will allow us to probe the growth of structure (and thus the nature of dark energy) as well as to study the evolution of the galaxy population over billions of years of the Universe¹s history.

Numerical simulations play a crucial role in our understanding of structure formation. They allow us to create model universes with varying physics (e.g. the nature of dark matter or astrophysical processes such as star formation) and thus allow us to test the sensitivity of observable properties to these variations. Simulations also allow us to create a “movie” of the universe allowing us to study the time evolution of structure formation in detail, something that is not possible with observations.

At JBCA, we use simulations to study the formation of galaxies and clusters. We are particularly interested in the hydrodynamics of the gas and feedback processes - outflows from stars and super-massive black holes. We are a UK node in the Virgo consortium, a large, international group of astrophysicists who use simulations to study galaxy formation and large-scale structure. As part of Virgo we regularly use large supercomputers as part of STFC¹s DiRAC network.

Projects:

- Developing the next generation of cluster simulations
- Simulating feedback from super-massive black holes in galaxies and galaxy clusters
- Modelling the HI Universe in the SKA era

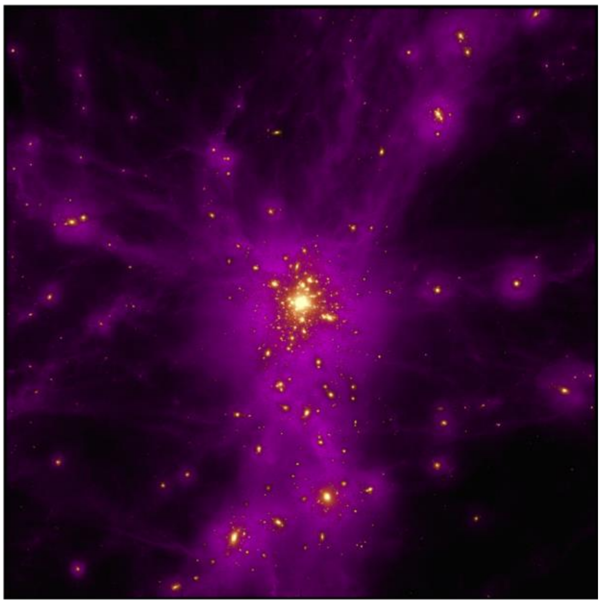


Figure: image from a simulated galaxy cluster. Hot, ionised gas (visible in X-rays) is shown in purple while the stars are shown in yellow.

Pulsars, Fast Radio Bursts, and Gravitational Waves

Dr. Michael Keith (michael.keith@manchester.ac.uk)

Pulsars are rapidly rotating neutron stars which sweep out beams of radiation along the poles of their extremely strong magnetic fields. We observe a pulse of radio waves from the pulsar each time its beam of emission sweeps across the Earth. The most rapidly rotating pulsars, which have spin periods of a few milliseconds, act as incredibly stable clocks and can be used in experiments of gravitational physics. For example, we are working as part of a large international collaboration, the European Pulsar Timing Array, to detect gravitational waves from supermassive black-hole binaries at the centre of distant galaxies. This is complimentary to the gravitational wave observations done by the LIGO collaboration for which the 2017 Nobel Prize in Physics was awarded.

Part of this research involves developing data science techniques for the study of our large pulsar datasets. For example, by applying gaussian process modelling and other related techniques within a Bayesian framework we can try to better model the long-term variations in radio pulsars. This not only gives us new insight into the underlying physics of the radio pulsars, but also provides powerful tools to improve our detection algorithms for the gravitational wave experiment.

Another hot topic in the field of time-domain radio astronomy is the recent discovery of Fast Radio Bursts (FRBs). These are individual pulses of radio emission that appear to come from the distant universe. The origin of FRBs is still unknown, but believed to be related to some highly energetic phenomenon such as the collapse of a neutron star into a black hole. We are involved in several surveys to detect more FRBs, including the SUPERB survey using the Parkes Radio Telescope in Australia. Parkes has been responsible for the discovery of more than half of all known pulsars, and the SUPERB survey continues this legacy with the discovery of new FRBs and Pulsars.

The discoveries of surveys like SUPERB directly lead to new understanding of the pulsar and FRB populations. Further, the survey has been optimised to detect pulsars that are most suitable for the gravitational wave detection experiments. Therefore joining these surveys provides a great opportunity to impact a wide range of science goals.

This is just a snapshot of a little of the pulsar and FRB research carried out in the Pulsar and Time-Domain Astronomy group, so please do get in touch to discuss other project ideas.

Projects:

- Data science for the study of gravitational waves with high precision pulsar timing.
- Discovering Pulsars and FRBs with the SUPERB survey.

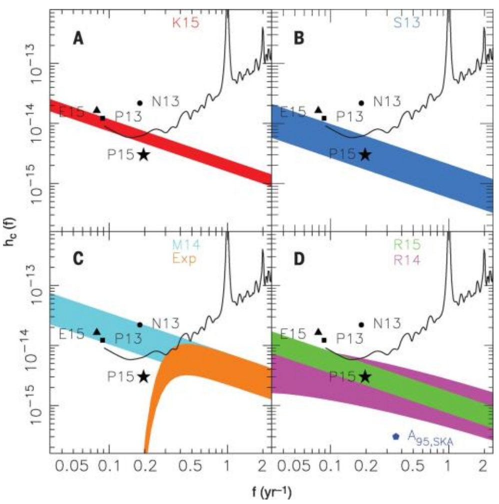


Figure shows the upper-limit on gravitational wave strain obtained from pulsar timing (solid line and symbols), compared to theoretical models for the expected gravitational wave signal (coloured bands), over a range of gravitational wave frequencies. (Shannon et al., 2015, Science, 349, p1522).

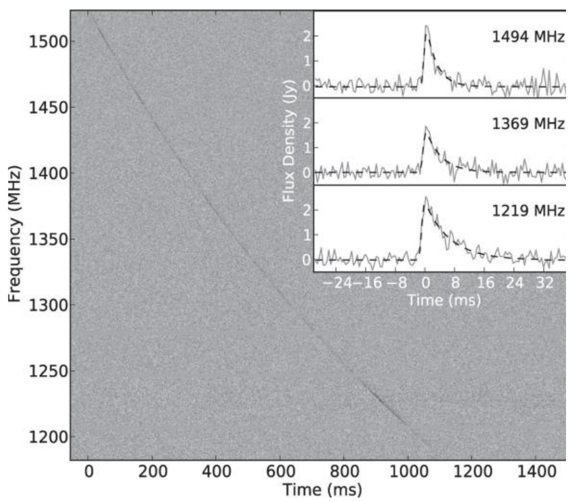


Figure shows an FRB recorded with the Parkes radio telescope. The grayscale image show frequency-dependent dispersion delay caused by the ionised plasma between galaxies. The inset shows the shape of the pulse changes at three observation frequencies (Thornton, et al. 2013, Science, 341, p53).

The Formation of Massive Stars in Our Galaxy and Other Galaxies

Prof. Gary Fuller (gary.fuller@manchester.ac.uk)

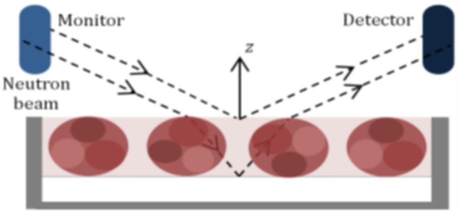
The conversion of gas into stars is one of the fundamental processes in galaxies. With their prodigious luminosity, energetic winds and their ultimate demise as core collapse supernovae, the massive stars which result from this process dominate the physical and much of the chemical evolution of interstellar medium. Understanding how these stars with masses greater than 8 times the mass of our Sun form is therefore a key astrophysical problem. It impacts a wide range of astrophysical issues from the lifecycle of baryons in galaxies including the origin of heavy elements essential to the formation of rocky planets and life, to the birthrate of supernovae, pulsars, blackholes and gamma-ray bursts. Starburst galaxies host the most extreme star forming environments known. A single starburst region can be forming stars at rates 10 to 100 times more rapidly than the whole Milky Way galaxy. Understanding how these regions form and evolve is essential to understanding both the evolution of individual galaxies, including the formation and feeding of their central supermassive blackholes, as well as the star formation history of the universe as a whole.

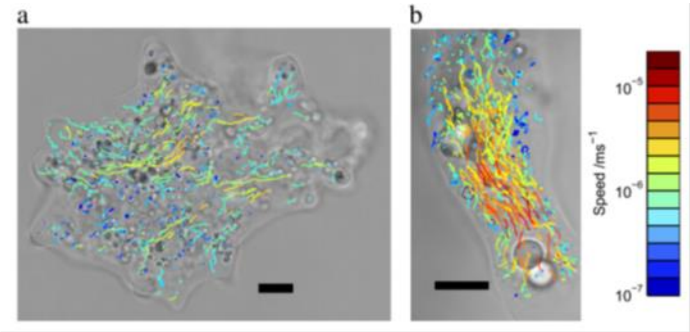
My group's research is focused on using a range of observations at infrared, millimetre/submillimetre and radio wavelengths from telescopes such as Herschel, ALMA and JVLA, and eventually SKA, together with numerical simulations, to study the formation and early evolution of massive stars in both our galaxy and starburst galaxies. The immediate aims are to understand the relative importance of the different physical processes involved in the formation of massive stars and the effect these forming massive stars have on their natal cocoons, as well as on larger scales. Ultimately the goal of this area of research is to build a predictive model of star formation.

Projects:

- Variable Radio Sources as Probes of Accretion and Outflow in Star Forming Regions
- The Structure, Kinematics and Evolution of Filamentary Molecular Clouds and Their Role in Massive Star Formation
- Using Dust Polarization to Probe the Magnetic Field in Massive Star Forming Regions
- Identifying the Precursors to Massive Stellar Clusters
- Connecting Star Formation in the Starburst Galaxy NGC253 and Star Forming Regions in the Milky Way Using The ALCHEMI Large Programme on ALMA
- Using The ALCHEMI Large Programme on ALMA to Study the Evolution of Starbursts in NGC253
- Vibrationally Excited Molecules as Probes of the Most Extreme Regions in Galaxies

BIOLOGICAL PHYSICS





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

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

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

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

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

Projects:

Biointerface

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

Neutron reflection study of protein adsorption.

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

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

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

Interfacial processes underlying antimicrobial actions and biocompatibility.

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

Computational systems biology and medicine

Prof. Henggui Zhang (henggui.zhang@manchester.ac.uk)

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

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

Novel non-invasive technology for diagnosing cardiac arrhythmic origins.

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

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

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

Artificial intelligence (AI) in diagnosing cardiac arrhythmias.

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

Biomolecular structure and dynamics

Dr. Jichen Li (j.c.li@manchester.ac.uk)

Water flow in confined nano graphene channels.

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

1. Nair, R.R.; Wu, H.A.; Jayaram, P.N.; Grigorieva, I.V.; Geim, A.K. Unimpeded permeation of water through helium-leak-tight graphene-based membranes. *Science* **2012**, *335*, 442-444.

2. The Observation of the Oxygen-Oxygen Interactions in Ices - Redefine the term of hydrogen-bonding between water – water molecules, Shun Chen, Zhiping Xu and Jichen Li, New J. Phys. 18 023052-58 (2016).

3. Effect of layered water structure on the anomalous transport through nanoscale graphene channels. S. Chen; X.C. Nie; H.P. Fang; N.R. Walet' Shiwu Gao and J.C. Li, to be published (2017).

Cellular tracking and self-assembly

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

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

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

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

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

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

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

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

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

COMPLEX SYSTEMS AND STATISTICAL PHYSICS

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

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

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

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

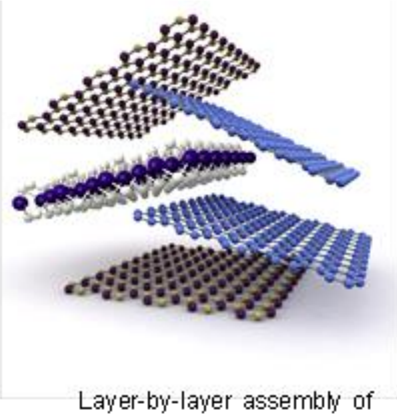
This is a fast-moving field and it is hard to say what exactly your project will be. This will also depend on your interests and preferences. We promise an exciting mix of theoretical analysis, computer simulation and interdisciplinary work with colleagues in the life sciences, mathematics, healthcare/medicine,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

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

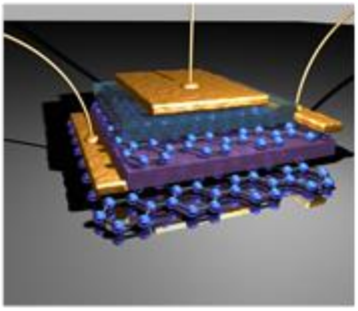
CONDENSED MATTER PHYSICS

Research in Condensed matter physics group is exceptionally broad, from electronic, optical, mechanical and magnetic properties of a whole family of atomically thin, two-dimensional materials to the physics of quantum fluids, intercalation-induced superconductivity in layered and two-dimensional materials and mass transport through atomically thin channels in 2D-materials based membranes.

Rotating millikelvin cryostat that allows visualization of vortex lines in superfluid



Layer-by-layer assembly of 2D heterostructures



Graphene=based vertical transistor

The focus in 2D materials research is currently shifting from studying the properties of graphene to other 2D crystals with a variety of electronic properties - insulators (hBN), semiconductors (phosphorene, MoS_2, WSe_2, etc.), superconductors ($NbSe_2$), 2D magnets (CrI_3) – and the so-called heterostructures, where atomically thin layers with different properties are assembled with monolayer precision to produce ‘materials by design’. Our research is supported by extensive cutting-edge facilities in the Schuster building and the National Graphene Institute, including clean-room microfabrication, measurements and characterisation. The quantum fluids research is supported by unique measurements systems, including ultra-low temperature rotating cryostats. More information is available at http://www.condmat.physics.manchester.ac.uk/ and http://www.graphene.manchester.ac.uk/. Research areas led by individual academics are described in more detail below.

Physics and applications of 2D materials and their heterostructures

Prof. Andre Geim (andre.geim@manchester.ac.uk)

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

Physics and applications of 2D materials and their heterostructures

Prof. Kostya Novoselov (konstantin.novoselov@manchester.ac.uk)

Two-dimensional crystals – one atom thick materials – are exciting objects, which often possess properties which are very different from their three-dimensional counterparts. We study their mechanical, electronic and optical properties, and investigate devices based on such crystals. The range of 2D materials available to us growth day by day. Collectively these crystals cover the very large range of properties: metals, semiconductors, insulators, ferromagnets, superconductors, etc. Furthermore, such 2D crystals can be assembled into three-dimensional heterostructures by putting several layers on top of each other. This allows unprecedented control on the properties of the resulting stack, and lead to discovery of new physical phenomena and creation of novel electronic and optical devices.

Projects:

- Quantum dots based on 2D atomic crystals
- Excitonic properties of van der Waals heterostructures
- Tunnelling phenomena in van der Waals heterostructures

Quantum fluids

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

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

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

Projects:

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

2D plasmonics in thin atomic layers

Prof. Sasha Grigorenko
(alexander.grigorenko@manchester.ac.uk)

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

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

Project: 2D plasmonics in thin atomic layers.

Superconductivity in layered and 2D materials and graphene as a ‘magnetic’ element for spintronic devices

Prof. Irina Grigorieva (irina.v.grigorieva@manchester.ac.uk)

Prof. Grigorieva’s current research focuses on two main areas: (i) search for new superconductors obtained by alkali-metal intercalation of naturally layered materials or stacks of atomically thin layers and (ii) exploiting possibilities to make graphene ‘magnetic’ for applications in spintronics. Superconducting paring in alkali-metal doped semiconductors or insulators often has a non-trivial nature either due to the interplay of the electronic states of the 2D layers and the intercalating metals or due to the non-trivial topology of the host material (for example doped topological insulators). The recently discovered possibility to make graphene ferromagnetic by proximity to known ferromagnetic materials may be exploited, for example, in magnetic tunnel junctions. We are currently looking for ways either to enhance this effect in graphene or to find other promising 2D materials for such devices.

Projects:

- Superconductivity by alkali-metal doping.
- Superconductivity in doped topological insulators.
- 2D materials for magnetic tunnel junctions.

Bridging electronics and mechanics at the nanoscale

Dr. Artem Mishchenko (artem.mishchenko@manchester.ac.uk)

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

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

Projects:

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

Graphene nanoelectronics and spintronics

Dr. Ivan Vera Marun (ivan.veramarun@manchester.ac.uk)

Dr. Ivan Vera Marun specializes in graphene nanoelectronics and spintronics. Spintronics is an emergent field that exploits the intrinsic angular momentum of the electron, besides its charge traditionally used in modern electronics. It lies at the interface between the traditional fields of magnetism and electronics, and becomes accessible only via nanotechnology.

Spin as an additional degree of freedom would provide enhanced functionality to electronics by enabling re-programmable circuits and low power ‘green’ electronics, while graphene is currently explored for its huge application potential. In this project we will explore spintronics (Nobel Prize in Physics 2007) in devices based on the remarkable one-atom-thick material graphene, the first truly two-dimensional material discovered in Manchester (Nobel Prize in Physics 2010). We work on state of the two-dimensional spintronic devices, either to enhance their electronic properties or to introduce novel physical effects.

Possible projects:

- Spin-dependent tunneling via 2D barriers.
- Spin transport in high-quality graphene transistors.
- Spin orbitronics in novel 2D heterostructures.

Probing properties of 2D materials and confined molecules at the nanoscale by scanning probe microscopy

Dr. Laura Fumagalli (laura.fumagalli@manchester.ac.uk)

2D materials have shown unique electronic/mechanical/optical properties on the nanoscale as well as the ability to trap liquids inside nanoenclosures. This has opened up exciting opportunities to study the properties of 2D nanoconfined systems that have strong impact in multiple research fields, from physics to chemistry and biology, but are inherently difficult to observe. Examples include physical phenomena such as surface coating and wettability, solid/liquid phase transitions and crystal growth, molecular and ion transport, DNA translocation and condensation. In our group we study these phenomena, which are governed by electrostatic and electrodynamics interactions on the nanoscale, by using and developing custom-made scanning probe techniques with nanometer and atomic scale resolution.

Projects:

- Measurement of the dielectric polarization properties of 2D confined molecules in real time during molecular processes.
- Development of high-resolution dielectric microscopy to access electrostatic and dielectric properties of 2D materials and confined molecules for the first time down to the single-molecule level.

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

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

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

Projects:

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

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

Currently, the Group investigates turbulence in superfluid 4He in the limit of zero temperatures. We possess three specialized cryostats, located in the Schuster building.

Projects:

Visualization of vortex lines in superfluid ^{4}He through fluorescence of molecules and nanoparticles, attached to vortices.

The aim of this project is to take photographs and videos of vortex lines, which will allow us to learn about the spectrum of Kelvin waves along vortex lines and the dynamics of their evolution. Various temperatures will be investigated but, first of all, we are in the limit of zero temperatures, ~0.1K, when vortex lines move with virtually no friction, hence their dynamics span a wide range of length scales and include novel mechanisms of energy dissipation. A novel type of apparatus will be built with most optical components held at low temperature inside a cryostat. The research is funded by a 4-year EPSRC grant “Microscopic dynamics of quantized vortices in turbulent superfluid in the T=0 limit”. The student will join the Research Associate, already working on the project.

Investigation of elementary excitations in superfluid ^{4}He responsible for the removal of energy from tangles of vortex lines (Quantum Turbulence) in the T=0 limit.

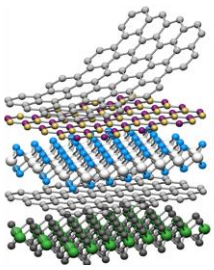
Superfluid helium is an inviscid liquid, capable of maintaining persistent flow forever. Yet, it is known that Quantum Turbulence decays even at $T = 0$, the energy being lost to some kind of elementary excitations of the superfluid. There exist several theories of processes involving emission of phonons, rotons and small quantized vortex rings. However, nobody yet knows – which of them is correct, if any. The project will aim at developing of three types of detectors, each sensible to one of these excitations. We will then place the detectors next to intense turbulence in superfluid ^{4}He at temperature ~0.1K. In a way, this will be similar to the scattering experiments at particle accelerators, where a range of detectors count events of different particles, originated from a high-energy event such as decaying quark-gluon plasma, hitting them.

CONDENSED MATTER THEORY

Theory of electronic and optical properties of 2D materials and their heterostructures.

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

Professor Vladimir Fal'ko offers projects that address microscopic and mesoscale theory of electronic and optical properties of 2D materials and their heterostructures. The development of Lego-type approach to creating new materials, by extracting individual crystal planes from layered materials (transition metal dichalcogenides, metal chalcohenides, or CrI_3 ($CrCl_3$), etc, etc) and placing them on top of each other in a designed sequence, has produced a new class of atomically thin hybrid materials: 2D van der Waals (vdW) heterostructures with many new interesting properties. In the projects offered on this topic, one will work on:



- Symmetry analysis, DFT modelling, tight-binding model and k.p theory for monolayer, few-layer and heterostructures of various 2D crystals.
- Formulation of effective theories for the moiré superlattice potential in heterostructures of various 2DM.
- Effects of the electron-electron and electron-phonon scattering on recombination of intra- and inter-layer excitons in such structures.
- Theory of excitonic complexes (trions, biexcitons, electron-hole droplets) in 2DM heterostructures.

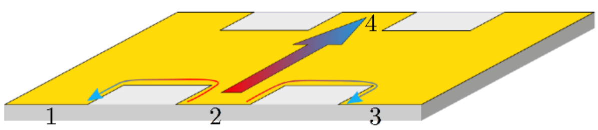
During this project, students will learn field theoretical methods and Green functions approach to condensed matter theory; methods of Boltzmann kinetic theory, analytical and computational quantum transport theory; group theory applications in solid state physics. Some of these projects will be carried out in collaboration with experimental groups of the European Graphene Flagship, and the choice of materials composition of heterostructures will be informed by the on-going technological progress and experimental observations.

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

Many-body phenomena in strongly-coupled 2D systems

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

Dr. Alessandro Principi offers projects on many-body phenomena in strongly-coupled 2D systems including developing a theoretical description of electronic transport focusing on the recently-discovered hydrodynamic regime and on dynamics of collective excitations of electrons in 2D materials. When systems are



strongly interacting, the electronic transport must be described in terms of collective variables, rather than single-particle properties. The role of spin-orbit interaction and/or of the Berry phase in this regime is unexplored, and potentially very important. The other direction of research is related to the formulation of general principles to overcome the current limitations to the “squeezing” of light to sub-wavelength scales by exploiting unusual properties of plasmons in 2D materials. In particular their sensitivity to magnetic fields, strain/density patterns, electrostatic gates, and artificial and Moiré superlattices. We wish to analyse the combined non-linear dynamics of fast electrons and plasmons (emerging as their Cherenkov radiation), in particular of the resonances that can occur when both particles and plasmons propagate at the same speed. During this project, students will learn a variety of advanced analytical techniques to study the effect of many-body interactions in 2D and topological materials.

https://scholar.google.co.uk/citations?user=Dnj-JZoAAAAJ&hl=en

Topological properties and effects of strong correlations in 2D materials

Prof. Paco Guinea (francisco.guinea@manchester.ac.uk) and Prof. Niels Walet (niels.walet@manchester.ac.uk)

Professors Paco Guinea and Niels Walet offer collaborative projects on topological properties and effects of strong correlations in 2D materials that combine analytical approaches to condensed matter theory (Guinea) with computational approaches to many-body physics (Walet). Examples of possible research projects include:

- the Majorana edge states in p-wave superconductors,
- edge conductance in superlattice graphene,
- topological effects in graphene heterostructure with a ferromagnet,
- behaviour of water in between graphene layers.

http://www.theory.physics.manchester.ac.uk/people/index.php?doc=walet

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

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

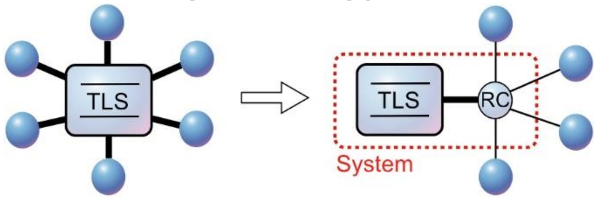
Dr. Yang Xian offers projects on quantum many-body theories and their applications in condensed matter physics. Many interesting physical phenomena are often the results of a combination of dynamic interaction between particles and their quantum mechanical nature. Magnetism, superfluidity and superconductivity are such examples. The project topics will include (a) investigation of dynamics of strongly correlated systems such as high-temperature superconductors, low-dimensional antiferromagnetic lattices and graphene ribbons, (b) physical properties of edge/surface states of fermionic systems (such as graphene ribbons) and bosonic systems (such as ferro- and anti-ferromagnets, photonic systems). During the project, the student will learn quantum many-body theories, particularly the coupled-cluster methods (CCM) and its extensions, and have applied to a number of quantum systems such as antiferromagnets, lattice gauge systems, and graphene.

http://www.manchester.ac.uk/research/yang.xian/

Theory of open quantum systems beyond weak-coupling regimes

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

Dr. Ahsan Nazir offers a project on the theory of open quantum systems beyond weak-coupling regimes. 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. Dr. Nazir develops new theoretical techniques to study such systems, and applies these approaches to understand the behaviour of quantum systems both in and out of equilibrium. In a departure from conventional open systems methods, and he explores the role of highly non-classical environmental states in faithfully representing system-environment (and intra-environment) correlations in the strong-coupling regime (see figure). Potential projects include: fundamental developments in the theory of strongly coupled open quantum systems and applications to many-body systems; studies of the consequences of strong-coupling on the laws of thermodynamics and quantum scale machines; the impact of environmental influences in solid-state quantum technology; vibrational influences in the optical and excitation properties of natural and artificial molecular aggregates



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

NUCLEAR PHYSICS

Exposing details of the nuclear force through lifetime measurements.

Dr. D. M. Cullen (dave.cullen@manchester.ac.uk)

The lifetime of a nuclear state is a fundamental observable which gives a direct probe of the nuclear force. We recently built a new triple-foil plunger device (Fig. 1) to measure the lifetimes of nuclear states beyond the proton dripline and to study nuclear shape coexistence with an unprecedented level of sensitivity. The first experiments will be performed in Jyvaskyla, Finland and HIE-ISOLDE, CERN and the data used to constrain theoretical nuclear models.

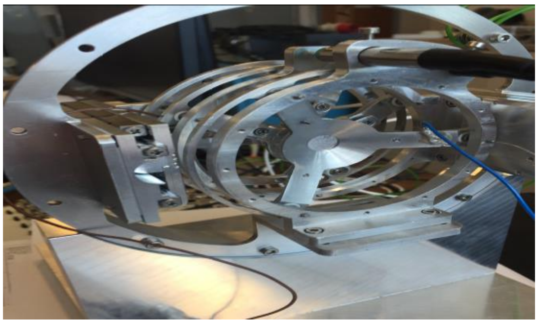
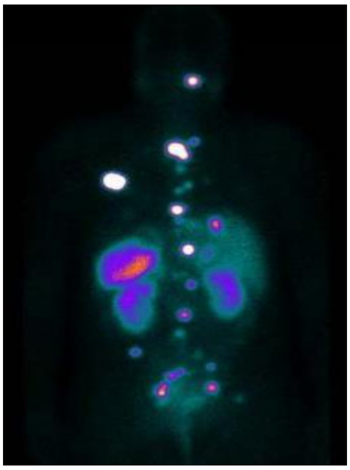


Figure 1. The Triple Foil Plunger for Exotic Nuclei (TPEN). TPEN contains a target and 2 degrader foils compared with the standard plunger. This produces two velocity regimes at each distance setting, thereby reducing the beam time required to measure lifetimes in exotic nuclei, or allows even more exotic nuclei further from stability to be studied.

Applied Nuclear Physics measurements.

Dr. D. M. Cullen (dave.cullen@manchester.ac.uk)

3D printing to improve patient dosimetry in Molecular radiotherapy (MRT). Our collaboration with the nuclear-medicine group at The Christie NHS Foundation Trust has established a fruitful interdisciplinary research program (2 pdras and 3 PhD students) which seeks to address the complex and interconnected problem of providing accurate patient specific dosimetry in MRT. This work has attracted continued STFC funding to develop more realistic 3D-printed patient-specific organs to allow more accurate patient dosimetry to be performed at the Christie.



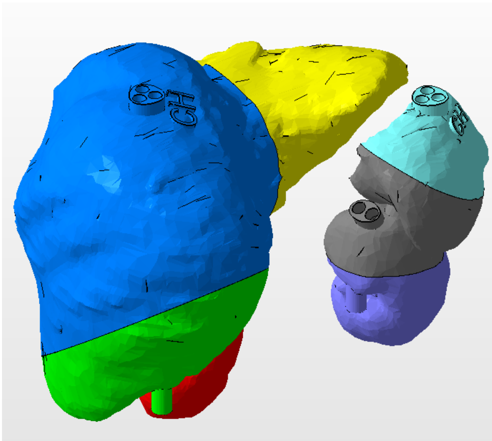


Figure 1. (left) Nuclear medicine image from radionuclide therapy targeting tumours. The physiological uptake in normal organs (spleen, kidney etc) is shown. (right) 3D printed patient-specific organs. More accurate dosimetry allows the optimisation of dose whilst keeping the dose to surrounding healthy organs within safe limits.

Improved Identification of illicit materials using an X-ray Backscattering technique. This research aims to demonstrate the potential improvements that can be made in X-ray backscattering techniques to better identify illicitly smuggled material in cargo / baggage. The will be achieved by combining a detailed understanding of the X-ray scattering processes and Monte-Carlo modelling with experimental results from poly-energetic X-ray sources and new high-efficiency, high-resolution CZT detectors. The project has Rapiscan Systems as industrial partner and currently funds (STFC) 1 pdra plus 1 PhD student.

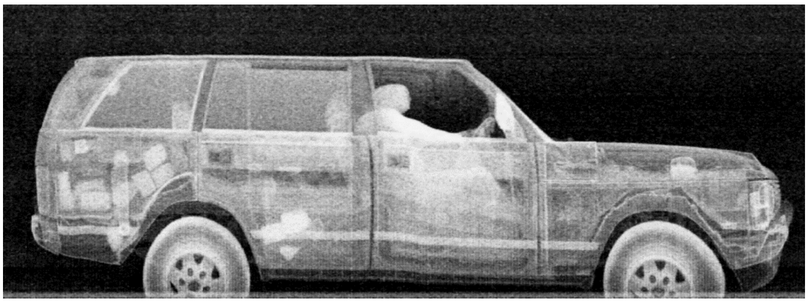


Figure 1. X-ray backscatter image of a car with contraband hidden within the body panels. These areas show up as brighter regions of the x-ray image. No detailed material information is currently possible. Obtaining detailed material information is the aim of this work.

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

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

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

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

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

Laser Spectroscopy at the limits of nuclear existence

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

How three-nucleon forces influence nuclear structure and the limits of nuclear existence remains a compelling question in nuclear physics. There are currently many different approaches being utilized around the world to measure the properties of nuclei that may help answer this question. Since laser spectroscopy measures nuclear observables without introducing any assumptions associated with a particular nuclear model it has become a very popular method. Until recently it could only be used to study isotopes that are produced in relatively large amounts, which has limited its application. Over the last 5 years the CRIS collaboration at CERN has developed new techniques in laser spectroscopy that have permitted measurements on beams of less than 10 atoms per second. This has greatly extended the reach of laser spectroscopy and has allowed it to study the most exotic nuclei for the first time. The project will be carried out at the ISOLDE facility, CERN, which is the premier radioactive beam facility at the precision frontier. There are currently PhD student projects in the area of ion trapping, production and application of negative ions for nuclear research and atomic physics. There is an opportunity in the project for students to spend a large fraction of their PhD at CERN.

Fission dynamics and nuclear astrophysics measurements at CERN

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

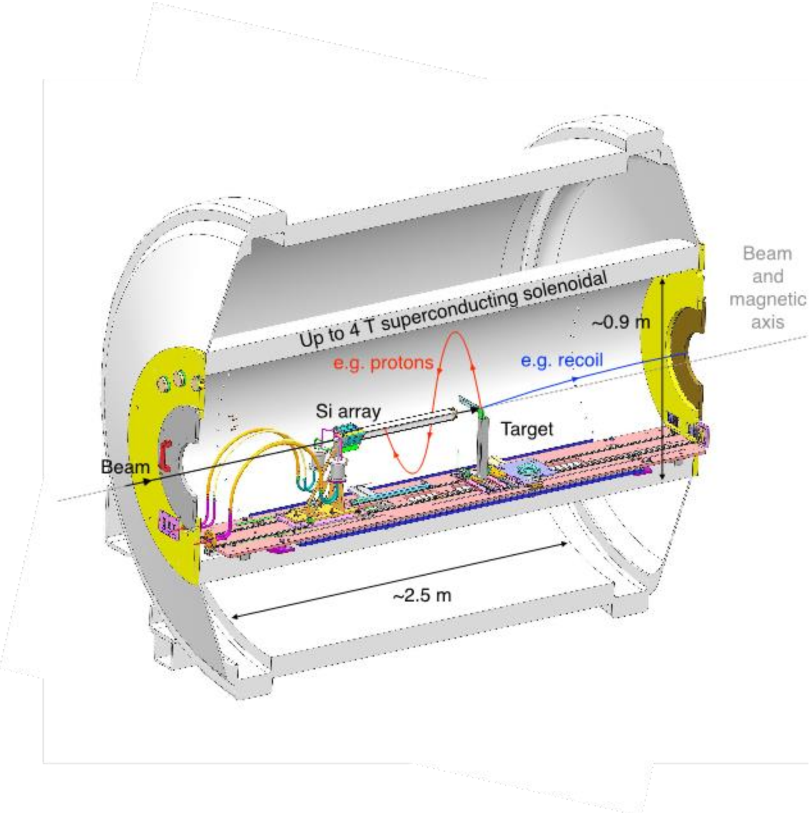
Projects involve the measurement of fission data from the Neutron Time-of-flight (n_TOF) facility at CERN. Neutrons of a broad spectrum of energies are produced by spallation of protons on a lead target. The neutrons are timed relative to the proton pulse and are used to induce fission on an actinide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

Exploring the Changing Shell Structure of Nuclei

Prof. Sean J Freeman (*sean.freeman@manchester.ac.uk*)

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

Single-nucleon transfer reactions offer a suitable probe of the single-particle characteristics via the spectroscopic factor (SF), measuring the overlap of the wave function of a state with simple single-particle configurations. Being subject to sum rules, SFs allow access to the occupancies of underlying single-particle orbits.
Phd projects in this area will involve using transfer reactions with radioactive beams to investigate the evolution of single-particle structure in to exotic regions of the nuclear chart. This work will predominantly take place at HIE-ISOLDE, CERN using the newly commissioned ISOLDE Solenoidal Spectrometer (ISS).


Beam
and
magnetic
axis
Up to 4 T superconducting solenoidal
~0.9 m
e.g. protons
e.g. recoil
Si array
Target
Beam
~2.5 m

NUCLEAR THEORY

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

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

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

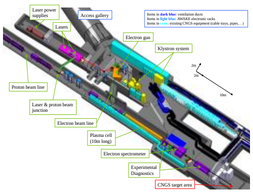
Niels Walet has expertise with a variety of first principles approaches to many-body systems, in particular the coupled-cluster method. In work with Mike Birse, he has implemented a stochastic variational method to calculate the properties of few-nucleon systems. First applications of this have been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

PARTICLE PHYSICS - ACCELERATOR

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

ALPHA Apparatus at CERN's Antiproton Decelerator facility

Ultrafast laser systems at PSI



AWAKE experiment at CERN

VELA facility at Daresbury laboratory

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

Some details of current projects are indicated below. Students are encouraged to contact potential supervisors directly, or Prof. R.M. Jones (roger.jones@manchester.ac.uk) for an overview of research opportunities.

Fundamental tests of antimatter gravitation with antihydrogen accelerators

Dr. William Bertsche (william.bertsche@manchester.ac.uk)

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

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

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

Terahertz driven linac: Shrinking the size and cost of particle accelerators

Dr Darren Graham (darren.graham@manchester.ac.uk) and Dr. Robert Appleby (robert.appleby@manchester.ac.uk)

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

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

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

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

Advanced Proton-driven Plasma Wakefield Acceleration Experiment (AWAKE) at CERN

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The development of the plasma accelerator has achieved significant breakthroughs in the last decade. The laser wakefield accelerator can routinely produce ~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.

Project opportunity: Studies will involve theoretical work (classical electrodynamics, plasma physics, accelerator physics, etc.) and also computer skill (particle-in-cell, parallel computing). The student will be part of the an existing international collaboration team and work on the key issues in the proton-driven plasma wakefield acceleration, e.g. the electron beam loading effect, the phase slippage, plasma and beam instabilities, collider design, particle-in-cell simulation of interactions between plasmas and beams, etc. The student will join in the design of the proton-driven plasma wakefield acceleration experiments and conduct the AWAKE experiments at CERN.

Project opportunity: A plasma beam dump uses the collective oscillations of plasma electrons to absorb the kinetic energy of a spent particle beam. Compared to the conventional beam dump, a plasma beam dump is much more compact and cost effective due to its large decelerating field associated. The beam dump project entails the dynamics of plasma-beam interactions and this will be investigated analytically. In addition, particle-in-cell simulations will be performed to understand the particle deceleration and re-acceleration processes. This is a multi-disciplinary topic as it involves plasma physics, accelerator physics and high performance computing.

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

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

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

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

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

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

Proton Radiotherapy & Synchrotron Radiation

Dr. Hywel Owen (hywel.owen@manchester.ac.uk)

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

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

LHC

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

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

PARTICLE PHYSICS - EXPERIMENTAL

Flavour physics

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

Project: LHCb: The charm and beauty of antimatter

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Dr. Mark Williams (mark.rj.williams@manchester.ac.uk)

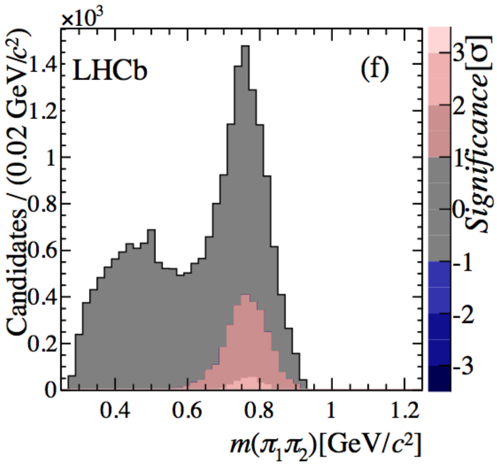
Dr. Evelina Gersabeck (evelina.gersabeck@manchester.ac.uk)

Manchester is one of the larger university groups working on the LHCb experiment and is involved in all current and future aspects of the experiment. This experiment is designed to search for physics from beyond the Standard Model through the analysis of matter-antimatter differences and rare decays of hadrons involving bottom and charm quarks. The group has been responsible for world leading analyses in both areas. We 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.

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

Flavour physics:

There are research projects in 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.



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

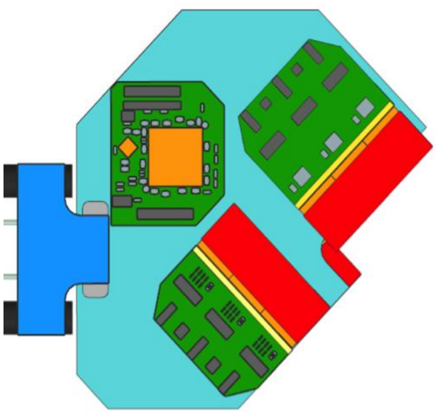
Many different measurements can be made in the rich field of quark and lepton flavour physics, and it is important to establish whether they can all be explained by the Standard Model or whether the hints of small differences turn out to be the first signs of some new physics. Our group drives innovation of analysis methods and we have been the first to exploit Graphical Processing Units (GPUs) in an LHCb analysis.

Detector operation:

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. Our group is responsible for the study of radiation damage, which is world-leading research as no silicon detector has been operated in a similar high-radiation environment to date. We also have a leading role in the implementation of LHCb's real-time alignment and calibration system, which is a novel approach that permits the acquisition of ready-for-analysis data straight out of the detector. Future projects in this area will focus on assessing the final detector performance and translating the lessons learned to the upgraded experiment.

Preparing for the next-generation experiment:

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 CO_2. 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.

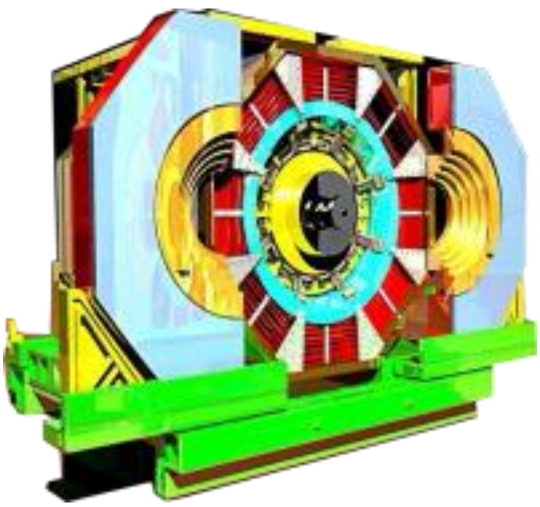
Designing the long-term future of LHCb:

Particle physics experiments operate on long timescales and our group is consequently also involved in developing crucial future detector systems. One is a new semiconductor detector to be used in the innermost regions of the tracking stations following the LHCb dipole magnet. The system should be installed around 2025. The second system is a novel vertex detector that, in addition to high position resolution, can also deliver precise timing information. This requires an ambitious R&D project to deliver a system that can cope with a factor ten more particles compared to the upgraded LHCb VELO.

Project: BESIII: The Chinese flavour factory

Main contact:

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



BESIII detector

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

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

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

Project: Mu2e: Precision muons at Fermilab

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The Mu2e experiment at Fermilab aims to improve the sensitivity in the search for muon-to-electron conversions in nuclei by several orders of magnitude. Our group is responsible for delivering a muon target monitor in collaboration with other UK groups. The project will start with the construction of the collimator system, which is our contribution, and move on to its commissioning.

In parallel, the project will contain a significant analysis component. The group's natural involvement is the precise determination of the flux of muons, i.e. the denominator of the conversion ratio. Students in this project will play a central role both on the technical side and analysis of one of the most ambitious particle physics experiments on the horizon.

Neutrino Physics

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

Project: The SBN Programme

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Dr. Andrzej Szelc (andrzej.szelc@manchester.ac.uk)

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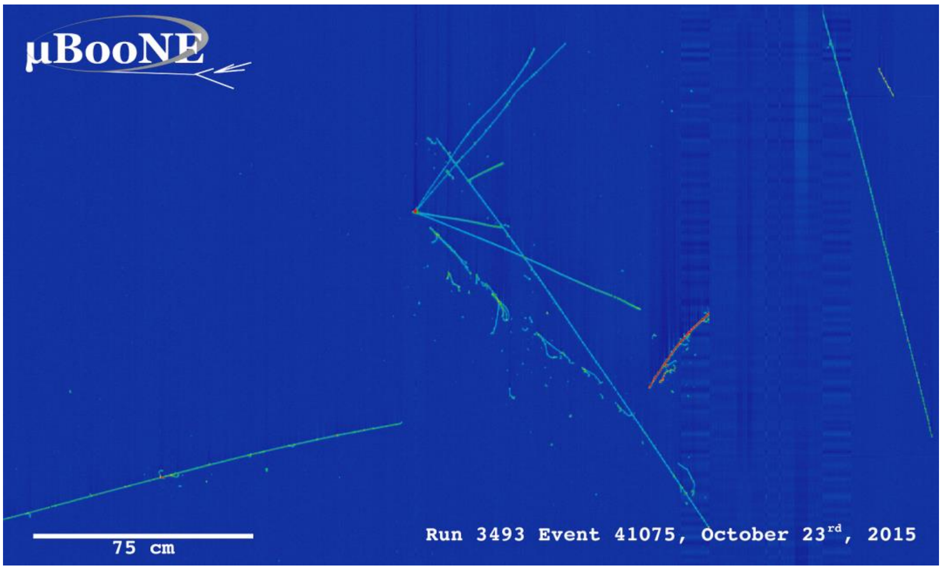

One of the first neutrino events observed by the MicroBooNE detector at Fermilab.

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

Project: LArTPC Detector Development

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Silicon photomultiplier and cryogenic photomultiplier covered in a blue-emitting wavelength-shifter under UV lamp light.

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 focus on development of light collection systems for LArTPC's. This will involve data analysis from test-beam experiments such as LArIAT and protoDUNE as well as Fermilab SBN experiments, developing simulations and working with small scale prototypes in the laboratory.

Project: SuperNEMO

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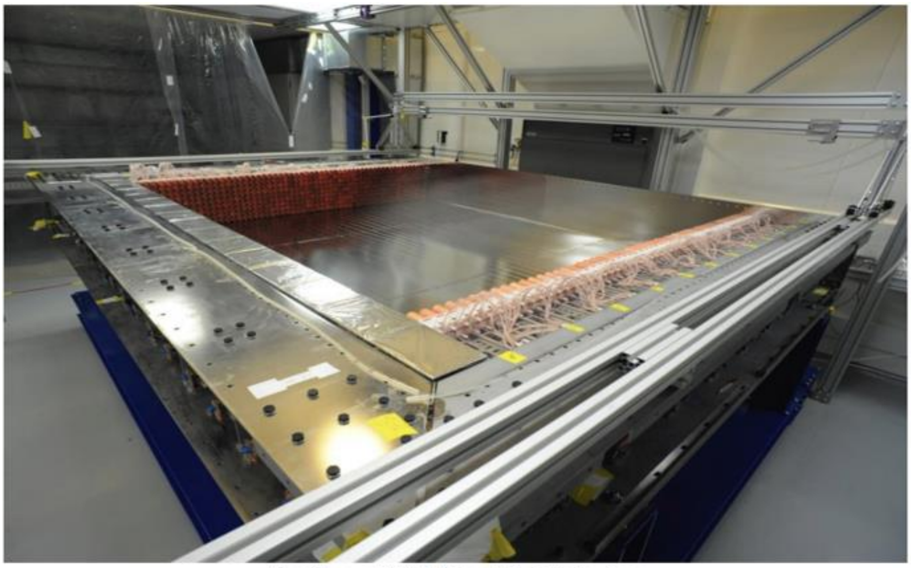

The SuperNEMO tracking detector

SuperNEMO is a new international project that is beginning data-taking in 2018. The experiment will search for neutrinoless double-beta decay, a process that is only possible if neutrinos have mass and are their own antiparticles. Discovery of neutrinoless double-beta decay would be ground-breaking, requiring us to change the Standard Model of Particle Physics, and potentially opening a path to explain the existence, and the small size, of neutrino mass. This PhD project will begin a few months after the experiment begins physics data-taking, at a point when the collaboration is working hard to understand the new detector, reconstruct the data, and develop physics analyses. The student will take a role in both the detector characterization and the development of the very first physics analyses from SuperNEMO. In addition to the search for neutrinoless double-beta decay, the data will be sensitive to a wide range of beyond-the-Standard-Model physics, including lepton flavour violation, right-handed W bosons, and Majoron exchange.

ATLAS Experiment

Project: The ATLAS Experiment (LHC)

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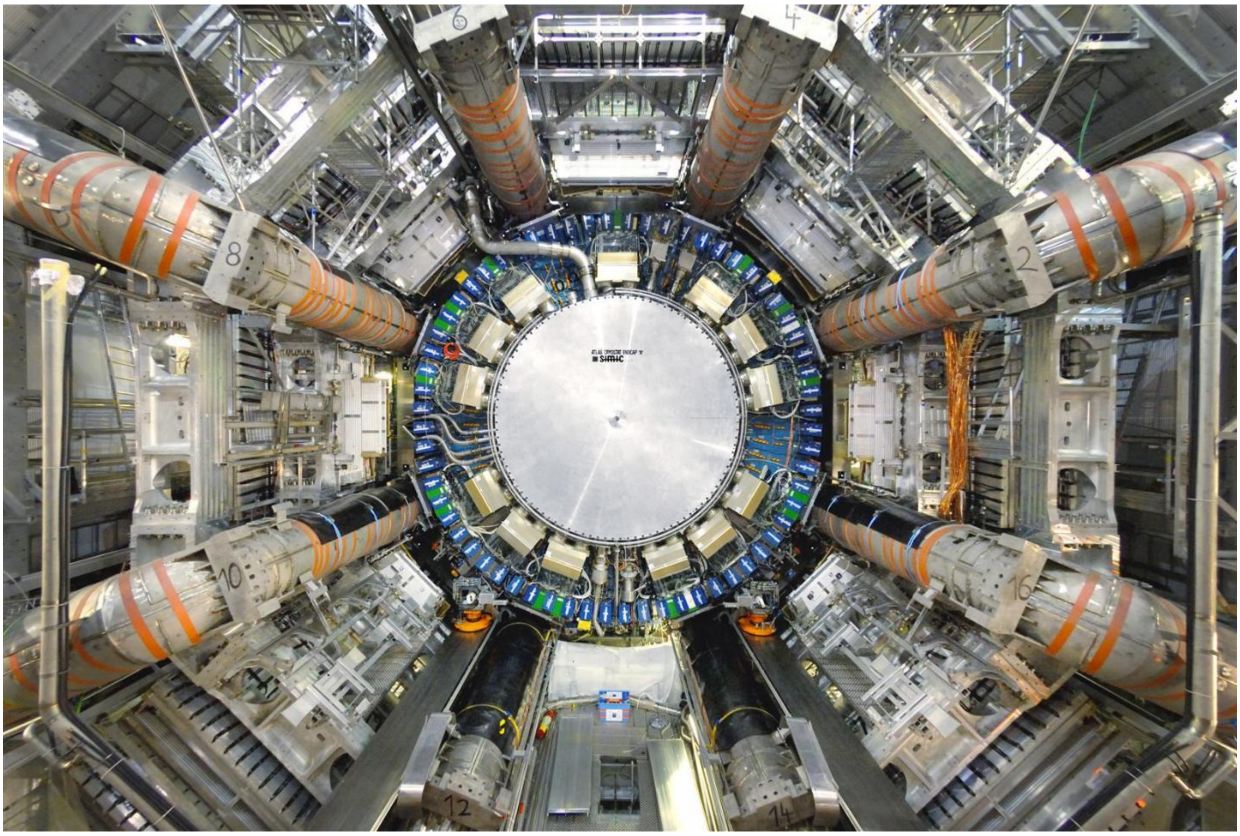


Manchester group members play leading roles in the ATLAS experiment, the largest particle physics experiment at the Large Hadron Collider (LHC) in Geneva, Switzerland. They coordinate international research teams in data analysis and in the development of new detectors and algorithms. By the end of 2018 ATLAS will have collected well in excess of 100 fb-1 of proton-proton collisions at a centre of mass energy of 13 TeV. This provides a data set that is unprecedented in size and energy in the history of particle physics colliders for testing the Standard Model with precise measurements and searching for signs of new physics phenomena beyond the Standard Model.

Our goals with these data include the search for: dark matter, extra dimensions, additional Higgs bosons, heavy Majorana neutrinos, supersymmetry, or new TeV-scale particles such as gravitons, leptoquarks, or new vector bosons (possible massive partners of the W and Z bosons). We perform this research from multiple angles. We search directly for these new physics phenomena as predicted by specific theories. We also make precise tests of the predictions of the Standard Model, in particular measurements of the properties of the recently-discovered Higgs boson. Such measurements are sensitive to potential differences that could provide the first hints of something completely new and unexpected.

The Manchester group offers a broad range of projects involving the analysis of a wide range of different types of events or `final states' at the LHC. We study, for example, events containing Higgs bosons, top and beauty quarks, multiple vector bosons (including events produced by the collision or `fusion' of two vector bosons), hadronic jets, and `missing transverse momentum'. The latter is a signature of weakly interacting particles that escape direct detection in the experiment (for example, neutrinos, but possibly also dark matter). A few more details of some of these possibilities are given in the following paragraphs, but cannot do justice to our full programme. Please get in touch with us.

Following the discovery of a Higgs boson in July 2012, the LHC experiments have focussed on determining its properties. The Manchester group has led the way in model-independent analysis of the Higgs boson production in proton-proton collisions, including the first-ever measurements of the Higgs boson differential cross sections using data in the diphoton decay channel. The group continues to make major contributions to the ongoing LHC Run-II model-independent Higgs analysis programme and is leading the effort to search for New Physics in the Higgs sector using this model-independent approach. This includes searches for CP-violation in the Higgs sector as well as searching for Higgs boson interactions with Dark Matter. Because of its large mass the top quark has a special place in our understanding of the Higgs mechanism. It is extremely important to measure directly the coupling of the Higgs boson to the top quark. Manchester is very active in searches for the associated production of Higgs bosons and top quarks, with Higgs decays to b quarks and also to multi-lepton final states (via the Higgs to WW decay). These events provide additional sensitivity to CP-violation in the Higgs sector. Many other properties of the top quark are being studied in Manchester, such as correlations between the final state particles that arise from the spin dependence of the weak interaction and the effects of the strong interaction between the quarks produced in top quark decays. We are also active in the search for events containing pairs of Higgs bosons in the ττbb final state that could be produced, e.g., in models containing Gravitons. The search for events containing four top quarks is another area of interest.

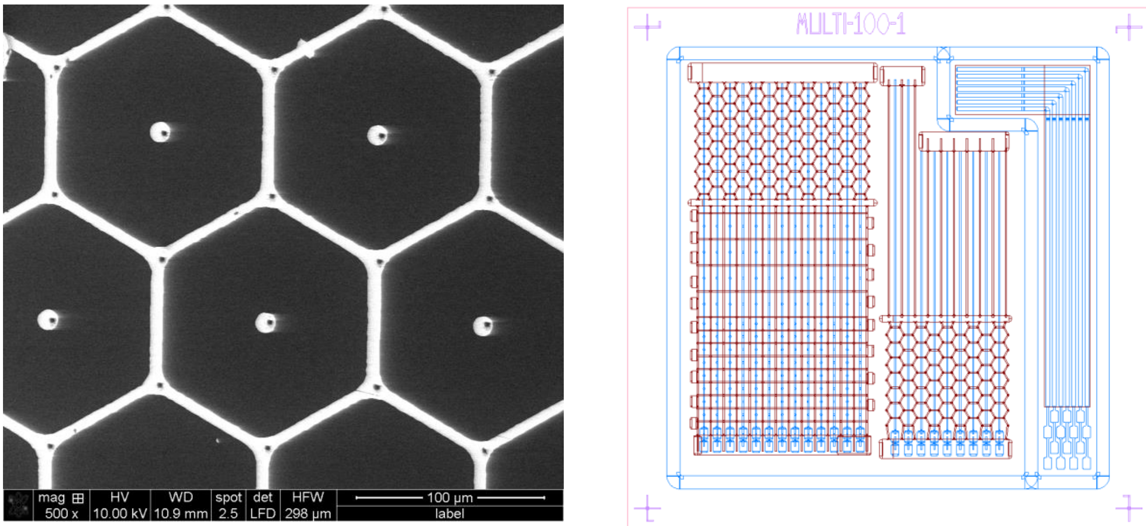
Processes in which both of the incoming protons emit a Standard Model vector boson (a W or Z boson) produce a very distinctive experimental signature and are particularly suited to studies of weakly interacting particles. In studying such `Vector Boson Fusion' (VBF) processes, the Manchester group has led the way within ATLAS: making the first observations of the VBF production of both W bosons and Z bosons in their decays to electrons and muons, as well as conducing novel searches for the VBF production of beyond the Standard Model dark matter particles. One of the novel features of this latter analysis was that the numbers of candidate events and their kinematic distributions were expressed as ratios to the already established SM VBF production of Z boson decays to electrons and muons. This `cross section ratio' approach has helped to minimise the effect of both experimental and phenomenological systematic uncertainties on the measurements. Looking to the future, as well as benefiting from the increased data set, we are extending this programme to include a wider range of possible final states, such as events containing b quarks, and tau leptons, and extending the range of possible new physics models that we can investigate.

We search for the direct production of new heavy, weakly interacting, particles also in two boson final states, as predicted by models that contain, e.g., Randall-Sundrum Gravitons or an extended gauge sector. Manchester has significantly contributed to the ATLAS search for Gravitons and lead the combination of leptonic and hadronic decay channels. Currently, we are optimising our searches with the complete run-2 data set to gain an even better sensitivity to new physics that might be just round the corner.

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

In addition to data analysis, the Manchester group has long-term involvement and leadership of the development of experimental 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 2035. 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.

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



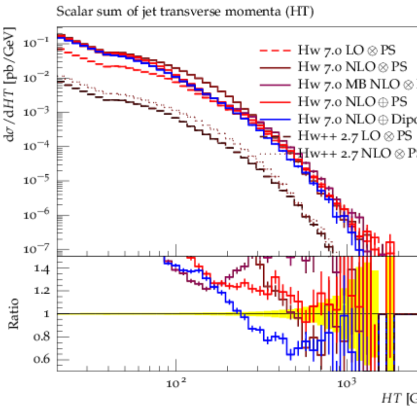
A SEM close-up picture of a 3D diamond test detector with metallisation pattern (left) and schematic of the metallisation-structure with hexagonal, rectangular and quadratic test structures, and a test strip detector on a 4.5x4.5mm2 area (right). The cell width of the 3D detector is 100□m.

One application of this new technology would be in the field of particle physics, specifically for the Phase-2 upgrade of the detectors at the Large Hadron Collider or at a future linear collider for a beam-calorimeter application. We also collaborate with The Christie Hospital to apply this technology to challenges in radiology. The objective is to use 3D diamond dosimeters for *in vivo* dosimetry applications for photon and proton beam therapy.

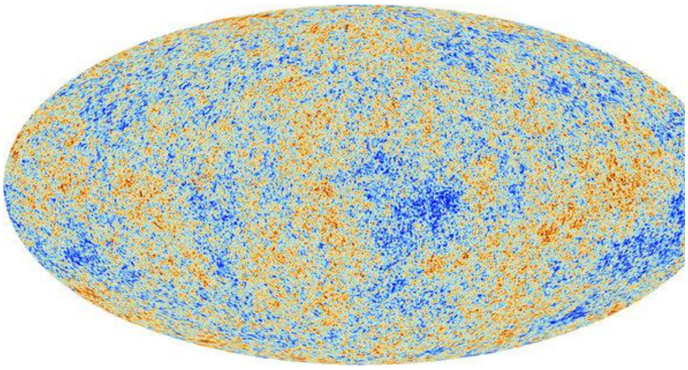
Possible PhD projects can combine activities from multiple of the above ATLAS research areas.

PARTICLE PHYSICS - THEORY

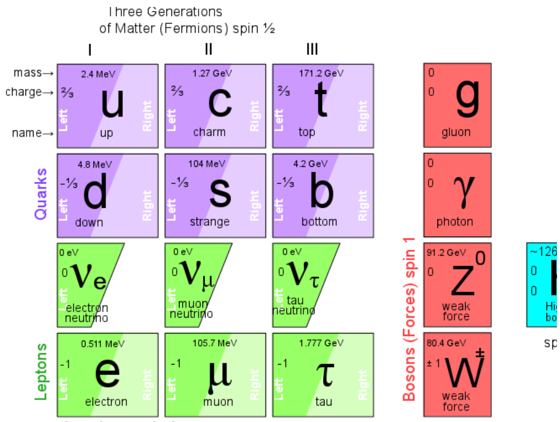
The Group has particular expertise in almost all aspects of Collider Physics phenomenology, in the Physics of the Early Universe, in Higgs and Neutrino Physics and in Physics Beyond the Standard Model. Our projects are often focused on aspects of theoretical physics that can be tested in ongoing or future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



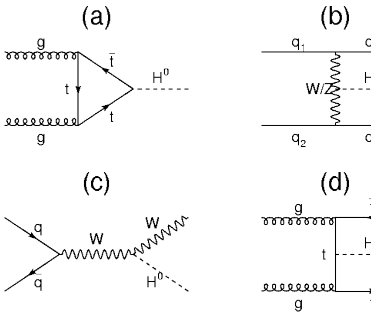
HERWIG 7.0 Higgs production



PLANCK CMB image



Standard Model



Higgs production channels

Beyond the Standard Model and Particle Cosmology

Prof. Apostolos Pilaftsis (apostolos.pilaftsis@manchester.ac.uk)

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

Early Universe and Particle Physics

Dr Fedor Bezrukov(fedor.bezrukov@manchester.ac.uk)

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

We are focusing on the study the inflationary models and relation to the properties of particle physics. The interesting questions include models with modified coupling of fields and gravity, scale invariant theories. At the same time, the models studied are relevant for Dark Matter generation, provide predictions for new physics searches in the laboratory. Collaboration with other groups within the School of Physics and Astronomy is crucial for the project.

Using QCD to explore the TeV scale at the Large Hadron Collider

Dr Mrinal Dasgupta(mrinal.dasgupta@manchester.ac.uk)

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

Automating QCD calculations

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

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

Monte Carlo Modelling of QCD Interactions

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

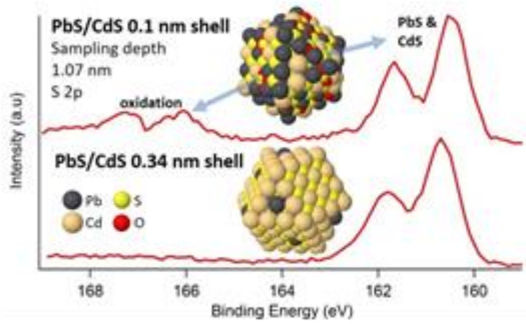
In high energy physics we are usually interested in interactions between partons (quarks and gluons) with high momentum transfer, producing new particles like the Higgs boson or supersymmetric partners, or more familiar ones like the top quark. These decay to produce further partons. However, partons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

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

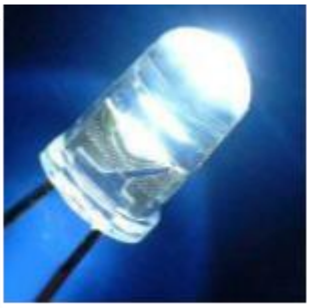
PHOTON PHYSICS

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

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



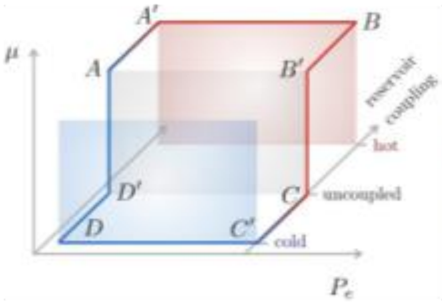
Synchrotron-excited nm-scale depth profiling used to understand passivation of the surfaces of quantum dot light harvesters.



An LED based on InGaN/GaN quantum wells.

Blood flow imaging in the hand of a patient with arthritis.

Students working in a laser lab in the Photon Science Institute



Modelling a quantum system coupled to its environment.

An atom cooling and trapping set-up, showing the source chamber (right), Zeeman slower (centre) and trapping chamber (left).

Carrier dynamics in GaN films and InGaN/GaN Quantum Wells

Dr. David Binks (david.binks@manchester.ac.uk)

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

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

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

Project:

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

Atomic collision physics using combined electron and laser beams

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

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

Projects:

- Electron impact ionization and excitation of atoms and molecules
- Looking for quantum interface in two-colour photoionization pathways
- Studying highly excited Rydberg atoms to produce q-bits
- Producing cold electrons from cold atoms for diffraction experiments and for injection into future accelerators

Spectro-microscopy of nanostructured materials

Dr. Patrick Parkinson (patrick.parkinson@manchester.ac.uk)

Over the past two decades, developments in nanostructured materials have enabled huge progress in electronics and optoelectronic devices. However, novel materials, particularly those with nanoscale dimensions present unique challenges for characterisation, where surface-effects become dominant and light-matter interactions can be modified by wavelength-scale geometry.

In my group, we are primarily concerned with how energy moves in nanostructured materials for optoelectronics applications (LEDs, lasers and photovoltaics). To study this, my group is developing automated spectro-microscopy techniques coupled to femtosecond lasers to allow the controlled study of carrier dynamics at the sub-micron length scale and sub-picosecond timescale. By combining advanced photonic characterisation with machine vision, we seek to take advantage of added information revealed through big-data approaches.

Projects:

- Development of novel spectroscopic methods: Novel materials often require novel spectroscopic approaches. Our group develop useful tools to address specific challenges - this recently includes single-photon interference spectroscopy, micro-transient absorption tools, and non-linear mapping for 3D reconstruction
- Semiconductor nanowire spectroscopy: While nanowires have high promise as future optoelectronics components, wire-to-wire inhomogeneity presents a unique challenge. We develop statistical approaches to understand and optimize this novel material
- Three-dimensional optoelectronic device characterisation: Nanoscale structured materials tend to exhibit highly inhomogeneous properties. The relationship between these local properties and macroscopic behaviour is unclear – by mapping properties in 3D, we relate these measurements to bottom-line efficiencies.

Understanding photovoltaics and photocatalysts at the atomic scale

Prof. Wendy Flavell (wendy.flavell@manchester.ac.uk)

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

How do we do this? My group uses world synchrotron facilities for surface spectroscopies (such as photoemission) to study light-harvesting quantum dots, organometal halide perovskites and heterojunctions for next-generation solar cells. Currently we are developing time-resolved measurements using laser-synchrotron pump-probe spectroscopy in order to probe the charge transport in real time at these interfaces. We also use advanced spectroscopies in the Photon Science Institute at UoM - including near-ambient pressure X-ray photoelectron spectroscopy (one of only around 30 machines available in the world). This helps us to understand the reactions of just the topmost few atomic layers of our nanomaterials with the atmosphere - critical to the long-term stability of solar cell devices containing them.

34 PhD students of 10 nationalities have graduated under my supervision.

Some recent papers: DOI:10.1039/c7nr00672a; DOI:10.1039/c7cc01538k; DOI:10.1063/1.4943077

Projects:

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

Optical techniques as medical diagnosis tools

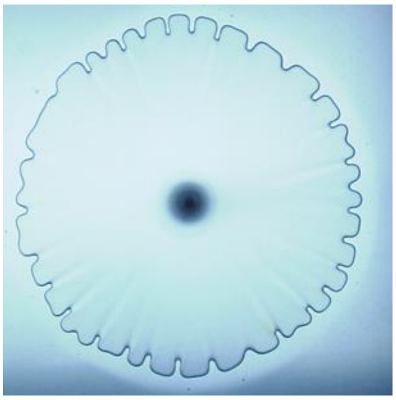
Dr. Mark Dickinson (mark.dickinson@manchester.ac.uk) in collaboration with Dr. Andrea Murray (andrea.murray@manchester.ac.uk)

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

Projects:

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

PHYSICS OF FLUIDS AND SOFT MATTER

Prof. Anne Juel (anne.juel@manchester.ac.uk) Dr. Draga Pihler-Puzovic (draga.pihler-puzovic@manchester.ac.uk)

Research in Physics of Fluids and Soft Matter is focused on the dynamics and instabilities of complex systems, from bubble flows to soft tissues, and encompasses both curiosity-driven and industrially-relevant phenomena. Our group currently consists of 10 members including two permanent members of academic staff (Prof Anne Juel and Dr Draga Pihler-Puzović). Laboratory-based research into nonlinear phenomena often reveals unexpected findings, which in turn requires interpretation via mathematical modelling.

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

Current research themes in our group include:

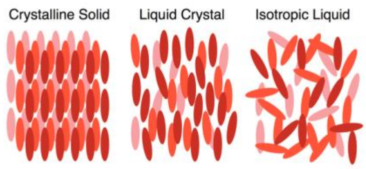
- Instabilities and pattern formation on the pore scale (AJ, DPP).
- Droplet microfluidics (AJ, DPP).
- Instabilities in soft materials (DPP).
- The dynamics of wetting (AJ).
- Yield phenomena in complex materials (AJ).

If you would like to know more, please contact anne.juel@manchester.ac.uk or draga.pihler-puzovic@manchester.ac.uk. PhD funding is available through EPSRC Doctoral Training Awards and CASE studentships.

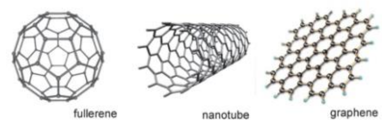
SOFT MATTER: LIQUID CRYSTALS

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

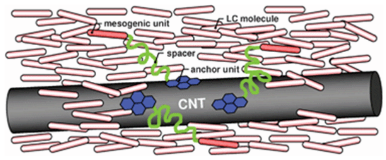
Our group primarily performs experimental research in different areas of soft condensed matter, liquid crystals, polymer modified liquid crystal composites, nanoparticle dispersions in anisotropic fluids and liquid crystal phases formed by colloidal materials, especially graphene oxide.
Investigations range from fundamental physical questions, such as chirality, scaling laws in defect annihilation and formation, domain coarsening, or fractal structures, to studies which are of relevance to the applications of liquid crystals in displays and non-display devices such as sensors or the development of multifunctional advanced materials.



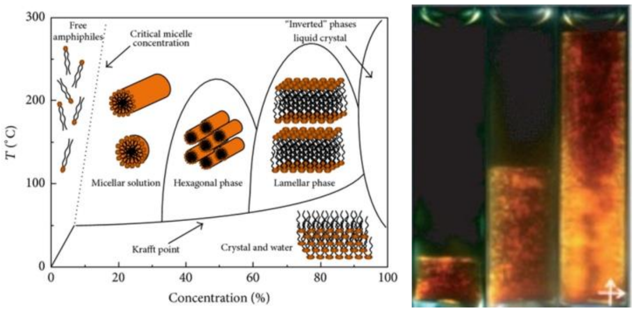
thermotropic liquid crystal



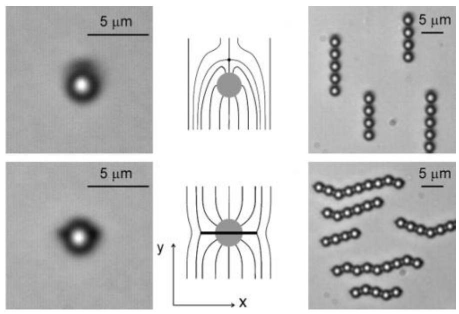
carbon nanoparticle dopants



novel functional materials

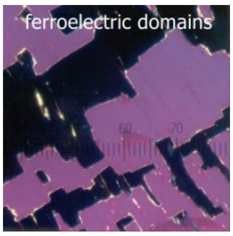


lyotropic liquid crystals of graphene oxide and colloids

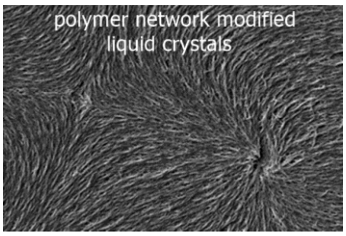


electrophoresis and colloid chaining

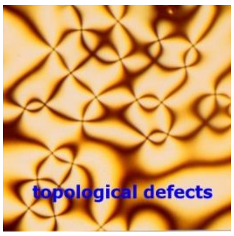
We use a range of in house experimental techniques such as optical polarized microscopy, various electro-optic and electric techniques, optical and dielectric spectroscopy, time resolved image analysis and specialized cell production. For some specialized techniques and material synthesis, we collaborate with different groups world-wide.



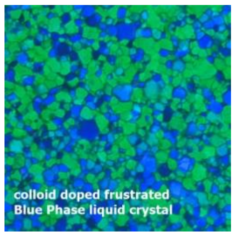
ferroelectric LC



polymer modification



defect annihilation



frustrated phases

Projects:

Myelin figures in the presence of nanomaterials

Myelin figures are long, thin, cylindrical structures of rolled up lipid bilayers, which are often observed in biological cells, but can also be generated from amphiphilic molecules in the presence of water in the laboratory. Such figures have been observed to grow in a filament like fashion when surrounded by a bulk solvent. At an initial stage, we will determine the growth dynamics in different solvents to gain an understanding of the role of carrier fluid viscosity. We will further characterize and analyse an elastic buckling instability, which can generally be observed.

In a further step, we will characterize the influence of 0D, 1D and 2D nanoparticle seeds on pattern and growth dynamics of the Myelin figures. These seeds can be fullerenes, nanotubes and graphene oxide, but also larger structures such as nanospheres, nanowires and nanoplates. Special notice will be given to the possible occurrence of nanomaterial incorporation into the myelin filament, as this could be transferred onto magnetic particles being surrounded by a double layer membrane, thus mimicking magnetotactic bacteria.

The obtained results will be compared to other liquid crystalline systems, such as the filament growth of the bent-core B7 phase, which also exhibits an elastic buckling instability when being formed in its own isotropic phase. This comparison will further the understanding of soft matter filament growth in general and it is anticipated to bridge several different systems to arrive at a universal description of this phenomena.

Photo-responsive ferroelectric and frustrated liquid crystals

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, the chiral 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.

Dispersions of liquid crystals with magnetic nanoparticles and ferrofluids

In recent years the dispersion of nanoparticles in liquid crystals has attracted increasing interest and attention, due to the possibility to tune physical properties of the liquid crystal phases on the one hand, and to exploit the self-assembly of the liquid crystal to induce self-assembly of nanomaterials, on the other. In most cases dielectric nanoparticles of spherical or cylindrical shape were used in nematic liquid crystals, or ferroelectric nanoparticles in nematic and ferroelectric liquid crystal phases.

In this project we will investigate the influence of magnetic particles as well as ferrofluids dispersed within the liquid crystal. This allows the steering of the material by two independent applied fields, addressing the nanoparticles by the magnetic field and the liquid crystal mainly by an electric field. We will study in how far magnetic nanoparticles can be aligned by the self-organization of the liquid crystal itself, as well as an additionally imposed magnetic field, and what influence a superimposed electric field exerts. Similarly, we will use ferrofluids, dispersions of magnetic particles in an isotropic liquid, with droplets then dispersed in a liquid crystal matrix, to determine the viscosities (and their anisotropy and temperature dependence) of the liquid crystal on a microscopic scale. For the latter, nematic, fluid smectic as well as lyotropic phases can be employed.

An experimental setup for the application of a magnetic field at varying amplitude will be constructed, and otherwise standard methods of liquid crystal electro-optics and simple fluid dynamics be employed.

Mixing spheres, rods and discs: inorganic liquid crystals

Besides amhiphilic molecules, also anisotropic ridged bodies, such as rods and plates can form lyotropic liquid crystals in the presence of a solvent, which is often water. This is due to excluded volume effects, and has been elaborated a few decades ago by a theoretical description of colloids derived by Lars Onsager. Inorganic liquid crystals have been observed for a range of colloidal particles such as vanadium pentoxide, which represent rod-like rigid objects, and clays, which represent disk-like objects. Additionally, many spherical nano-objects such as silicon oxide are available which are unable to form liquid crystals when dispersed in a carrier fluid by themselves.

We will initially study the phase diagrams and mixture behaviour of a range of different combinations, rods with disks, rods with spheres and disks with spheres, to gain an understanding at which concentration region a particular component

becomes destructive and suppresses the formation of self-organized liquid crystalline states.
In a second step, we will investigate ternary systems of spheres, rods and plates to understand the more complex steric interactions and their effects. Finally, we will in a third step, replace the isotropic carrier fluid with an anisotropic, nematic liquid crystal. This in turn can consist of rod or disk like molecules. These investigations will largely contribute to an understanding of the order behaviour and the physical properties of particle doped liquid crystals, which have recently, for particles of a single type, gained much attention in the area of nanotechnology. With this investigation we will extend existing efforts and understanding from a single type dopant to simultaneous three types of dopants.

Motion of spherical and elongated microparticles in liquid crystals

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, fuelled 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, if necessary.
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.

From dissolved polymer liquid crystals to polymer stabilized liquid crystals

In the past, investigation have been carried out which dissolve polymer chains in a liquid crystal phase, or, at the other extreme, produce a phase separated polymer network which bi-continuously is dispersed throughout the liquid crystal. The latter materials are called polymer stabilized liquid crystals, and are derived from photo-polymerization of a bi-functional monomer within the liquid crystal host.

Yet, not much attention has been paid to the region between those two extreme cases, between 0% crosslinking and 100% crosslinking. This will be the main area of this research, with a controlled variation of the crosslinking density, which can be achieved by photo-polymerization of mixtures of different concentration of bi-functional and mono-functional monomers within the liquid crystal phase.

Two types of liquid crystals will be studied, the common nematic liquid crystal as it is found in modern days displays, and chiral smectic, ferroelectric liquid crystals, which are used in micro-displays. For both types of liquid crystal, we will vary the crosslinking density from 0% to 100% and study the electro-optic and electric properties of the two material series. This will namely be threshold voltage, response times, viscosities and contrast ratio, along with dielectric spectroscopic studies of the different dielectric modes, which will change in amplitude and frequency, as the crosslinking density is changed. We will further develop methods which allow time resolved measurements, so that the electro-optic and electric parameters can be followed in situ as the polymerization takes place.

This will allow a detailed analysis and prediction of the liquid crystal electro-optics for nematic and ferroelectric liquid crystals, and thus a prediction on how to tune the material properties in a simple manner. Investigations of the morphology of the formed networks by SEM will further allow to develop a fundamental understanding of how polymerization conditions, crosslinking density and polymer morphology are related.

If you are interested in any of the projects on offer, or would like to obtain more detail, please do not hesitate to email me, and we can arrange for a discussion meeting in person.