Physics Trinity Term - 2021

MPhys Projects
Trinity Term
2021

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Foreword

The MPhys project, as a major part of the MPhys course has often been considered the most enjoyable part of the course. From the comments made by students over several years, many students get a real buzz from a good project. Read this booklet carefully to find out which projects are available and what you have to do.

You will start your Major Option Classes and your MPhys project Michaelmas Term 2021. You may be given some reading or work to do over the long vacation, and you will therefore be a little better informed and prepared. The project may be your first insight into life in a physics research group and be a chance to see developments at the cutting edge of the subject. It is also a first look at problems whose solution may well be unknown, to both you and your supervisor.

To get the most out of your project you must choose carefully and prepare well. Contact potential project supervisor early and please complete the project choice form (available online) by the end of 8th week.

Please do contact the Assistant Head of Teaching, carrie.leonard-mcintyre@physics.ox.ac.uk if you have any questions.

MPhys Industrial Projects

MPhys Industrial Projects

Industrial MPhys projects were introduced in 2018, following the success of the BA industrial project scheme. These projects are proposed and led by an external company, driven by physics-related problems. These problems will improve your employability and transferable skills in an increasingly competitive jobs market. Some of the companies are also actively looking to hire graduates.

You will be supervised mainly by the industrial supervisor, with additional support from an Oxford co-supervisor. You are expected to have regular (typically weekly) interactions with the industrial supervisor, just as if they were based in the Physics Department. Modest funding is available for visits to the company – there will clearly be some variation across projects, for example regular visits to a local company by bus are feasible, but if the company is further away less frequent visits are anticipated, or your supervisor may prefer to visit you. The Oxford co-supervisor will normally have more of an oversight role – they will, for example, prepare a risk assessment for experimental work, and you should talk to them if you have problems with your industrial supervisor.

In every other respect (allocation, reports, assessment) the industrial MPhys projects are identical to the MPhys projects offered from within Physics. Projects are allocated in the same way as, and alongside, the MPhys projects, so you can apply for a mixture of project types. If you would like to discuss a project before applying for it, please contact the Oxford supervisor in the first instance, who can make an introduction to the company.

The information in this handbook is accurate as at **10 May 2021**, however there may be changes, in particular to the projects listed.

Choosing your MPhys project

How to go about choosing a project

Around two thirds of the 4th year students may expect to be allocated one of their choices of project. For the remaining third we try to allocate a project in a similar area of interest and also taking the students choice of Major Options into account. Some projects are more popular than others, for instance projects relating to Biophysics, therefore you are advised to select carefully your lower choices. Perhaps there is a project that you would like to do, but this is not listed in this handbook, in which case you may approach potential supervisors with your ideas.

Please inform the Assistant Head of Teaching of the topic, the title and the supervisor, if you have made your own arrangements. You are also encouraged to write a short statement if you have any particular strengths or experience relating to your choices, or if you are choosing a project with your future career in mind.

Although every effort is made to include all possible information about and on the MPhys projects offered, new projects may become available after the publication of the *MPhys Projects Trinity Term* and infrequently a project may have to be withdrawn. All changes will be published at http://www2.physics.ox.ac.uk/students/undergraduates.

Project allocation

Projects are allocated by the Assistant Head of Teaching using the student's choices submitted onlline.

For the allocation exercise, the student name and college are hidden to prevent any bias. All the project choice forms are entered into an access database. All ten choices are listed in order of preference and additional comments are recorded.

For very popular choices we use the following procedure:

(i) Supervisors are consulted as they may be contacted by prospective students about the projects they are offering, although this is not essential for the allocation of the project. Supervisors' input is essential in trying to match projects to students;

(ii) The outcome of the latest examination results, normally that of third year, Part B, ranking will also be used to assign students to projects. Exceptionally, second year, Part A, ranking will be used when Part B results are not available.

(iii) The PJCC (Physics Undergraduate Consultative Committee) is also consulted on an annual basis about the process. If you are not happy with the MPhys project you have been allocated, you are encouraged to discuss other possibilities with the Assistant Head of Teaching .

(iv) Should it still prove difficult to assign the project, each student who wishes to be allocated the specific project is assigned a number and then the winner is drawn from a hat.

Project risk assessment

Assessing risks is an essential element of training for project work. It is good practice for students and supervisors to complete the risk assessment associated with the project before starting. Please see http://www2.physics.ox.ac.uk/study-here/mphys-and-ba-project-information.

Project assessment

Project Assessors are appointed every year to assess all the MPhys projects. The assessors are appointed by the relevant physics sub-Departments, the Physics Department or less frequently from another department of the University. The assessors on this committee are usually not Physics Finals examiners, but they may serve in this capacity.

The **expert** assessor will generally come from the sub-department to which the project is assigned and they will have more specialist knowledge in the field of the project, or one closely related. The **non-expert** assessor will generally work in a different area of physics from the subject of the report and will mark reports chosen from other physics sub-Departments. Each written MPhys report will be assessed by an expert (junior) and a non expert (senior) assessor.

Each MPhys candidate will be expected to attend a meeting with the two assessors of their project to discuss the written report. The purpose of this meeting is to help the assessors with assessing the candidates written report. Crucially the meeting helps clarify any issues that the assessors have after having read the written report. The assessors will read the supervisor's report on the project to learn what special difficulties were encountered, the extent of the initiative shown by the candidates, and so on.

The meeting will last about 20 minutes and will be rather informal. It will not require the preparation of a special presentation; indeed no visual aids other than your report (and your log book, if appropriate) will be allowed. The candidate will be expected to start the meeting by giving a short summary of the project, lasting no more than 5 minutes. The rest of the meeting will consist of a question and answer period, which has the primary purpose of clarifying any issues that the Assessors have with the written report.

The meetings with the candidates are scheduled for 5th week in Trinity Term. The precise criteria for the overall assessment of the project will finalised by the examiners. How the final project mark is calculated will be published in the Examination conventions produced by the examiners. The overall assessment embraces the quality both of the underlying scientific work and the presentation in the report.

Any change to the project assessment, the meeting and submission are published in the *Examination Convention*s at Examination Matters

The *MPhys Project Assessment form* will be published on the Examination Matters normally before the end of Hilary Term.

Examination Conventions

The Examiners are responsible for the detailed weightings of papers and projects. The precise details of how the final mark is calculated is in the *Examination Convention*s at Examination Matters Students are notified by e-mail when they become available.

Weightings for the MPhys and Papers

The precise details of how the final mark is calculated is published in the *Examination Conventions* at Examination Matters.

Project Outcomes

The outcomes of projects are very flexible and the results may not be precisely as described by the project description in this handbook. Remember that they are intended as an introduction to research and the unexpected often happens!

According to the QAA benchmark statements for physics ‘Open-ended project work should be used to facilitate the development of students’ skills in research and planning (by use of data bases and published literature) and their ability to assess critically the link between theoretical results and experimental observation’ ref.: Quality Assurance Agency for Higher Education, subject benchmark: Physics, astronomy and astrophysics 2008.

Project prizes

A number of prizes may be awarded for excellence in various aspects of the MPhys projects including but not limited to the list below:

(a) The Gibbs Prize for Best MPhys Research Project.

(b)The Gibbs Prize for the best use of experimental apparatus in an MPhys project.

(c) A Physics Prize for an MPhys project in Atomic and Lasers Physics.

(d)The BP Prize for an MPhys project in Theoretical Physics Project.

(e) The Johnson Memorial Prize for an MPhys in Astrophysics.

(f) The Johnson Memorial Prize for an MPhys in Atmospheric, Oceanic and Planetary Physics.

(g) The Met Office Prize for a Project in Atmospheric, Oceanic and Planetary Physics.

(h) A Physics Prize for an MPhys Project in Condensed Matter Physics.

(i) The John Thresher Prize for an MPhys Project in Particle and Nuclear Physics.

Timetable for Students

Trinity Term 2021

Week 1 Publication of the *MPhys Projects Trinity Term* **http://www2.physics.ox.ac.uk/students/undergraduates**

Before deciding on a project students are encouraged to discuss any projects, in which they are interested, with supervisors, but there is no obligation to do so and allocation of projects does not depend on doing this**.**

Week 8 Complete the *Project Choice Form*
(Fri 15:00) [On-line or by e-mail]

July -August **Provisional Allocation of Projects**
Third year results published and provisional allocations made
Majority of MPhys Project allocations made

September **Publication of the Project Allocation List** **http://www2.physics.ox.ac.uk/students/undergraduates**
Students read the introductory papers on their project

Michaelmas Term 2021

Week 0 Publication of the *MPhys Projects Guidance* **http://www2.physics.ox.ac.uk/students/undergraduates**
(Mon) [e-mail notification] Talk to your college tutor about the project you have been allocated.

Weeks 1 & 2 **Compulsory Safety Lecture and Risk Assessments** **Consult lecture list**
Completion and submission of your *Risk Assessment Acknowledgement* form.
Compulsory attendance of the Project Safety Lecture. You will **NOT** be allowed to start your project if you have **not** completed and submitted your *Risk Assessment Acknowledgement* form ***online*** to **teachingadmin@physics.ox.ac.uk**.. Students meet supervisors to get instructions including alternate arrangements if the supervisor has to leave Oxford during the project period.

Week 3 Project period starts. Please note: the total effort devoted to the project should be equivalent to **20** working days full time activity, plus about six weeks for analysis, write up and literature review during Michaelmas and Hilary terms. Students should discuss with the supervisor(s) a project plan to accommodate both their project and Major Option Classes

Students need to understand that outcomes of projects are uncertain and the project may change from the description originally provided. Projects are an introduction to research and are not necessarily predictable.

Weeks 7 Discuss plan of project report with supervisor(s). Students must prepare a short progress report (one side of an A4 sheet of paper) outlining plan for the project and/or literature review.
The report is submitted ***online*** to **teachingadmin@physics.ox.ac.uk**.
This progress report is also for your College tutorm records .

Hilary Term 2022

Weeks 1 - 8 MPhys project period continues

Week 6* 'How to write an MPhys Project Report' lecture **Please consult the lecture list for details**

Week 3 or 4 Talk to your college tutor about the progress of your project.

Week 9 Provide a draft (as complete as possible) of MPhys report to your supervisor. You and your supervisor must complete and sign the *Project Draft Form*.
(See **http://www2.physics.ox.ac.uk/students/undergraduates**)

Week 10 Deadline for receiving comments from supervisor.

The schedule for handing in the draft report and receiving comments can be changed by mutual agreement.
Please let Carrie Leonard-McIntyre know of changes of more than one week.

Trinity Term 2022

Week 1 MPhys project report submitted online.
(Mon 12 noon) Any change to the submission is published in the **Examination Conventions** at Examination Matters
at **https://canvas.ox.ac.uk/courses/67877/pages/examination-matters?module_item_id=738728**
On line project submission with the Declaration of Authorship and SpLD if appropriate)in pdf format.

Timetable for Supervisors

Hilary Term 2021

Week 1-8 Call for MPhys Projects starting in Michaelmas Term starts. **E-mail**

Trinity Term 2021

Week 1 Publication of the *MPhys Projects Trinity Term*

http://www2.physics.ox.ac.uk/students/undergraduates

Students may contact you to learn more about your projects. They are not obliged to do this and the allocation of projects is not in any way dependent on them doing so.

July - September **Provisional Allocation of Projects**
Third year results published and provisional allocations made.

September **Publication of the Project Allocation List** **http://www2.physics.ox.ac.uk/students/undergraduates**
Students read the introductory papers on their project

Michaelmas Term 2021

Weeks 1 & 2 **Compulsory Safety Lecture and Risk Assessments** **Consult lecture list**
Completion and submission of your *Risk Assessment Acknowledgement* form.
Compulsory attendance of the safety lecture.
Students will **NOT** be allowed to start their projects if they have not completed and submitted their *Risk Assessment Acknowledgement* form ***online*** to **teachingadmin@physics.ox.ac.uk**.
Students meet supervisors to get instructions including alternate arrangements if the supervisor has to leave Oxford during the project period.

Week 3 Project period starts. **Please note:** the total effort devoted to the project should be equivalent to **20** working days full time activity during Michaelmas and Hilary terms. [Guidance: the total effort devoted to the project should be equivalent to **20** working days full time activity, plus about six weeks for analysis, write up and literature review during Michaelmas and Hilary terms.]
You must discuss with the student(s) the project plan to accommodate both their project and Major Option Classes.

Weeks 7 Discuss plan of project report with your supervisor(s). Student to have prepared a short progress report (one side of an A4 sheet of paper outlining plan for the project and/or literature review

Students need to understand that outcomes of projects are flexible and the project may change from the description originally provided. Projects are not necessarily predictable and can be an introduction to research.

Hilary Term 2022

Weeks 1 - 8 MPhys project period: during this period all of the experimental and theoretical work necessary for the project should be completed. You should meet the student regularly and leave your contact details for the student to contact you should the need arise. You should encourage the student to begin the project write-up as early as possible.

Week 9 Full as possible draft of the MPhys report handed in by student to you and *Project Draft Form*.
(See **http://www2.physics.ox.ac.uk/students/undergraduates**)
The completion of the *MPhys Draft Form* confirms that the draft report has been seen and the form must be sent to **Physics Teaching Faculty Office**, signed by both student and supervisor.
Please notify the Physics Teaching Faculty Office of any delay in returning the completed form.

Week 10 Comments by supervisor on draft report is given to the student.

The schedule for handing in the draft report and receiving comments can be changed by mutual agreement.
Please let Carrie Leonard-McIntyre know of changes of more than one week.

Trinity Term 2022

Week 1 MPhys Student submits their final report on-line.
Any change to the submission is published in the **Examination Conventions** at Examination Matters at **https://canvas.ox.ac.uk/courses/67877/pages/examination-matters?module_item_id=738728**
Deadline for return of Supervisor's Report Form.

MPhys Project Descriptions

Atomic and Laser projects

A&L01 Relativistic Molecular Dynamics Simulations

Modeling many-body systems is one of the core challenges of modern physics. The standard numerical approach consists of following each particle. The classical equations of motion are then solved by calculating the force produced by all other particles onto every single particle. This numerical technique is known as Molecular Dynamics. While Molecular Dynamics can be generalized to quantum systems by introducing appropriate interaction potentials, the extension to relativistic many-body systems has not been developed in details. In this project, we propose to extend the current Molecular Dynamics to relativistic systems by replacing the classical equations of motion with their fully relativistic counterparts, but with each particle interacting with non-relativistic potentials. This approach is viable for studying mildly relativistic systems, and it could be used to study electron-positron plasmas relevant in many astrophysical systems. The project demands good analytical and programming skills (C/C++, Python, or similar).

Supervisor: ***Prof G Gregori***
Email: ***Gianluca.Gregori@physics.ox.ac.uk***

A&L02 Peter Norreys' Atomic & Laser projects

When intense laser pulses propagate in plasma, a rich variety of wave-wave processes are seeded and grow rapidly from background noise. These highly non-linear waves then organise themselves so as to cascade the incident laser energy out of the focal region where it needs to be deposited. This has the deleterious effect of reduced coupling of the incident energy to the target and, with that, the available ablation pressure and peak implosion velocity of inertial fusion targets. However, if one is able to both control and then utilise these wave-wave processes, then it might be possible to reduce the drive energy for high gain inertial fusion to below 1 MJ needed for a fusion reactor, as well as generate laser pulses of unprecedented peak powers and energy densities. Two state-of-the-art projects are offered to investigate this exciting physics.

A&L0201 Two Plasmon Decay Instability

The student will start by compiling and running known test cases using the Laser-Plasma Simulation Environment code (LPSE) simulation code that we have acquired, in collaboration with the Laboratory for Laser Energetics at the University of Rochester. LPSE contains a practical numerical model that solves the coupled vector equations for the propagation of nearly monochromatic, coherent, electromagnetic waves in inhomogeneous plasma. The student will then upgrade the code to include new physics to study the effect of the two-plasmon decay instability using beams with orbital angular momentum for large density scale-lengths associated with inertial fusion implosions.

A&L0202 Stimulated Raman scattering instability

The student will start by compiling and running known test cases using the OSIRIS particle-in-cell simulation code that we are running, in collaboration with the University of California Los Angeles and IST, Lisbon, on the ARCHER2 National Supercomputer to simulate experimental data obtained on the Medium TeraWatt (MTW) Laser Facility at the Laboratory for Laser Energetics at the University of Rochester. LPSE The student will study the extent of the laser pulse bandwidth and its chirp on the growth of the stimulated Raman scattering instability in the MTW conditions.

A&L0203 A study of two colour implosions for inertial fusion

Previous experimental work has suggested that low convergence ratio implosions of wetted foam capsules result in performance that is close to one-dimensional using the National Ignition Facility. This has led to the identification of a new regime for such experiments, where (by keeping convergence ratio low and restricting other key implosion parameters) instability growth is expected to be small and experimental performance is expected to be well described by simulation codes. While previous work has been in an indirect drive configuration, our work has concentrated on the direct drive approach, which allows the low convergence ratio to be compensated through higher capsule absorption to enable performance more relevant to ignition. A 1D simulation campaign has identified promising performance in this regime, and 2D simulation work to confirm these results is in progress. The student will use the Hyades 1D radiation hydrodynamic simulation code to study the effect of changing the colour of the final drive pulse to minimise the drive energy. If time allows, the best results will be extrapolated to two dimensions using the RIGEL radiation hydrodynamics simulation code at the University of Rochester.

A&L0204 Compressed sensing for ultra-fast imaging

The SHRIMP device is new ultra-fast imaging concept based upon the combination of compressed sensing with chirped laser pulses allows users to choose a frame interval (temporal resolution) between nanoseconds and femtoseconds, where group velocity dispersers such as glass blocks, optical fibres, grating arrays, or a combination may be used to temporally stretch an optical probe pulse. A lossless compressed imaging design then allows for the efficient capture of a three-dimensional signal S(x; y; t) on two-dimensional CCD arrays, after one manipulates S(x; y; t) into a format where a compressed sensing reconstruction is possible. The student will explore the possibility of combining the SHRIMP with another ultra-fast imaging device - the SPIDER (which stands for Spectral Phase Interferometry for Direct Electric-field Reconstruction) - to obtain a full 3d intensity profile in both time and space on the femtosecond timescale. The student will build the device in the Clarendon Laboratory during the project.

Supervisor: ***Prof P Norreys***
Email: ***Peter.Norreys@physics.ox.ac.uk***

_A&L03_ Superresolution imaging via linear optics in the far-field regime

Rayleigh's criterion defines the minimum resolvable distance between two incoherent point sources as the diffraction-limited spot size. Enhancing the resolution beyond this limit has been a crucial outstanding problem for many years. A number of solutions have been realized; however, all of them so far relied either on near-field or nonlinear-optical probing, which makes them invasive, expensive and not universally applicable. It would therefore be desirable to find an imaging technique that is both linear-optical and operational in the far-field regime. A recent theoretical breakthrough demonstrated that "Rayleigh's curse" can be resolved by coherent detection the image in certain transverse electromagnetic modes, rather than implementing the traditional imaging procedure, which consists in measuring the incoherent intensity distribution over the image plane. To date, there exist proof-of-principle experimental results demonstrating the plausibility of this approach. The objective of the project is to test this approach in a variety of settings that are relevant for practical application, evaluate its advantages and limitations. If successful, it will result in a revolutionary imaging technology with a potential to change the faces of all fields of science and technology that involve optical imaging, including astronomy, biology, medicine and nanotechnology, as well as optomechanical industry.

Epidemiological conditions permitting, the students will perform experiments in an optics lab and use advanced data processing techniques, including machine learning, to analyse the results. Affinity to experimental physics is required, as well as some programming skills (python preferred) and basic understanding of artificial neural networks.

Supervisor: ***Prof A Lvovsky***
Email: ***alex.lvovsky@physics.ox.ac.uk***

_A&L04_ Optical neural networks

The project is to implement artificial neural networks using optics rather than electronics. The training of neural network consists of linear operations (matrix multiplication) combined with nonlinear activation functions applied to individual units. Both these operations can be implemented optically using lenses, spatial light modulators and nonlinear optical techniques such as saturable absorption. However, one crucial element of the training procedure - so-called backpropagation - has so far remained elusive. Our group has developed an idea to overcome this obstacle and implement pure optical backpropagation in a neural network, thereby enabling the training that is practically electronics-free. We confirmed the viability of this approach by simulation. Our next goal – and the goal of this doctoral research project – is to set up an experiment and test the method in a practical setting.

Epidemiological conditions permitting, the students will perform experiments in an optics lab and use advanced data processing techniques, including machine learning, to analyse the results. Affinity to experimental physics is required, as well as some programming skills (python preferred) and basic understanding of artificial neural networks.

Supervisor: ***Prof A Lvovsky***
Email: ***alex.lvovsky@physics.ox.ac.uk***

_A&L05_ Quantum dots for quantum information processing - experiments and theory

This project is developing single-photon sources based on quantum dots (also known as 'artifical' or 'designer' atoms) for photonic quantum communication and information processing. You will learn to characterise the spectroscopic signatures of the quantum emitters using the standard tools and techniques of quantum optics, including micro-photoluminescence spectroscopy, single-photon detection and manipulation. The quantum dots are based on a novel material (perovskite crystal) that is predicted to be transformative for future optoelectronics, photovoltaics and quantum computing. The scope of this project encompasses a theoretical stream for students inclined towards simulations and analytical models using Hamiltonians and for the more inquisitive, master equations. The balance between theory and experiment will depend on the student.

Supervisor: ***Dr T Farrow***
Email: ***tristan.farrow@physics.ox.ac.uk***

_A&L06_ Using a quantum computer to implement quantum algorithm

The advent of quantum computers such as IBM-Q and the development of languages to programme them has made it possible to run quantum simulations. Although today's machines are in their infancy and the simulations have yet to demonstrate an advantage over classical simulations, significant strides are being made in this fast-evolving and exciting field. Quantum simulators are of intense interest to industry looking to simulate the properties of molecules and their reactions with other molecules, seeking to make high-capacity batteries, capture carbon efficiently, design drugs or prevent rust on aircraft, or find arbitrage opportunities in financian markets. This project will develop quantum algorithms to simulate a range of dynamical scenarios, such as organic or inorganic molecules (e.g. FMO, which can be found in living systems or quantum dots), logistical problems (e.g. travelling salesman), or others, and will implement the algorithm on IBM's quantum computer (IBM-Q). The results of the simulation will be benchmarked against a classical simulation. Inquisitive students will seek to optimise the design of the quantum algorithm to improve its performance where possible

Supervisor: ***Dr T Farrow***
Email: ***tristan.farrow@physics.ox.ac.uk***

_A&L07_ Laser Cooling and Trapping of Neutral Atoms

Cooling and trapping of neutral atoms with laser light is a well established technique to prepare ultra-cold atomic samples in a large variety of experiments, ranging from dense degenerate quantum gases to fully controlled single atoms being used as stationary quantum bits in quantum computing applications.

In this project, the student will be given the opportunity to model and simulate a range of different techniques for trapping and manipulating single atoms in the micro-Kelvin range. Trapping techniques under investigation include various different geometries of magneto-optical atom traps, optical molasses for atom cooling dipole-force traps for holding and manipulating single atoms. The project will be primarily theoretical, but the student is going to have the opportunity of getting acquainted with some of the atom-trapping technologies in our laboratories.

These proposed activities are all element of a larger research project that is aiming at the implementation of elementary quantum processors which use single trapped atoms as quantum bits. Depending on the overall progress, some details of the suggested MPhys project might well change.

Supervisor: ***Prof A Kuhn***
Email: ***axel.kuhn@physics.ox.ac.uk***

A&L08 **Light-Atom Interfacing in Optical Cavities**

A reliable interface between stationary quantum bits (atoms) and flying qubits (photons) is one of the key elements in many approaches to scalable quantum computing. Whilst the fundamental working principles of such an interface are well understood, many details depend on the specific implementation.

In this project, the student will be given the opportunity to model and simulate light-matter coupling in optical resonators in the strong-coupling regime. Various coupling methods, like e.g. Purcell-enhanced photon emission, adiabatic coupling, photon reabsorption and impedance matching in networks of coupled cavities are going to be explored and compared.The project will be primarily theoretical, but circumstances permitting the student is going to have the opportunity of getting acquainted with cavity-based single-photon sources in our laboratories.

These proposed activities are all element of a larger research project that is aiming at the implementation of elementary quantum processors which use single trapped atoms as quantum bits. Depending on the overall progress, some details of the suggested MPhys project might well change.

Supervisor: ***Prof A Kuhn***
Email: ***axel.kuhn@physics.ox.ac.uk***

A&L09 **Experimental Quantum Computing in Ion Traps**

This will be a lab-based project contributing to apparatus development for experiments in trapped-ion quauntum computing. The specific work will depend on the status of our research at the time. Please contact Dr D.Lucas d.lucas@physics.ox.ac.uk for more info about details of the project, and see www.physics.ox.ac.uk/users/iontrap for background information about the research group.

Supervisor: ***Prof D Lucas***
Email: ***david.lucas@physics.ox.ac.uk***

A&L10 **Modelling of modulation transfer spectroscopy**

Ultracold atoms provide a versatile platform for studying many-body quantum physics. The major technique for cooling atoms into the ultracold regime is laser cooling. This relies on very precise control of laser wavelength (around 1 part in a billion), to achieve this lasers are often referenced to atomic transitions using Doppler-free spectroscopy techniques. One such technique is modulation transfer spectroscopy (MTS) in which a phase-modulated pump beam and probe beam are passed through an atomic vapour. The non-linear medium of the vapour results in a wavelength dependent transfer of the modulation from the pump to the probe beam.

The aim of this project is to model the MTS process for particular transitions in erbium atoms. At first this will be done for a single applied laser excitation wavelength but will then be extended to the more complicated situation of the same atoms being simultaneously probed with two wavelengths. An improved understanding of MTS should enable the optimisation of the technique for stabilising the lasers required for cooling of erbium atoms.

While a large part of this project will be theoretical/computational there will also be the opportunity to compare predicted results to experiments.

Supervisor: ***Prof R Smith***
Email: ***robert.smith@physics.ox.ac.uk***

A&L11 **Simulations of a narrow-line magneto-optic trap**

Ultracold atoms provide a versatile platform for studying many-body quantum physics. The starting point for producing ultracold atoms is a magneto-optic trap (MOT) which comprises counter-propagating laser beams combined with a quadrupole magnetic field to simultaneously cool and traps atoms.

The aim of this challenging project is to simulate this process for the case of erbium atoms.

While a large part of this project will be theoretical/computational (involving programming probably in C++ /Rust/ Python) there will also be the opportunity to compare predicted results to experiments.

Supervisor: ***Prof R Smith***
Email: ***robert.smith@physics.ox.ac.uk***

A&L12 **An investigation of flying focii**

If a short laser pulse is focused with a conventional mirror then all the frequencies are focused to the same point. Recently there has been considerable interest in the “flying focus” which can generate a focal region which moves forwards - or even backwards - at arbitrary velocity.

A flying focus is generated by focusing a frequency-chirped pulse with a hypergeometric lens (related to a zone plate). With a hypergeometric lens each frequency component is focused to a different longitudinal position, and hence by controlling the chirp of the incident pulse it is possible for the focused pulse to move forwards or backwards.

Related to this idea is simultaneous spatial and temporal focusing (SSTF). Here a spatially-chirped beam (one in which the frequency varies with transverse position) is focused by a conventional optic; all frequencies are focused to the same point, but since it is only at the focus that all frequencies are present, the duration of the pulse increases with distance away from the focus. As such the region of high intensity is more strongly localized than in the absence of SSTFC.

These ideas have considerable potential in applications of laser-plasma interactions, such as laser-driven plasma accelerators, photon accelerators, and x-ray generation. In this project the student will investigate - analytically and numerically - the flying focus and SSTF systems. The objective will be to establish a framework which can describe both effects, and to investigate how these can be used to enable complete control of the spatial and temporal distributions of the focused pulse. The project will require a good understanding of modern optics and food analytical and programming skills (Matlab, Python, or similar).

Reading

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[3] D. H. Froula, J. P. Palastro, D. Turnbull, A. Davies, L. Nguyen, A. Howard, D. Ramsey, P. Franke, S. W. Bahk, I. A. Begishev, R. Boni, J. Bromage, S. Bucht, R. K. Follett, D. Haberberger, G. W. Jenkins, J. Katz, T. J. Kessler, J. L. Shaw, and J. Vieira, Phys. Plasmas 26, 032109 (2019). DOI: https://doi.org/10.1063/1.5086308

Supervisor: ***Prof S Hooker***
Email : ***Simon.Hooker@physics.ox.ac.uk***

A&L13 Wakefield acceleration driven by a flying focus

In a laser-driven plasma accelerator an intense laser pulse propagates through a plasma and drives a trailing plasma wave. The electric fields formed within the plasma wave can be one thousand times greater than those used to accelerate particles in a conventional radio-frequency accelerator, which allows the length of the accelerator to be shrunk by the same factor.

There are two key issues in laser-driven plasma accelerators. First, the electrons to be accelerated have to be injected into, and trapped within, the plasma wave before they can be accelerated. Second, when they reach high energies the electrons outrun the plasma wave, which travels at the group velocity of the laser (< c) - this phenomenon is known as "de-phasing".

A so-called "flying focus" may offer novel ways of overcoming these issues. In this approach the large spectral bandwidth of a short laser pulse is used in conjunction with a chromatic focusing element to generate a focused pulse which moves forwards - or even backwards - at arbitrary velocity. This approach could be used to reduce the speed of the driving laser pulse, which would aid electron injection, or to increase the speed to that of light in vacuo, which would overcome electron dephasing.

In this project the prospects of using flying foci to control electron injection and/or overcome dephasing will be explored through numerical simulations. The project will require a good understanding of modern optics and good analytical and programming skills (Matlab, Python, or similar).

Reading

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[2] A. Sainte-Marie, O. Gobert, and F. Quéré, Optica 4, 1298 (2017). DOI: https://doi.org/10.1364/OPTICA.4.001298

[3] D. H. Froula, D. Turnbull, A. S. Davies, T. J. Kessler, D. Haberberger, J. P. Palastro, S.-W. Bahk, I. A. Begishev, R. Boni, S. Bucht, J. Katz, and J. L. Shaw, Nature Photon 12, 262 (2018). DOI: https://doi.org/10.1038/s41566-018-0121-8

[4] D. H. Froula, J. P. Palastro, D. Turnbull, A. Davies, L. Nguyen, A. Howard, D. Ramsey, P. Franke, S. W. Bahk, I. A. Begishev, R. Boni, J. Bromage, S. Bucht, R. K. Follett, D. Haberberger, G. W. Jenkins, J. Katz, T. J. Kessler, J. L. Shaw, and J. Vieira, Phys. Plasmas 26, 032109 (2019). DOI: https://doi.org/10.1063/1.5086308

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A&L14 Entanglement analysis in an analytically solvable model

The study of ground states in many-body physics has tremendously benefited from new concepts inspired by quantum information theory. One prime example is the area law for entanglement. It states that for ground states of translationally invariant lattice models with local interaction, the entanglement of a subsystem merely grows proportionally to the boundary area of the subregion [1]. In the proposed project we will study an analytically solvable model of particles in a harmonic trap with harmonic pair interactions [2] to explore entanglement in continuous systems, and without translational symmetry. The hope is to establish an analogue of the area law for systems which are more relevant in quantum chemistry. While an analytic approach is preferable one may also resort to numerical tools to determine the mode-reduced density matrices for different spatial regions. Part of the project will also be to clarify how to "integrate out modes" (see also [3]).

[1] J.Eisert, M.Cramer, M.B.Plenio, Rev. Mod. Phys. 82, 277 (2010)

[2] C.Schilling, Phys. Rev. A 88, 042105 (2013)

[3] G.G.Amosov, S.N.Filippov, Quantum. Inf. Process. 16, 2 (2017)

Requirements: strong analytical background, excellent knowledge of harmonic oscillator states and of the second quantization

Mandatory: potential students should meet the supervisors for an informal project discussion before applying for the project

Supervisor: ***Prof V Vedral***
Email: ***vlatko.vedral@qubit.org***

A&L15 An electronics project

Diffraction is most often encountered when a coherent light source scatters from a periodic array of atoms, for example a grating. However, the complementary effect, where atoms can scatter off a periodic array of light, has also shown to occur. The method of Bragg diffraction is a valuable tool to study the momentum distribution of a trapped quantum gas. Bragg diffraction is facilitated when an atom absorbs a photon from one incident laser beam whilst emitting coherently into another laser of a slightly different frequency, thus acquiring a kick in the process. This method has been recently demonstrated to investigate the momentum distribution of a interacting Bose-Einstein condensate [1]. We aim to extend this method in investigating a BEC trapped in a quasi-two-dimensional geometry. The student will design and assemble the optical and electronic hardware required for the apparatus. They will then align the two Bragg beams on to the Bose-Einstein condensate and perform measurements of the momentum distribution and the dependence on trap geometry and atomic density. [1] I. Gotlibovych, Phys. Rev. A 89, 061604 (2014)

Supervisor: ***Prof C Foot***
Email: ***Christopher.Foot@physics.ox.ac.uk***

A&L16 Role of Generalized Pauli Constraints in time evolutions

A recent breakthrough in quantum information theory has shown that fermionic occupation numbers do not only obey Pauli's exclusion principle but are even further restricted by so-called generalized Pauli constraints (GPC) [1]. Various recent studies of concrete systems have confirmed the physical relevance of the GPC for ground states (see, e.g., Refs. [2,3]): The corresponding occupation numbers were found to (approximately) saturate some GPC. This so-called pinning effect leads to a variety of remarkable implications. One of them is that quantum systems with pinned occupation numbers may have a restricted time evolution [4]. This generalizes the well-known consequence of the exclusion principle, namely that electrons in atoms or solid materials cannot fall down to lower lying occupied energy shells. In this project, time evolutions for two systems (a harmonic model and the few site Hubbard model) should be analytically discussed and the role of the GPC therein should be explored. For instance, can a transition from pinning to non-pinning be induced in the Hubbard model by an external magnetic field? In the ideal case, also an experimental setup shall be proposed allowing one to measure the pinning effect and thus experimentally verify the GPC.

[1] M.Altunbulak, A.Klyachko, Commun. Math. Phys. 282, 287 (2008)

[2] C.Schilling, D.Gross, M.Christandl, Phys. Rev. Lett. 110, 040404 (2013)

[3] F.Tennie, D.Ebler, V.Vedral, C.Schilling, Phys. Rev. A 93, 042126 (2016)

[4] C.Schilling, Phys. Rev. B 92, 155149 (2015)

Requirements: strong analytical background, good knowledge of harmonic oscillator states and of the second quantization

Mandatory: potential students should meet the supervisors for an informal project discussion before applying for the project

Supervisor: ***Prof V Vedral***
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A&L17 Applying the principles of machine learning to optimise quantum-matter experiments

The applicant will apply optimal control and machine learning routines to an experimental apparatus that produces a quantum gas at temperatures below 1 microkelvin. This will automate the optimisation procedures that we regularly carry out 'by hand' (and brain) to improve the efficiency of the experiment. Techniques such as the Bayesian 'search and find' routine or gradient descent can locate fine features or establish global optima in high-dimensional parameter spaces. This has been demonstrated to work elsewhere [1]. The applicant should be able to program effectively in Matlab, which will speed up integration with current experimental control software.

[1] Fast machine-learning online optimization of ultra-cold-atom experiments. P. Wigley et al. Scientific Reports volume 6, Article number: 25890 (2016)

Supervisor: ***Prof C Foot***
Email: ***Christopher.Foot@physics.ox.ac.uk***

A&L18 Interpretation of inelastic X-ray scattering measurements using machine learning

X-ray inelastic (Thomson) scattering is a popular and information-rich diagnostic in plasma physics, commonly used to study the temperature and density conditions of extreme states of matter similar to those found in astrophysical objects and fusion plasmas. But interpreting the complex and noisy experimental data, normally measured integrating over the time and space of emission, remains a significant theoretical challenge.

In this project, the student will investigate how machine learning techniques can be applied to the robust interpretation of X-ray scattering data, and will deploy algorithms to evaluate the uncertainties in data published in the literature. This work will be used to both validate current results and conclusions, but also to inform future experimental setups and investigations.

The project demands good analytical and programming skills (C/C++, Python, or similar).

Computer-based project, requires computer usage

Supervisors: ***Dr S M Vinko*** and ***Prof G Gregori***
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A&L19 Coherent X-ray microscopy for nano-imaging

The development of bright, coherent x-ray pulses from free-electron laser (FEL) sources is revolutionising x-ray science, allowing advances across a diverse range of fields ranging from non-linear x-ray optics and biomolecular imaging to the investigation of matter in extreme conditions. Many experiments require stringent control over the parameters of the x-ray pulses interacting with the studied samples, but the single-shot characterisation of femtosecond FEL pulses still poses significant practical challenges.

In this project, the student will perform Fourier analysis on interferometric data obtained at the Coherent X-ray Imaging endstation (CXI) of the LCLS x-ray FEL at SLAC (https://lcls.slac.stanford.edu), using a newly developed two-frequency shearing method. The results of the analysis will yield the full phase and intensity profile of the nano-focused x-ray beam at CXI, for a single ultra-short x-ray pulse. The aberrations of the beam and the quality of the nano focus vs. the alignment of the focussing mirrors will be investigated, and the developed algorithms fielded at the LCLS.

The project demands good analytical and programming skills (C/C++, Python, or similar).

Computer-based project, requires computer usage

Reading: Schropp et al., Scientific Reports 3, 1633 (2013), DOI: 10.1038/srep01633

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A&L20 **tbc**

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A&L21 **tbc**

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A&L22 **Cavity-enhanced laser frequency locking to the 5S¬1/2-6P1/2 rubidium line**

Quantum computing with trapped ions relies upon a multitude of lasers operating at precisely defined frequencies, used for cooling, preparation and manipulation and readout of the ion qubits. In neutral-atom experiments, the lasers required are typically frequency-stabilised via Doppler-free saturation-spectroscopy-locking techniques to a room-temperature vapour of the target species. However, atomic ions cannot be stably confined without additional electromagnetic traps and, in the absence of a direct reference, lasers are stabilised via locking to carefully isolated optical cavities made of ultra-low-expansion glass – an expensive and imperfect alternative. However, in a few serendipitous cases it is possible to use a transition in one atomic species as a frequency reference for a laser driving a transition in another.

The 710.9624 THz, 5S1/2-6P1/2 transition in rubidium-85 offers such a rare opportunity for a neutral-alkali atomic frequency reference within easy reach of the principal dipole transition of a popular group-II ion qubit candidate, namely the 710.9627 THz, 5S1/2-5P1/2 transition in 88Sr+ [1]. A laser suitable for cooling and manipulation of strontium ions can be referenced to this rubidium transition via an additional 300 MHz FM sideband, but the relative weakness of the 5S1/2-6P1/2 line means that the absorption of a probe beam through a room-temperature rubidium vapour cell is too weak to generate a suitable signal for locking. A recent successful student project showed that a useful lock signal can be generated by heating the cell to 130oC, increasing the vapour density and so the number of atoms interacting with the laser. A more elegant solution is to use an optical cavity placed around the cell to increase the interaction length by effectively sending the light multiple times through the same vapour. This approach, known rather verbosely as Noise-immune cavity-enhanced optical-heterodyne molecular spectroscopy (NICE-OHMS) [2], has been widely used to lock lasers to weak transitions in molecules, and should lend itself well to our application.

This project will involve hands-on work in the Ion Trap group laboratories and the successful student will gain experience in a range of experimental methods in atomic and laser physics. The system for implementing the NICE-OHMS technique will be built by the student, requiring the design, construction and analysis of various optical systems, including an optical cavity. Additionally, locking the laser to a hyperfine component of the 5S1/2-6P1/2 transition will require electronic signal processing for the generation of a suitable locking signal for our external cavity diode laser. Finally, modelling the observed spectra and correct analysis of the experiment will require good understanding of the atomic physics of alkali metals and their interaction with laser light.

References:

[1] Madej, A., Marmet, L. & Bernard, J. - Rb atomic absorption line reference for single Sr+ laser cooling systems. Appl Phys B 67, 229–234 (1998)

[2] Foltynowicz, A., Schmidt, F., Ma, W. et al. Noise-immune cavity-enhanced optical heterodyne molecular spectroscopy: Current status and future potential. Appl. Phys. B 92, 313 (2008)

Supervisors: ***Dr J Goodwin*** and ***Dr J A Blackmore***
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Atmospheric, Oceanic and Planetary Physics projects

AO01 Dynamics of atmospheric circulation and droughts in Africa in a changing climate

This project combines elements of climate dynamics and dynamical systems theory with statistical and machine learning methods for analysis of selected climate datasets. We will examine variability and change of the Hadley cells (the large-scale latitude-height tropical circulation of the tropospheric heat engine) and horizontal moisture transport that exert a substantial influence on precipitation in tropics. Droughts in Africa are recurrent extreme climate events with potentially tremendous socio-economic consequences. There are indications that frequency, duration and intensity of droughts in Africa is increasing due to long-term global climate change. However, disentangling anthropogenic influence from natural variability in Africa is an interesting challenge.

This study aims to advance our understanding of the dynamics and predictability, and improve risk assessment and attribution of meteorological droughts (low precipitation events) in Africa from the conditional perspective of the large-scale circulation. The dynamical aspects of this study will encompass the decomposition of vertical flow into the local Hadley and local Walker circulations. We will use a clustering method and the convergent cross mapping based on the Takens' embedding theorem to explore the relationship, including causality, between key climate change and variability indices and droughts in Africa, in conjunction with aspects of circulation crucial for the formation of precipitation patterns. This project would be suitable for a student interested in investigating Earth's climate as an example of a complex dynamical system with tangible impacts on our rapidly expanding society, and in developing additional skills as a versatile data scientist.

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AO02 Study of clouds and gas abundances in Venus's deep atmosphere.

In this project, observations of scattered sunlight made with Venus descent probes in the late 1970s and early 1980s (Pioneer Venus, VENERA 11, 13, 14) will be re-analysed with our state-of-the-art radiative transfer and retrieval code, NEMESIS, to determine vertical profiles of cloud, dust and gaseous abundances. Radiative transfer modelling and inversion techniques have improved dramatically in the intervening 40 years, and hence these data are ripe for reanalysis. In addition, a new fleet of Venus missions is in development, including entry probes and cloud-level balloons, several of which might include cameras and/or solar panels, so there is renewed interest in understanding light at all altitudes in the Venus environment. This project could also be extended to thermal fluxes, and/or to examine similar mission proposals to make in-situ observations in the atmospheres of Uranus and Neptune.

A familiarity with Unix systems would be highly desirable and some knowledge of programming languages such as Fortran, C, IDL, Python, etc. is essential.

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AO03 Satellite Measurements of Ammonia in the Atmosphere

Ammonia (NH3) is a common by-product of agriculture. Released into the atmosphere it is converted into aerosols which have an adverse effect on air-quality. In the UK this is of particular concern since NH3 concentrations do not appear to be decreasing.

Using its infrared absorption features, it is possible to detect NH3 using current satellite instruments such as IASI on the MetOp polar orbiting satellites. However the spatial resolution is coarse (12km) and the signal/noise is low, so that only large concentrations can be detected reliably.

The aim of this project is to quantify the current detection limits of ammonia with the IASI instrument but also to see what improvements can be anticipated from two new instruments due for launch in the next couple of years: the IASI-NG (next generation) instruments with improved spectral resolution, and the IRS instrument on the new Meteosat geostationary satellites, with improved spatial resolution.

The project is entirely computer based and experience with python would be useful.

Supervisor***: Dr A Dudhia***
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AO04 The Earth's Infrared Spectrum

The Infrared Atmospheric Sounding Interferometer (IASI) is a nadir-viewing instrument on the polar-orbiting MetOp satellites, measuring the infrared emission spectra from the earth, each instrument providing over a million spectra a day.

One rapid method of processing such data is to fit each spectrum with a set of model-generated spectral signatures representing the expected variability in atmospheric and surface conditions (eg temperature, humidity, clouds) and, having removed these components, and anything left, other than noise, is 'unexpected'.

The project is to analyse the 'residual spectra' after such a fitting process and attempt to identify the origins of the resulting features, which may be atmospheric, surface, instrumental or modelling in origin.

The project is entirely computer based, and experience with python would be an advantage.

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AO05 Study of clouds and gas abundances in Neptune's turbulent atmosphere

In this project, new observations of the turbulent atmosphere of Neptune made with the MUSE and SINFONI instruments at ESO's Very Large Telescope in Chile will be analysed. Both MUSE and SINFONI are integral field unit spectrometers that record images where each individual pixel is in fact a complete spectrum covering the wavelength range 490 – 930 nm for MUSE and 1500 – 2500 nm for SINFONI, returning 'cubes' of data that contain an incredible amount of information. The visible/near-infrared spectrum of Neptune is formed by the reflection of sunlight from its cloud layers, modulated mostly by the absorption of gaseous methane and also Rayleigh scattering at blue wavelengths. At wavelengths of low absorption sunlight can penetrate to, and be reflected from, the deepest cloud layers, while at wavelengths of high absorption only sunlight reflected from the upper layers can be observed. Hence, such spectra can be inverted to 'retrieve' the cloud structure and reflectivity as a function of location and altitude, provided we know the vertical and latitudinal distribution of methane. For many years it was assumed that the vertical profiles of methane observed by Voyager 2 in 1986 could be used at all locations. However, HST/STIS observations of Uranus, recorded in 2002, revealed that the abundance of methane varies with latitude. Fortunately, the MUSE wavelength range covers spectral features that allow variation in cloud height to be discriminated from variations in methane abundance, allowing both quantities to be determined reliably. Meanwhile, the SINFONI wavelength range allows us to detect and measure the abundance of hydrogen sulphide in Neptune's (and also Uranus's) atmosphere, allowing our research group to confirm, recently, and for the first time, that both planets really do smell of rotten eggs!

In this project, these VLT observations will be reduced and analysed with our radiative transfer and retrieval tool, NEMESIS, to map the distribution of cloud, and update and refine our determinations of the latitudinal variation in the abundance of methane and hydrogen sulphide in Neptune's stormy atmosphere.

A familiarity with Unix systems would be highly desirable and some knowledge of programming languages such as Fortran, C, IDL, Python, etc. is essential.

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AO06 Using Artificial Intelligence to classify volcanic ash in satellite observations

Volcanic ash clouds are a significant hazard to aviation and Volcanic Ash Advisory Centers (VAACs) are responsible for tracking these hazardous clouds. Satellite observations are an important tool used by VAACs to identify ash clouds and so improvements in satellite-based detection algorithms may lead to better advice to aviation. The use of Machine Learning (ML) has shown some promise in classifying ash and dust clouds in satellite imagery (e.g. Picchiani et al., 2011; Li et al., 2016; Liu et al., 2021). However, for ML algorithms to be effective, large amounts of good quality training data are required. Given that VAACs routinely classify ash clouds (in the form of polygons defined by latitude/longitude coordinates) there is an opportunity to combine this information with satellite data to generate a new, expert-labelled dataset appropriate for training supervised ML classification algorithms. The Earth Observation Data Group maintains an archive of satellite imagery for various volcanic eruption events. Of particular interest is the July 2020 eruption of Nishinoshima (Japan), which was observed to emit ash continuously for over a week by numerous satellite platforms.

This project will explore the efficacy of supervised ML algorithms in classifying satellite pixels as volcanic ash. The project will involve:

I. Processing geostationary satellite data (Himawari-8) and labelling satellite pixels that fall within volcanic ash advisory polygons

II. Running and testing various ML algorithms on the newly developed labelled dataset

III. Comparing the results of the ML algorithms against standard physics-based detection algorithms

Skills required

Practical experience with computer programming is an advantage. This project will use the Python programming language for scientific data analysis, processing of satellite imagery and implementing ML algorithms (e.g. Scikit-learn, PyTorch, TensorFlow). Github will be used for documenting and sharing code developed during the project.

Supervisors: ***Dr A Prata*** and ***Prof R G Grainger***
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AO07 **Pattern formation in ice covered oceans**

Much of the natural world is shaped by fluid flows over evolving surfaces. The effects of rotation and convection, which refers to fluid motion caused by the presence of density gradients, on phase-changing boundaries, which can either melt or grow, are central to understanding a number of geophysical and astro- physical phenomena. Primary examples include: the evolution of the Earth's inner core [1], changes in the ice covers of the Earth's polar regions [2], the evolution of ice-covered interior oceans of Enceladus [3] and Europa [4], to name a few. A fundamental understanding of the evolution of these systems can be developed by considering the effects of rotational and convective motions of a fluid on the growth/melt of its solid phase and how the evolving solid phase affects fluid motions. To this end, the principal goals of this project are: (a) to explore the effects of rotational and convective motions of a fluid on the morphological stability of a layer of its solid phase, and (b) to understand the patterns that emerge from such interactions.

We will use a combination of mathematical analysis and numerical methods to solve the equations of motion for the fluid, solid, and the fluid-solid interface and explore the conditions under which the solid layer be- comes unstable and melts. Furthermore, the patterns that emerge at the interface will be explored and their impact on the stability of the system will also be studied. Such an approach has been used to understand the combined effects of shear and buoyancy on a layer of ice [5], and these techniques will be extended to understand the effects of rotation.

This project provides an opportunity to combine techniques from fluid dynamics, theoretical modelling and computational physics, to tackle a problem involving the nonlinear dynamics of rotating flows. Whilst com- putational methods and programming will be used during the project, no prior familiarity is required beyond the level of the usual undergraduate computing laboratory practicals.

Suggested background reading:

References

[1] M. Monnereau et al., Lopsided Growth of Earth's Inner Core, Science 328, 1014 (2010).

[2] R. Kwok and N. Untersteiner, The thinning of Arctic sea ice, Phys. Today 64, 36 (2011).

[3] J. R. Spencer and F. Nimmo, Enceladus: An active ice world in the Saturn system, Annu. Rev. Earth Planet. Sci. 41, 693 (2013).

[4] M. H. Carr et al., Evidence for a subsurface ocean on Europa, Nature 391, 363 (1998).

[5] S. Toppaladoddi and J. S. Wettlaufer, The combined effects of shear and buoyancy on phase boundary stability, J. Fluid Mech., 868, 648 (2019).

Supervisors: ***Dr S Toppaladoddi*** and ***Prof A Wells***
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AO08 Estimating Surface Reflectance Using a Neural Network

Aerosols are particles suspended in the atmosphere such as soot, dust, and acid droplets. By acting as nucleation sites for water droplets and ice crystals, aerosols can change the properties of clouds through a complex series of interactions that are currently the most uncertain influence on future climate. Aerosols also impact human health when small particles enter the lungs and blood stream. As they only remain in the atmosphere for a few days to weeks, there is great need for regular observations to monitor the loading of aerosols around the world.

Researchers in Oxford have produced a high quality climate record of aerosol properties using a series of satellite radiometers. This is a difficult measurement over land as only a small fraction of the light observed was scattered by aerosols, making measurements highly sensitive to our assumptions. This project will work to improve our record of this Essential Climate Variable by quantifying our sensitivity to various land surfaces.

Our calculations currently use observations of the surface from another satellite, but errors result from differences in the precise wavelengths monitored by each instrument. Our current correction is no longer fit for purpose. The student will produce a training dataset of surfaces as seen by multiple satellite instruments and generate a neural network that extends our existing wavelength correction. These will then be trialled within our satellite processor to assess the impact on the aerosol retrieval.

This research will be computer-based, so prior experience of scientific computer programming in IDL or Python is beneficial, if not required. Familiarity with basic statistical analysis is essential.

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AO09 Determining volcanic ash type from satellite data

Ash clouds are one of the many hazards associated with volcanic eruptions: they affect health, cause considerable damage to infrastructure and pose a significant threat to aircraft. Airspace closure during the 2010 eruption of Eyjafjallajökull led to billions of dollars of loses. Using satellite instruments, it is possible to obtain vital information about ash clouds including the ash optical depth and effective radius (which together can be used to compute the mass) and altitude. One satellite instrument used for quantifying information about volcanic ash is the Infrared Atmospheric Sounding Interferometer (IASI): a hyperspectral infrared instrument on-board three meteorological satellites.

Methods for quantifying information about volcanic ash usually make assumptions about the ash optical properties which are linked to the ash type. The refractive indices of a variety of ash samples have been measured in the lab (Reed et al. 2018; Deguine et al. 2020) and these are used to create look up tables which are used within the IASI ash retrieval (Ventress et al., 2016). The aim of this project is to develop a method to identify volcanic ash type from the IASI spectra so that the most appropriate one can be selected for use in the Ventress et al. (2016) ash retrieval.

The project may involve:

(1) Exploring modelled volcanic ash spectra to identify the differences caused by different ash types

(2) Running the IASI ash retrieval for the different ash types and investigating how this affects the results

(3) Develop a method to determine the best ash refractive indices to use for different eruptions.

The project is computer based and will use the Interactive Data Language (IDL) on machines which run the Linux operating system. Prior experience of either of these (or programming in general) would be useful but is not essential.

References

Deguine, A., Petitprez, D., Clarisse, L., Guđmundsson, S., Outes, V., Villarosa, G. and Herbin, H. (2020) Complex refractive index of volcanic ash aerosol in the infrared, visible, and ultraviolet, Appl. Opt, 59, 884-895. https://doi.org/10.1364/AO.59.000884

Reed, B. E., Peters, D. M., McPheat, R., & Grainger, R. G. (2018) The complex refractive index of volcanic ash aerosol retrieved from spectral mass extinction. Journal of Geophysical Research: Atmospheres, 123, 1339– 1350. https://doi.org/10.1002/2017JD027362.

Ventress, L. J., McGarragh, G., Carboni, E., Smith, A. J., and Grainger, R. G. (2016) Retrieval of ash properties from IASI measurements, Atmos. Meas. Tech., 9, 5407–5422, https://doi.org/10.5194/amt-9-5407-2016.

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AO10 The fractal dimension of clouds

Recent years have seen an increase in the production of global convection-resolving (or at least convection-permitting) atmospheric simulations. These simulations are very realistic when compared to observations. A good example of this can be seen in images of simulated cloud condensate fields, rendered in such a way that they can be directly compared to satellite images of the Earth (Fig. 2: Stevens et al, 2019). While it can be difficult at first glance to distinguish between model and observed data, on closer inspection, the satellite image can be identified. The fractal nature of the clouds, degree of convective organisation, and spatial distribution of clouds all differ subtly between different models and between models and observations.

This project will systematically compare ultra-high-resolution climate model data with observational datasets to quantify the ways in which simulated clouds differ from those observed. In a successful MPhys project carried out in 2020-21 we demonstrated that clouds in high-resolution models are indeed fractals, as they are in observations, and quantified the performance of models over the Maritime Continent. This project will follow on in one of several new directions, depending on the interests of the student:

• a geographical comparison. Are models uniformly skilful at representing clouds, or can we detect regional variations, for example, comparing cloud structure over different ocean basins with those that form over land?

• an extended analysis of observational data. In both models and observations we detected substantial temporal variability in the measured fractal dimension. Why? – is it a purely stochastic process, or are there underlying physical drivers?

• an inter-model comparison. We have access to a large selection of different model simulations, which have been produced with different assumptions in the model equations. Can fractal dimension discriminate between models?

A key goal of producing such high-resolution climate model simulations is that we can use them as a proxy for the true atmosphere to understand atmospheric processes and predictability. Such datasets have several advantages over using observations, including good spatial and temporal coverage, their high resolution, and the availability of a range of variables that are difficult to directly observe. However, if they are poor representations of the true atmosphere, their use is limited. Only by quantifying the difference between models and observations, as in this project, can we assess the degree to which a model can 'stand in' for observations to help us understand the real atmosphere.

Prerequisites:

This project is best suited for someone with experience in coding, preferably in Python.

References:

Stevens, B., Satoh, M., Auger, L. et al. DYAMOND: the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains. Prog Earth Planet Sci 6, 61 (2019). https://doi.org/10.1186/s40645-019-0304-z

The DYAMOND project website https://www.esiwace.eu/services/dyamond

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AO11 Tipping points in the climate system

Many phenomena in the climate system exhibit bimodal behaviour. From the El Nino-Southern Oscillation, to the Asian Monsoon, to Sudden Stratospheric Warmings – we observe rapid transitions from one climate state to another, often within just a few days or weeks. Are these transitions predictable?

This project will assess whether such transitions can be considered as tipping points associated with bifurcations in the structural stability of the climate system. For such a system, varying a control parameter causes the system to pass a critical threshold, resulting in a sudden and substantial shift in the state of the system. On approaching a bifurcation-induced tipping point, the system shows a critical slowing down. This means that such transitions can be predicted in advance. In contrast, transitions in other systems are noise induced: consider a particle in a double potential well, which may jump from one well to the other due to random perturbations. Such noise-induced transitions are not predictable.

The student will begin by creating a pair of idealised models to represent regime transitions in a system undergoing a bifurcation, and for a bimodal system driven by noise. These models will serve as a benchmark to compare real-world data to. The student will then select a range of climate phenomena exhibiting regime behaviour, and analyse the appropriate timeseries to assess the underlying dynamical behaviour. In this way, we seek to find precursors to common climate transitions, to improve our forecasts of these often high-impact events.

Prerequisites:

This project will be computationally based, and so an enthusiasm for coding is essential. However, experience with coding is not necessary and can be learnt on the job. An understanding of bifurcations, e.g. from the short option on Chaos, Random Processes and Predictability, will be beneficial.

References:

Introductory seminar on "Is climate change predictable? The case of tipping points", by Peter Ditlevsen: https://www.youtube.com/watch?v=_37DSn77Xzg

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AO12 Characterising recurrent climate cycles and teleconnections through atmospheric angular momentum fluctuations

The Earth's climate is observed to exhibit a variety of recurrent phenomena on timescales ranging from months to decades. Some of these phenomena occur as repeatable (albeit weakly or strongly chaotic) cycles that may either be localized to particular geographical locations or can act to couple fluctuations coherently between different parts of the planet. Such cycles may be apparent in different observed atmospheric variables, including atmospheric temperature, winds and angular momentum. They include phenomena such as the tropically-focused Madden-Julian oscillation (on timescales of 2-4 months), which affects patterns of tropical convection, the Arctic Oscillation (on timescales of 1-2 years) affecting the behaviour of storm tracks at high northern latitudes, and longer timescale climate cycles such as the El-Niño Southern Oscillation (with periods of 3-6 years) and the North Atlantic and Atlantic Interdecadal Oscillations (on timescales of up to 20-30 years).

In the present project we propose to explore the properties of fluctuations contained in a relatively novel time series of atmospheric axial angular momentum per unit mass, integrated in height from the surface to the lower stratosphere and covering an interval of more than 50 years of observations. The time series is unusual in partitioning angular momentum into a series of latitude bands covering the entire globe, allowing the possibility of detecting and characterizing recurrent phenomena that are coherent across different locations (so-called teleconnections). It is proposed to apply a variety of analysis methods, including those developed to analyse nonlinear oscillations and synchronization phenomena in chaotic dynamical systems. This project will require good computation skills and some background in the mathematics of nonlinear dynamics.

Supervisor: ***Prof P Read***
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AO13 Quasi-geostrophic modeling of zonal jets, waves and vortex interactions on Jupiter and Saturn

The visible atmospheres of Jupiter and Saturn are dominated by patterns of strong zonal (East-West) jet streams and bands of ammonia ice clouds, within which are observed a variety of wavy meanders and compact, coherent anticyclonic and cyclonic vortices. The latter includes features such as Jupiter's Great Red Spot (a huge anticyclone 3 x the size of Earth that has been present for at least 300 years) and similar smaller features on both Jupiter and Saturn, and a remarkably symmetric hexagonal wave near Saturn's north pole. The detailed mechanisms for the formation of these jets, waves and vortices are still not fully understood though some features are beginning to be reproduced in various types of numerical model.

In the present project we propose to explore a simplified numerical model capable of simulating some of these kinds of feature. The modelling approach is based on the quasi-geostrophic approximation, in which the horizontal flow is assumed to be close to a geostrophic balance between pressure gradient and Coriolis forces. This leads to a simplified mathematical form that is easier and quicker to solve than the full Navier-Stokes equations. We propose to use and extend an existing model code (such as the Python Quasigeostrophic Model - https://www.gfdatabase.com/2018/11/pyqg-python-quasigeostrophic-model/) to simulate flows that may emulate the dynamics of a set of eastward and westward zonal jets at mid-latitudes on Jupiter or Saturn. With suitable representations of forcing and dissipation the zonal jets can be sustained and the dynamics of embedded vortices and waves can be simulated. Possible scenarios to be investigated may include the interactions of the Great Red Spot with smaller vortices (e.g. as observed recently by the Juno spacecraft) or the formation of Saturn's north polar hexagon. This project requires good computational skills e.g. using Python or Fortran.

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AO14 Signatures of Southern Hemisphere Natural Climate Variability

Several studies have looked at the impact of solar variability and volcanic eruptions at the Earth's surface, including work here at Oxford led by Professor Gray. One approach has been to use multiple linear regression, including indices to represent, for example, the 11-year solar cycle, volcanic eruptions and long-term trends associated with greenhouse gases. A recent study highlighted that, for example, the impact of 11-year solar variability on mean sea level pressure (mslp) and sea surface temperatures (SST) in the European / N. Atlantic sector was lagged by a quarter cycle i.e. 3-4 year. This has particular potential benefits for long-term (seasonal, decadal) forecasting since the 11-year solar cycle can be reasonably well forecast and may therefore give valuable additional capability for seasonal forecasting over Europe. A mechanism for this lag has been proposed, in collaboration with Met Office colleagues, involving an influence on the mixed layer of the ocean in winter that can be perpetuated through to the following summer and thus provides a positive feedback.

In recognition of the importance of seasonal forecasting over Europe, previous effort has been focused on the Northern Hemisphere winter response over Europe. However, there are some interesting signals apparent in the Southern Hemisphere that deserve attention, and also in summer time in both hemispheres. In this project we plan to expand the sphere of interest, to examine to examine the Southern Hemisphere response. This will be carried out using existing tools, primarily the multiple linear regression employed in previous studies. The study will examine the Hadley Centre mslp and SST datasets. There is also the potential to collaborate further with Met Office colleagues, who have a set of climate model ensembles for the period 1960-2010 with and without a solar cycle in the imposed irradiances, so that mechanisms may be further explored.

Skills required

This project is entirely computer-based, examining both observational and climate modelling data requiring experience of UNIX and IDL/Python.

Supervisor: ***Prof L Gray***
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AO15 Deep learning using high temporal resolution satellite data

The planetary energy balance between incoming and outgoing radiation, and hence global temperature, is very sensitive to the properties and distribution of clouds in the atmosphere. Large continuous decks of stratocumulus clouds occur in the cold upwelling regions of the major oceans and play a crucial role in this balance.

An important and poorly understood phenomena occurs where a large region of the cloud deck dissipates and leaves open regions, so called Pockets of Open Cells (POCs). It has been hypothesized that these occurrences are affected by anthropogenic activity, specifically through aerosol perturbations. Hence, POCs could have important implications for climate change.

Previous work has developed a model to detect and classify these important phenomena in individual satellite images using deep neural networks deployed on large cloud-hosted GPU clusters. This project will build on that work by developing a temporal aspect to the model (using e.g. Long Short Term Memory) to understand the temporal evolution, and critically the physical mechanisms, of POC formation. These implications will feed back into regional and global assessments of their effect on global cloud forcing.

An interest in state-of-the-art machine learning techniques and some basic Python experience is essential, but training will be provided.

Supervisors: ***Dr D Watson-Parris*** and ***Prof P Stier***
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AO16 **Lagrangian analysis of aerosol optical properties**

In the context of climate change, atmospheric aerosols such as dust, biomass burning or anthropogenic aerosols (pollution) play an important role in the climate system. They can warm or cool the atmosphere, depending on their chemical and microphysical properties, as well as their interaction with radiation and clouds. Despite improved in-situ and remote sensing observational methods, the aerosol properties, along with their associated effects remain a large source of uncertainty when quantifying and interpreting the aerosols impact on climate. The study of aerosol optical and microphysical properties becomes even more complex when the properties of aerosols transported over large distances are altered due to aging processes linked to photochemical interactions.

This project attempts to estimate the changes in aerosol optical properties during transport.

Satellite imagery allows for large spatial coverage retrievals, while in-situ technics are spatially limited, but have lower measurement uncertainties. A synergy of these methods along with a Lagrangian tracking of different air masses, could improve the aerosol characterization and our understanding of aerosol effect on climate.

The candidate should have an interest in atmospheric science and some basic Python experience, but training will be provided.

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AO17 **Exploring interactions between climate change and economic growth**

Integrated assessment models (IAMs) are widely-used tools for climate change policy analysis, addressing questions such as determining the level of carbon tax required to stabilise temperatures at 2 degrees above pre-industrial (or, following the Paris Agreement, "well below 2 degrees"). Current IAMs include a rather limited representation of potentially non-linear feedbacks between climate change and the rate of economic growth. While there is a literature dating back decades on non-linear climate change and an entirely separate literature on non-linearity in macro-economics, much less has been written on possible non-linear interactions between the two. This project will begin from a simple linear climate model coupled to idealised representations of global damage and the global economy to explore how interactions between climate change and economic growth might result in interesting behaviour in IAMs, such as bifurcations (sometimes called "tipping points") between different climate policy regimes.

The student will have to be familiar with the chaos components of the B1 course. Having attended the S-25 option would be helpful, but not essential (notes are on weblearn). Familiarity with some form of mathematical programming language such as matlab or IDL would be helpful, and an interest in economics and interdisciplinary problems essential.

Background reading: The Climate Casino: Risk, Uncertainty, and Economics for a Warming World by William Nordhaus, and for a our starting point see Allen (2016), "Drivers of peak warming in a consumption-maximising world", Nature Climate Change, http://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate2977.html

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AO18 **Topographic impacts on viscous flow of Greenland outlet glaciers**

The Greenland ice sheet discharges into the ocean through an array of hundreds of outlet glaciers [1], the dynamics of which an have important implications for predicting future sea level changes, and interpreting past glacial dynamics. Outlet glacier dynamics involve viscous fluid flow, driven by pressure gradients induced by varying thickness of the ice, and resisted by basal and lateral drag forces [2]. Satellite observations show a distribution of ice velocities and varied evolution of the glacier terminus positions across this range of glaciers [1,3]. At any one time a fraction of glaciers may have a retreating terminus, whilst others in the same region have an advancing terminus despite likely similar climate forcing. A variety of factors impact outlet glacier dynamics, but this project will focus on the role of spatial variations in the bedrock topography over which the ice flows.

The goal of this project is to develop a simplified computational model of viscous ice sheet flow, and use this to understand how outlet glacier flow responds to spatial variations in glacier width and bedrock depth. We will use a computationally efficient flow-band model, which is a depth- and width- integrated description for viscous flow of a thin sheet of ice along a glacier catchment [4,2]. The model will be applied first to idealised configurations to understand the physical mechanisms of how spatial variations in width influence the ice sheet flow. An ensemble of simulations with randomly generated bedrock topography can then be used to explore the distribution of ice flow behaviour that arises, and investigate the role of topography in understanding the observed patterns of glacier advance and retreat.

This project provides an opportunity to learn and use computational methods alongside theoretical fluid mechanics to tackle a geophysical problem. Whilst prior experience with a programming language such as MATLAB/Python/etc. would be an advantage, there is potential for students to learn the necessary skills during the project.

Suggested background reading:

[1] Moon et al (2012), 21st-century evolution of Greenland

outlet glacier velocities, Science, vol. 336, p576, https://doi.org/10.1126/science.1219985

[2] Schoof & Hewitt (2013) Ice sheet dynamics. Annu. Rev. Fluid Mech. 2013. vol. 45, p217. https://doi.org/10.1146/annurev-fluid-011212-140632

[3] Murray et al (2015) Extensive retreat of Greenland tidewater glaciers, 2000–2010 Arct. Antarct. Alp. Res., vol. 47:3, p427. https://doi.org/10.1657/AAAR0014-049 [4] Enderlin et al (2013) High sensitivity of tidewater outlet glacier dynamics to shape. Crysophere vol. 7, p1007, https://doi.org/10.5194/tc-7-1007-2013

Supervisor: ***Prof A Wells***
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AO19 Isentropic view of the atmospheric circulation and extreme events

This study explores the internal variability and long-term change of the atmospheric general circulation in connection with extreme thermal events using isentropic vertical coordinates. Extreme weather and climate events threaten human health and many aspects of socio-economic structure supporting our growing global society. Furthermore, in our changing climate many classes of extremes are expected to increase in frequency, intensity and extent. In practical sense this project will focus on the analysis of weather and/or climate data through the application of statistical and/or machine learning methods for the benefit of our understanding as well as potentially leading to actionable information for multiple stakeholders.

The dry and moist isentropes are two-dimensional surfaces of constant potential and equivalent potential temperature, respectively. The flow across isentropes reveals information about atmospheric heating (upward) and cooling (downward), while the flow along them provides insight into the zonal and meridional heat transport. Such diagnostic approach will enable us to connect the surface heat and cold waves with the large-scale circulation variability and change including better thermally characterized vertical structure. For example, the July 2018 heat wave in Japan – having the first significant attribution of mortality to anthropogenic forcing factors in the country's history - had a towering circulation signature reaching essentially upward to the tropopause (the boundary between the troposphere and the stratosphere: 10-12 km using the lapse rate minimum). We look forward to work with student(s) interested in climate dynamics and extreme events as well as in developing as a data scientist.

Supervisors: ***Dr N Fučkar a***nd ***Prof M Allen***
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AO20 Understanding the Heat Flow around the Lunar Surface for Mission Planning

Several remote sensing missions have shown measurements that suggest surface and buried subsurface water ice almost certainly exist mixed in with the soil at the South and North pole of the Moon. PROSPECT is an ESA instrument that will land at the Lunar south pole onboard the Russian Luna27 lander in the next decade. Its primary mission goal is to drill and directly sample the water present there. The primary dataset for its landing site selection is thermal infrared models coupled with a diffusion model which highlight regions where temperatures are low enough for water to remain stable over billions of years. Some regions have incredibly low surface temperatures < 30K – the coldest natural places in the solar system. These are in places on the Moon known as permanently shadowed regions – since due to constant low solar angles and topography – they are always in shadow. In these regions the only source of heat transfer is from scattered radiation from nearby terrain.

We have a thermal model that can simulate the Lunar surface temperature, but would like to update some of the functions incorporated inside this model biased on new laboratory studies. Using the newly updated model we can then re-simulate potential landing sites for PROSPECT to check if water ice is still predicted to be present. Depending on the student (if they are interested in laboratory work) we could also complete some laboratory experiments to test key assumptions in the models.

Reading : King and Warren 2020 – "The Oxford 3D Thermophysical Model with application to PROSPECT/Luna 27 Study Landing Sites"

Skills: Coursework covering the fundamentals of radiative transfer e.g. from Atmos or Astro major options. For the computer-based elements programming experience is useful.

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AO21 tbc

More details from the supervisor.l

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AO22 tbc

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Astrophysics projects

AS01 A search for Hydroxyl as a signpost to galaxy mergers in the Universe

The star-formation rate and the assembly of massive elliptical galaxies are inextricably connected to how galaxies merge over cosmic time. Recently merged (luminous and ultra-luminous infrared) galaxies provide the perfect conditions for detecting Hydroxyl (OH) megamasers, which are often found within 1 kpc of heavily dust-obscured active galactic nuclei. OH megamasers are therefore ideal luminous radio beacons for tracing the merger history of the Universe. The Arecibo OH megamaser survey, which detected 52 masers out to z=0.23, represents the current state-of-the-art in our understanding of the nearby megamaser population. The MIGHTEE (PI Jarvis) survey will provide a unique opportunity to carry out a deep blind search for OH megamaser emission (and OH absorption) between z=0 and 0.85. The low redshift luminosity function of (15), would imply a detection yield a minimum of 10 OH megamasers. However, this number is highly dependent on the evolution of the galaxy merger rate as a function of redshift, which could easily lead to an order of magnitude more in MIGHTEE. In this project the student will use the new MIGHTEE data to search for OH megamasers and to place the first constraints on the merger rate of galaxies to high redshift using this information. A successful search of the data should lead to a publishable result.

The project will be computer based and given the large data volumes involved the search can be run remotely on servers in Oxford and South Africa.

Supervisor: ***Prof M Jarvis***
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AS02 The birth places of neutron stars

Neutron stars are among the fastest moving stars in our Galaxy due to the kicks they get during their births in Supernova explosions. One can use the proper motions of the pulsars to trace back their locations of birth because the massive progenitors stars exist predominantly in stellar clusters. Pinning down the birth locations can reveal poorly known properties such as the exact age of a neutron star or allow to better constrain its distance. This project will investigate neutron star birth places based on new data of stellar clusters from the Gaia satellite as well as new pulsar proper motions measurements at radio and X-ray wavelengths. The project demands good analytical and programming skills (C/C++, Python, or similar)

Supervisors: ***Dr B Posselt*** and ***Dr A Karastergiou***
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AS03 The cool gas fuelling distant radio galaxies with MeerKAT

All galaxies are thought to contain a massive central black hole. During a brief and extreme period of activity, the matter accreting onto this black hole releases a huge amount of radiated energy known as an active galactic nucleus (AGN). In some cases these AGN radiate across the entire electromagnetic spectrum and can outshine even the entire stellar light from the rest of the galaxy. However, the majority are not very bright at most wavelengths and are only detected by radio telescopes. Nontheless, these radio galaxies can still release a huge amount of energy in the form of giant collimated jets of plasma, sufficient to drive gas out of the galaxy and prevent further star formation. At Oxford, we are using the MeerKAT radio telescope in South Africa to study the kinematics of cold gas in radio galaxies that are billions of light years away. MeerKAT is the most sensitive radio interferometer in the world, allowing us to make deep images of the radio sky in exquisite detail. The student will use data from this telescope to detect and model the absorption lines seen against the radio emission due to surrounding clouds of neutral gas. This approach allows both the abundance and kinematics of gas to be determined on sight-lines towards the radio source, establishing in individual active galaxies the existence of infalling clouds, feedback-driven outflows and circumnuclear discs. During the project the student(s) will be expected to carry out analysis of the MeerKAT data, requiring some coding in Python or similar language, and careful theoretical interpretation. This is a unique opportunity to work with real astronomical data from a pathfinder telescope to the Square Kilometre Array.

Supervisor: ***Dr J Allison***
Email: ***james.allison@physics.ox.ac.uk***

AS04 Illuminating the interstellar medium towards relativistic jets with MeerKAT

Stellar X-ray binary systems comprise a black hole or neutron star that is accreting material from a massive companion. The accretion discs in these systems are luminous in high energy X-rays and periodically form highly collimated relativistic outflows of plasma, which emit synchrotron radiation that can be best detected at radio wavelengths. These extreme stars allow us to study the astrophysics of mass accretion onto compact objects and jet formation, from which we may determine how seed black holes formed in the early Universe and the role of supermassive black holes in the growth and evolution of galaxies. At Oxford we are using the new MeerKAT radio telescope in South Africa to observe the relativistic jets from hundreds of X-ray binaries. MeerKAT is the most sensitive radio interferometer in the world, allowing us to make deep images of the radio sky in exquisite detail. In this project we will pioneer a technique that uses spectroscopic information from the telescope to detect absorption due to cold atomic hydrogen clouds that intercept our sight line. Since we know the distribution and kinematics of atomic hydrogen in the Galaxy, we will use this spectroscopic information to determine the distance to each X-ray binary. This will allow us to determine the physical properties of the compact star, including luminosity, temperature, accretion rate, mass and spin. We can also use this information to measure the temperature of the intervening hydrogen gas, allowing us to measure the distribution of cold, star-forming, interstellar medium throughout the galactic plane. During the project the student(s) will be expected to carry out analysis of the MeerKAT data, requiring some coding in Python or similar language, and careful theoretical interpretation. This is a unique opportunity to work with real astronomical data from a pathfinder telescope to the Square Kilometre Array.

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AS05 **Measuring stellar population parameters from integrated early-type galaxies spectra**

A galaxy spectrum encodes an enormous amount of information about its dynamical state, chemical composition and star formation history. Hence, the analysis of the spectral energy distribution of a galaxy allows us to trace back its formation process, relating the assembly mechanisms to its intrinsic properties – such as mass or size – or to the environment where it was born (i.e. field, group or cluster).

With the exception of very nearby galaxies where individual stars can be resolved and studied, for more distant galaxies one has to infer properties of the stellar population by looking at the integrated light from all of the stars that form the galaxy.

The underlying assumption is that a galaxy can be broken down into one (or more) Single Stellar Populations (SSP), representing a generation of coeval stars originally chemically homogeneous.

In this project the student will fit integrated spectra of near-by very massive and passive galaxies (ETGs) from the Kilo Degree Survey (KiDS), which have been also spectroscopically observed by the Sloan Digital Sky Survey (SDSS), using the state-of-the-art SSP models to obtain a constrain on the mass-weighted age, metallicity and alpha-element abundance of the galaxies' stellar populations.

Since KiDS provides precise measurements of the sizes and stellar masses, as well as information about the evinronment in which the objects live, the student will be able to correlate these quantities with the star formation histories derived from stellar population fitting.

The tool that will be used is the ppxf full-spectral fitting code (https://pypi.org/project/ppxf/) written by Prof. Michele Cappellari, while the SSP models are the MIUSCAT models (http://research.iac.es/proyecto/miles/pages/ssp-models.php) besed on observed stars.

The project demands basics programming skill (Python, or IDL preferred).

Supervisor: ***Dr C Spiniello***
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AS06 **INSPIRE: INvestigating Stellar Population In RElics**

INSPIRE is an on-going project targeting 52 ultra-compact massive galaxies at z<0.5 with the X-Shooter@VLT spectrograph (XSH).
These objects, all showing evidence of passive stellar population from their optical colours, and all having small sizes (R< 2kpc) and large stellar masses (M*>6x10^10 Msun), obtained from the analysis of multi-band images from the Kilo Degree Survey, are the perfect candidates to be ``relics'': massive red-nuggets formed at high-z (z>3) through a short and intense star formation burst, that evolved passively and undisturbed until the present-day.
Relics are local "laboratories" to study the processes that shaped the mass assembly of massive galaxies in the high-z Universe, and disentangle between possible formation scenarios for massive galaxies.
In this project the student will participate in all the phases of the data analysis, from reduction to kinematics and stellar population fitting.

The tools and pipelines are all already written, although some fine-tuning might be necessary, thus basics programming skill (Python, or IDL preferred) are required. In details, the student will learn how to use the ESO Reflex workflow to reduce galaxies' spectra, and the ppxf full-spectral fitting code (https://pypi.org/project/ppxf/) written by Prof. Michele Cappellari, to compute the stellar velocity dispersion, age and metallicity of the ~20 objects observed as part of the INSPIRE DR2.

Supervisor: ***Dr C Spiniello***
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AS06 **Finding rare treasures in VEXAS**

The aim of the VISTA EXtension to Auxiliary Surveys (VEXAS), is to provide spatial coverage that is as uniform as possible in the multi-wavelength sky in order to supply the astronomical community with reference magnitudes and colours for various scientific uses: object; photometric redshifts of large galaxy samples; searches of exotic objects.

Strongly lensed quasars (QSOs) are rare objects that require a close alignment between a quasar and a massive galaxy. According to the most recent estimations of (Oguri & Marshall, 2010), this happens once in 10000. However, they are very valuable systems that can provide unique insights into a large number of open issues in cosmology (e.g. measuring the expansion of the Universe) and extragalactic astrophysics (e.g. inferring galaxies' masses).

The most successful way to look for lensed QSOs is based on multi-colour pre-selection of QSOs and galaxies from wide-field surveys, followed by morphological criteria to isolate the rare cases of veritable lenses.

With VEXAS, we do not have to rely on colours, since we have a machine-learning based classification of ~100 millions sources in the Southern Hemisphere.

Moreover, VEXAS covers the region dec<-70deg which is still almost completely unexplored for the strong gravitational lens search.

The student will work with the VEXAS DR2 classified optical+NIR tables, select only these objects classified as galaxies and then apply the 'Multiplets' method that we developped in Khramtsov et al., 2019 (https://ui.adsabs.harvard.edu/abs/2019A%26A...632A..56K/abstract) in order to select plausible strongly lensed quasar candidates.

The project demands basics programming skill (Python, or IDL preferred).

Supervisor: ***Dr C Spiniello***
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AS07 **The Investigating radio galaxies with the MIGHTEE survey**

Radio galaxies are active galactic nuclei (AGN) which produce large jets of relativistic particles from the supermassive black hole at their centre. These jets can be thousands of light years across (many times the size of the galaxy itself) and are visible at radio wavelengths. It is thought that these jets play an important role in the evolution of galaxies by suppressing star-formation in massive galaxies, but this is not well understood.

This project will use radio images from the MIGHTEE survey - a survey currently underway with the MeerKAT radio telescope in South Africa - to study radio galaxies. The student will measure the sizes and/or classify the radio morphologies of a sample of radio galaxies detected in the MIGHTEE early science data. They will then use data from optical and infrared telescopes - for example the VIDEO near-infrared survey - to investigate the relationship between the radio jet properties they have measured and the host galaxy properties, such as star-formation rate.

This project could potentially lead to a publishable paper so is ideal for someone looking to pursue a PhD in astronomy. Some experience with python or similar would be an advantage but is not essential.

Supervisor: ***Dr I Whittam***
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AS08 Investigation of bleed trails in LSST camera data

The LSST survey is a next generation optical survey which will be carried out at the currently in-construction Vera Rubin Observatory. One of its scientific aims is to constrain our knowledge about dark energy through weak lensing measurements of galaxies. These weak lensing methods involve precise measurements of the shapes of galaxies which can be subject to large systematic errors both astronomical and instrumental, which must be well understood and characterised."bleed trails" are one of the phenomena inherent in CCD imagers as used by the LSST camera. They occur where a very bright object causes the pixels to become oversaturated. Despite their ubiquity, and important role in affecting measurements, no major effort has been directed to fully understand the details of the physics behind the formation of bleed trails, though the basic mechanisms are of course known.

Using a combination of experimental data from the Oxford OPMD lab, and on-sky data from the LSST camera auxilliary telescope, accompanied by device simulation results, the student will investigate the physics of bleed trails in CCD sensors. There will be opportunities for the student to be involved in the design of the OPMD lab experiments and this will involve working with optical and electronic components. Previous experience of programming (python) would be advantageous. This would ideally suit a student who is interested in working with (sometimes temperamental) experimental data.

Supervisors: ***Prof I Shipsey*** and ***Dr D Weatherill***
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AS09 Direct oversampled PSF measurements on LSST sensors

The LSST survey is a next generation optical survey which will be carried out at the currently in-construction Vera Rubin Observatory. One of its scientific aims is to constrain our knowledge about dark energy through weak lensing measurements of galaxies. These weak lensing methods involve precise measurements of the shapes of galaxies which can be subject to large systematic errors both astronomical and instrumental, which must be well understood and characterised.

It is crucially important to understand the point spread function (PSF) of the instrument, which has contributions from the atmosphere, the telescope optics and the detector. We are concentrating on measuring the detector PSF, and are working on developing new and novel methods to directly measure an oversampled detector PSF in the Oxford OPMD lab using an interferometric method.

The student will contribute to the design and build of one of these experiments, and hopefully carry out the first single pixel direct oversampled PSF measurements on sensors used for the LSST camera. This will involve hands on lab work with optical and electronic components. Some programming experience in the python language will be highly beneficial.

Supervisors: ***Prof I Shipsey*** and ***Dr D Weatherill***
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AS10 Too close for comfort: is the hot Jupiter WTS-2 b spiralling into its host star?

The TESS mission launched in April 2018 and has since been observing the entire night sky to detect transiting planets i.e. those planets which pass in front of their host star along our line of sight. TESS observes patches of the sky for 80 days continuously to build up the all-sky picture. This means it can find both new planets, and deliver high quality follow-up light curves of know exoplanets. In this project, the student will extract the light curve of the known planets WTS-2 b from the TESS full frame images using tools provided by the transiting exoplanet community. WTS-2 b is a hot Jupiter in a very short orbit that was discovered in 2014. Based on exceptions from tidal decay theory, WTS-2 b is expected to be spiralling into its host star, which would cause its transit to arrive earlier and earlier. The goal to to use the TESS light curve to determine if it is possible to detect the earlier arrival time in the new light curve in comparison to the discovery light curves and to see if indeed the planet is spiralling into the host star, or if there is missing physics from the prescription of tidal decay. The project involves working with observed data using programming skills mostly in Python or similar.

Supervisor: ***Prof J Birkby***
Email: ***jayne.birkby@physics.ox.ac.uk***

AS11 The prospect of studying atmospheres of exoplanets in the habitable zones of nearby stars with high resolution spectroscopy

High resolution spectroscopy is a new and powerful technique for characterizing exoplanet atmospheres. Key to its successful is its ability to resolve the spectral features of different molecules in the atmosphere (such as water, carbon monoxide, methane) into a dense forest of individual lines arranged into a unique pattern for each species. Typically, the planet's host star outshines it by a factor of 1000-10 million, meaning that the spectrum of the planet containing all the information on its composition, structure, and atmospheric dynamics (e.g. winds, rotation period) is buried in this glare. However, due to the orbital motion of the planet, its spectrum undergoes Doppler shift that can be considerably larger than the host star. Consequently, removing spectral features that stay constant in time can reveal the faint Doppler-shifting planet spectrum underneath, allowing us to directly study the spectrum of its atmosphere. In this project, the student will explore the boundaries of this technique. For hot Jupiters, the Doppler-shift is very large which makes it easy to disentangle the planet spectrum, but for planets on wider orbits with smaller Doppler-shift it can be very challenging. The goal of the project is to determine which rocky planets in the habitable zones of different nearby stars would be accessible with this technique, and to potentially explore modifications to the technique that would enable a greater range of orbital separations to be studied. The project involves simulating spectral data with programming skills mostly in Python or similar.

Supervisor: ***Prof J Birkby***
Email: ***jayne.birkby@physics.ox.ac.uk***

AS12 Exploiting gravitational lensing to reveal distant galaxies

Gravitational lensing has the power to reveal otherwise hidden galaxies. Massive foreground clusters lens the background galaxy population, allowing faint galaxies at high-redshifts to be discovered. In addition to strong lensing by clusters, background galaxies can be lensed by a single massive elliptical galaxy, resulting in an image of the distant object that is both brighter and multiply imaged [1,2]. In this project you will search for lensed high-redshift galaxies using our unique photometric dataset in the VIDEO survey [3]. This data, which covers several square degrees on the sky, is the perfect combination of depth and area to discover new gravitational lensed systems, and provides a practice dataset for upcoming very wide area datasets (e.g. LSST and Euclid). Using the photometric redshifts and masses for galaxies in the field, you will first select the most massive galaxies (our lenses) in the field. Around these objects you will then search for multiply imaged sources using the photometric data. Once a sample has been established, you will work to understand the properties of the lensed galaxies by compiling the multi-wavelength data available. The lensed galaxies will be perfect candidates for detailed follow-up observations with other telescopes (e.g. Hubble, ALMA).

[1] http://adsabs.harvard.edu/abs/2012ApJ...761..142M

[2] http://adsabs.harvard.edu/abs/2008ApJS..176...19F

[3] http://www-astro.physics.ox.ac.uk/~video/public/Home.html

The project will be computational. Some coding experience will be helpful, but is not essential.

Please feel free to e-mail me for more details.

Supervisor: ***Dr R Bowler***
Email: ***rebecca.bowler@physics.ox.ac.uk***

AS13 Relativistic Jets from Black Holes

Astrophysical black holes (BH) are central to high-energy / relativistic astrophysics, and of deep importance to all of physics. Not only do they generate the most intense gravitational fields in the universe, the singularities at their centres hold the key to reconciling quantum mechanics and general relativity, yet are hidden from our view by event horizons. Their enduring importance has been recognised by both the 2017 and 2020 Nobel prizes in physics.

Stellar mass (~7 solar masses) BH observed in X-ray binaries (XRB) straddle the range in mass for relativistic objects between the neutron stars and the lowest mass LIGO-detected BH. They represent, largely, a pristine sample of BH which have not merged with another BH or stellar remnant and in some cases at least (the young, high-mass XRB systems) may still posess their birth spin, unaffected by accretion. They are the closest BH to earth, and are the only examples in nature of BH in which the response of the relativistic jet to changes in the accretion flow can be repeatedly studied on humanly-accessible timescales. All of the physical insights from BH XRB jets (e.g. estimating their formation, energy and propagation) are relevant for the other BH observed in the wider universe, including Active Galactic Nuclei (AGN), Tidal Disruption Events (TDEs) and GRB/GWs.

The relativistic jets from these systems are observed in the radio wavelength band, in which is encoded information about the size, internal energy and magnetic field density of the synchrotron-emitting ejecta. We have developed a new, simple, technique for investigating these properties under the assumption that peaks observed in radio 'light curves' (flux vs time) correspond to changes from optically thick to optically thin to synchrotron self-absorption. Initial studies have revealed surprising properties of the ejecta, hinting at constrained expansion rates and underestimates of internal energy. In this project the student will work with the supervisor to apply this new technique to an existing large sample of radio data from stellar BH to understand the picture for the overall population. This will involve working with python code, handling multiple data sets and interpreting the results in terms of synchrotron emission. A successful outcome would be a significant piece of novel research and could well lead to a refereed publication.

Supervisor: ***Prof R Fender***
Email: ***rob.fender@physics.ox.ac.uk***

AS14 Uncovering the physics of quasi-periodic oscillations in recent observations of black hole X-ray binaries

Black hole X-ray binaries (BH XRBs) are systems with a stellar-mass black hole and a star in a binary orbit. Gas is stripped from the star and accretes onto the black-hole, through an accretion disc which emits X-rays. We see additional high-energy X-rays from a cloud of hot electrons close to the BH known as the corona. A fraction of photons from the corona irradiate the disc and are reflected back into our line of sight to imprint characteristic features on the spectrum including an iron K alpha fluorescence line at ~6.4 keV. The line shape is distorted by the gravitaitonal pull of the black hole and by Doppler shifts due to the rapid orbital motion of disc material.

BH XRBs often show a quasi-periodic oscillation (QPO) in their X-ray flux with a period that slowly drifts from ~10s to ~0.05s over observations spaced ~days-weeks apart. The physical origin of the QPO has long been debated, but is often attributed to Lense–Thirring precession, a General Relativistic effect causing the corona to precess as the spinning black hole twists up the surrounding space–time. This predicts the centroid energy of the iron line to vary between red- and blue-shifted over the course of each QPO cycle, as the corona illuminates the receding and approaching sides of the disc. Such a modulation of the line energy has recently been observed for the first time with a sophisticated new technique, known as phase-resolved spectroscopy, that uses Fourier transforms to constrain how the X-ray spectrum changes over each QPO cycle. However, the line modulation has only been searched for in a few observations, and many questions remain about whether its properties change with QPO period or from one XRB to the next, and even whether it can be explained by mechanisms other than Lense-Thirring precession.

This project will apply the phase-resolved spectroscopy technique to new, high-quality data from NASA's Neutron Star Interior Composition Explorer (NICER) onboard the International Space Station. A mixture of NASA software and proprietary code will be used to extract and model the QPO phase-resolved spectra, which will provide insight into the QPO mechanism.

To get the most out of the project the student will need to be comfortable with using the Fourier transform and have some experience with Python. An enthusiasm for high energy astrophysics and General Relativity are desirable, but no formal training is required.

Supervisor: ***Dr A Ingram***
Email: ***adam.ingram@physics.ox.ac.uk***

AS15 The resolved star formation history of Andromeda

Determining the process which are responsible for cutting off star formation in galaxies is one of the major outstanding problems in galaxy evolution. One way to tackle this is to infer the star formation history of a galaxy using indicators of recent and past star formation. Indicators include spectroscopic emission lines or using the global (or resolved) colours of a galaxy. Methods which use spectroscopic indicators produce more accurate results, as the colours of a galaxy are degenerate with other galaxy properties such as mass and metal content. However, upcoming large galaxy surveys such as the Large Synoptic Sky Survey (LSST) at the Vera Rubin Observatory (scheduled to start in 2023) will only provide imagery for the billions of galaxies targeted, and not spectroscopy. We must therefore fully understand the limitations of inferring star formation histories using galaxy colours.

In this project, the student will analyse optical and ultraviolet imagery of the nearby Andromeda galaxy, M31, to derive the colours in each pixel and use those as inputs into an existing star formation history inference code. This will provide a detailed and resolved star formation history across the disk of M31. Andromeda is an incredibly well studied system, with many different methods used previously in the literature to determine an accurate and precise resolved star formation history, e.g. the PHAT survey (see Williams et al 2017). The aim of this project is to compare the results of these previous studies, with the star formation histories derived using the resolved colours in order to understand the limitations of this method. This will then inform what techniques should be applied to eventual LSST data sets and what the caveats on colour derived star formation histories are. This project would suit a student with broad interests in observational astronomy, and some knowledge of coding in Python. The work is entirely computer based and would not be affected by any COVID restrictions.

Supervisors: ***Dr B Smethurst*** and ***Prof C Lintott***
Email:***rebecca.smethurst@chch.ox.ac.uk*** and ***chris.lintott@physics.ox.ac.uk***

AS16 Is Betelgeuse a supernova progenitor?

In late 2019 Betelgeuse, previously one of the ten brightest stars in the northern sky, began to fade dramatically until it was fainter than over 20 other stars in the night sky. Speculation soon followed that Betelgeuse might be about to go supernova.

The world-wide telescopes that comprise the Global Jet Watch have been following Betelgeuse since before its recent dramatic fading, and in this project the student will investigate these time-lapse spectroscopy and time-lapse photometry data, and compare them with existing models. This investigation will make use of spectroscopic diagnostic tools and techniques to explore these data-streams, as well as literature research.

The project demands good analytic skills, as well as continual access to a computer.

This project can be carried out remotely in the event of further lockdown restrictions

Supervisor: ***Prof K Blundell***
Email: ***katherine.blundell@physics.ox.ac.uk***

AS17 Multiple periodicities in the multi-star system Sheliak

The iconic multiple star system known as Sheliak (aka Beta Lyrae), has been puzzling astronomers for two centuries. It has orbits within orbits and it is a very active system, containing an accretion disc and, reportedly, oppositely-directed jets.

In this project, the student will investigate new time-lapse spectroscopy and time-lapse photometry from the world-wide telescopes known as the Global Jet Watch. This investigation will make use of spectroscopic diagnostic techniques to explore these data-streams and elucidate the relationships between the different periodicities in this exotic system, as well as literature research.

The project demands good analytic skills, as well as continual access to a computer.

This project can be carried out remotely in the event of further lockdown restrictions.

Supervisor: ***Prof K Blundell***
Email: ***katherine.blundell@physics.ox.ac.uk***

AS18 Accretion and outflows in the slowest classical nova: AG Peg

The world-wide telescopes that comprise the Global Jet Watch have been observing the time evolution of AG Peg for the past few years. The nature of its time evolution has led to it being regarded as "the slowest known classical nova" which therefore affords the opportunity to study nova phenomena at a rather more leisurely pace than is possible for normal nova eruptions. Its spectra show dynamical signatures of its outflows and accretion and these will be the focus of this project.

For this project the student will successive spectra that have captured the evolving behaviour of AG Peg. This investigation will make use of spectroscopic diagnostic tools and techniques to explore these data-streams, as well as being informed by current models in the research literature.

The project demands good analytic skills, as well as continual access to a computer.

This project can be carried out remotely in the event of further lockdown restrictions.

Supervisor: ***Prof K Blundell***
Email: ***katherine.blundell@physics.ox.ac.uk***

AS19 Eccentric orbits and evolving outflows in CI Cam

CI Cam is a binary star system containing a B[e] supergiant which has, in recent years, been reported to have exhibited relativistic radio jets, a circum-binary disc (i.e., matter that is orbiting around two stars, not just a single star), while its stars follow highly-eccentric orbits as well as being a supernova imposter.

The student will for this project be exploring modern spectroscopic and photometric time-series data observed by the world-wide telescopes that collectively form the Global Jet Watch, and testing what has been observed against models that have been proposed in the research literature. This investigation will make use of spectroscopic diagnostic tools and techniques to explore these data-streams, as well as being informed by current models in the research literature.

The project demands good analytic skills, as well as continual access to a computer.

This project can be carried out remotely in the event of further lockdown restrictions.

Supervisor: ***Prof K Blundell***

Email: ***katherine.blundell@physics.ox.ac.uk***

AS20 Exploration of the prevalence of jets following classical nova eruptions

In early 2021, McLoughlin et al announced the discovery of jets in the immediate aftermath of a classical nova eruption. This discovery was deduced from persistent patterns of spectral signatures in time-lapse spectroscopy from the world-wide telescopes that comprise the Global Jet Watch. More novae have detonated in the Galaxy in Q1/Q2 of 2021 and the analysis of the spectroscopic data-streams on these will be the main focus of this MPhys project, with the main goal being to establish the prevalence (or otherwise) of jets in classical nova events.

Depending on the interests and aptitudes of the student tackling this project, it will be possible to pursue this investigation employing machine learning techniques to compare their efficacy compared with traditional fitting approaches.

The project demands good analytic and programming skills (Python or similar) as well as continual access to a computer.

This project can be carried out remotely in the event of further lockdown restrictions.

Supervisor: ***Prof K Blundell***
Email: ***katherine.blundell@physics.ox.ac.uk***

AS21 Atmospheric physics and astrophysics time-series data calibration optimisation

The accurate calibration of time-series data on varying targets in the Galaxy is critically important for many different areas of time-domain astronomy. This project seeks to identify a robust methodology to model and trace the "top-of-atmosphere flux" for astronomical targets of interest [using time-series meteorological data collected by the Global Jet Watch] and hence attain the most accurate flux-calibrated spectrophotometry possible [using time-series astronomical data collected by the Global Jet Watch]. There is open-source code already available and so an MPhys student (who already has fluency in Python) would work on implementing/testing this (not trying to start from scratch).

The project demands good analytic and programming skills (Python or similar) as well as continual access to a computer.

This project can be carried out remotely in the event of further lockdown restrictions.

Supervisors: ***Prof K Blundell*** and: ***Prof T Woollings***
Email: ***katherine.blundell@physics.ox.ac.uk*** and
tim.woollings@physics.ox.ac.uk;

AS22 Galaxy Mergers and Quenching

The present-day galaxy population is undergoing significant quenching, as systems transition from vigorous star formation to mostly quiescent evolution. A huge variety of mechanisms have been proposed to account for this behaviour, amongst them the effects of major mergers of galaxies. This project makes use of a large sample of mergers and post mergers classified by citizen scientists through the Galaxy Zoo project to investigate the effects of mergers, and to quantify for the first time their contribution to the quenching of the population as a whole. Data from the Sloan Digital Sky Survey is supplemented by recent classifications of DeCALS, a deeper survey which is more capable of identifying low surface brightness merger signatures, and which may include the southern sky for the first time. The project will require moderate python, though this could be learnt along the way if necessary.

Supervisor: ***Prof C Lintott***
Email: ***chris.lintott@physics.ox.ac.uk***

AS23 A Machine Enabled Search for Ring Galaxies

Ring galaxies are typically the result of a merger or interaction, and as such can help us understand how such events trigger star formation and affect the galaxies involved. While many have been found serendipitously, a systematic search has not been carried out. This project will train modern deep learning networks - probably a convolutional neural network - on a sample of rings identified by participants in the Galaxy Zoo project to search for rings. The aim is to provide limits on the prevalence of rings in the galaxy population, and to study the properties of the resulting sample. It therefore combines a chance to learn the tools of data science with a chance to do some astrophysics. Students picking this project should enjoy coding - as there will be a lot of it - but it should be fine to learn as you go if necessary.

the long-running Galaxy Zoo project, which records galaxy morphologies, key to tracing a galaxy's dynamical history, but there is a possible extension to other projects, including a search for exoplanets in TESS data which should be available from Hilary 2019.

The project will involve working with TensorFlow or similar machine learning implementations, and with code written in Python. Though prior experience with these tools is not necessary, it would suit a student who wants to acquire skills appropriate for data-driven science and who is happy writing their own code. Links to the Zooniverse's outreach program are also possible.

Supervisor: ***Prof C Lintott***
Email: ***chris.lintott@physics.ox.ac.uk***

AS24 Finding the optimal way of extracting density profiles from Gaia data

The Gaia spacecraft has recently provided full six-dimensional phase-space information (three positions and three velocities) for the stellar motions in the Milky Way. This new dataset is allowing us to infer the density distribution of the Milky Way with unprecedented accuracy using dynamical models. However, the Milky Way is not axisymmetric and not in equilibrium. This implies it may not satisfy the dynamical model's assumptions to sufficient accuracy. Here the student will asses the reliability of the dynamical models using N-body simulations of galaxies similar to the Milky Way, by checking how different modelling assumptions affects the results. Using these simulations, the student will try to find optimal ways of extracting density distributions from the Gaia data.

Special skills: Knowledge of the Python programming language.

Supervisor: ***Prof M Cappellari***
Email: ***michele.cappellari@physics.ox.ac.uk***

AS25 & AS26 Weak lensing with the Euclid mission

The ESA Euclid mission will launch in 2022 and carry out a survey of cosmological weak gravitational lensing, to measure the universe's geometry and its growth of structure, with unprecedented accuracy. In order to realise the science goals, we must carefully propagate our understanding of the measurement process into the data analysis. This project will investigate the effect of errors in the modelling of the telescope and detector point spread function on the cosmological accuracy that can be obtained. This will involve first evaluating the effect of instrumental effects on the weak lensing shear measurement, and then propagating those through to the estimation of cosmological parameters. This project will use some existing software, but additional coding in python by the student will also be required.

Supervisor: ***Prof L Miller***
Email: ***Lance.Miller@physics.ox.ac.uk***

AS27 & AS28 Very-high-energy gamma-ray astrophysics with the Cherenkov Telescope Array

Very high-energy gamma-ray astrophysics is an exciting field spanning high-energy particle physics and extreme processes in astronomy. Our investigations range from the nature and variety of particle acceleration around supernovae and black holes, to physics beyond the Standard Model including dark matter, axion-like particles and Lorentz invariance violation.

The group in Oxford works on both experiment and theory. We are members of the High Energy Stereoscopic System (H.E.S.S.) in Namibia, presently the world's largest gamma-ray observatory, and the next-generation gamma-ray observatory, the Cherenkov Telescope Array (CTA). CTA will consist of up to one hundred telescopes using state-of-the-art photomultiplier detectors and high-speed digital signal processing to detect and characterize the electromagnetic air shower caused when an astrophysical gamma-ray enters the Earth's atmosphere. The telescope prototypes are under construction, and deployment to the observatory sites at Paranal, Chile, and La Palma, Canary Islands, will commence in 2020.

M.Phys. students will have an opportunity to choose their project from a variety of our activities. On the experimental side of the prgramme, we are leading efforts to develop advanced analysis techniques for the large volumes of data that will be generated when CTA becomes operational, including co-ordination of the CTA Machine Learning Task Force. On the theoretical/observational side, we have recently developed a new class of models for the broad-spectrum emission from relativistic jets in active galaxies, which let us use the gamma-ray to investigate the physical properties of the jet and the black hole at its base. We now propose to extend these models to look in particular at the entrainment of heavy particles as the jets propagate through their host galaxy, the resulting possibility of hadronic particle processes within the jets, and propagation effects in intergalactic space that may provide evidence for axion-like particles or Lorentz invariance violation.

These projects are particularly suited to students who are taking astrophysics or particle physics major options.

For more information please contact Professor Garret Cotter.

Supervisor: ***Prof G Cotter***
Email: ***Garret.Cotter@physics.ox.ac.uk***

AS29 The Tully-Fisher relation as a tool to study galaxy growth.

The dynamical scaling relations of disk galaxies exhibit tight correlations between the main galaxy properties: size, mass and rotational velocity. Among these is the Tully-Fisher relation (TFr), linking the baryonic content of a galaxy to its rotational velocity. Comparing the TFr at different redshifts is a powerful tool to constrain gas accretion and more generally how galaxies grow. The presence of a significant TFr evolution suggests an imbalance in the accretion histories and mass assembly of Dark Matter (DM) and baryons. At low redshifts neutral hydrogen (HI) is used as the kinematic tracer, as it provides the best measure of the total gravitational potential of a galaxy. However, HI remains undetectable in emission at significant redshifts. Carbon monoxide (CO) has been used as the kinematic tracer at high redshifts, but its distribution is known to be compact and may not probe the DM halo potential. A careful and homogeneous study of the CO- and H I-based TFrs at $z \approx 0$ is thus required to investigate how the choice of kinematic tracer affects the zero-point, slope and scatter of the TFr.

The student will conduct this study using existing CO ($J = 1 - 0$) and HI mapping of a sample of galaxies in the Ursa Major cluster. This study will allow us to gauge the reliability and limitations of CO as a kinematic tracer, what will improve our current understanding of the evolution of the TFr with redshift. The student will learn how to analyse 3D radio data, as well as will gain experience working with photometrical data and statistical techniques. Knowledge of python and astropy is a plus, but not required.

Supervisor: ***Dr A Ponomareva***
Email: ***anastasia.ponomareva@physics.ox.ac.uk***

AS30 Astro Optimal collection of new data for Cosmology

Modern physics problems often involve making predictions for large amounts of data using supervised machine learning algorithms e.g. photometric redshifts for large astronomical datasets - an essential requirement for contemporary efforts to measure the equation of state of Dark Energy. Recent work has focussed on quantifying how much uncertainty on predictions is from intrinsic variation in the data, and how much is from lack of training data. In this project, the student will investigate how to statistically determine what is the optimal new data to collect to improve predictions for a range of problems (in particular galaxy redshifts for cosmology), and trial the algorithm on new data sets. This will involve reducing data, applying supervised machine learning algorithms to astrophysical data sets, and finding new ways to use existing algorithms. The project requires basic programming skills (Matlab, python or similar).

Supervisor: ***Dr P W Hatfield***
Email: ***peter.hatfield@physics.ox.ac.uk***

AS31 Fast statistical methods for redshift uncertainties in weak lensing data

Cosmological weak lensing experiments offer a unique window to study the impact of dark energy on the growth of structure and the geometry of the Universe. However, their main source of systematic uncertainty lies in the poor knowledge of the galaxy redshift distributions. This project will focus on applying advanced statistical and computational methods (Hamiltonian Monte-Carlo and Gibbs sampling) to the problem of robustly marginalizing over these uncertainties to recover unbiased constraints on cosmological parameters.

Skills: coding experience with python is recommended.

Supervisor: ***Prof D Alonso***
Email: ***david.alonso@physics.ox.ac.uk***

AS32 Measuring magnification by Large Scale Structure in the VIDEO dataset

Gravitational lensing denotes the process by which the path of light is bent by the presence of matter, leading to measurable distortions in observed galaxy properties such as shape, size and brightness. The measurement of large statistical samples of weakly lensed galaxies can therefore be used to investigate the matter distribution and geometry of the universe. “Magnification bias” describes the change in number density of distant background sources due to the change in observed flux and position of lensed galaxies. The measurement of this affect relies mainly on accurate photometry, and can therefore be used on faint or distant galaxies which cannot be used for a traditional shape measurement analysis, but requires tight control of the properties of the galaxy population used for such studies.

In this project, you will attempt to measure the magnification signal in the VIDEO dataset (http://www-astro.physics.ox.ac.uk/~video/public/Home.html). You will select a sample of source galaxies and lenses, investigate and remove confounding factors in the dataset, and apply statistical measures to measure properties of the large scale structure in the VIDEO field.

This project will require some coding, and will give you experience in research, manipulating astronomical data-sets, understanding the processes by which we measure galaxy properties from astronomical images, and applying statistical measures to extract a cosmological signal.

Supervisors: ***Dr C Duncan*** and ***Prof M Jarvis***
Email: ***christopher.duncan@physics.ox.ac.uk***; and ***matt.jarvis@physics.ox.ac.uk***

AS33 Designing a frequency comb source for HARMONI line spread function calibration

HARMONI is the first light integral field spectrograph for the Extremely Large Telescope. Part of the instrument’s calibration involves calibrating the “line spread function” (LSF) – the response of the instrument to a truly monochromatic source. The LSF is expected to vary considerably with position along the (pseudo) slit and with wavelength. Accurate knowledge of the LSF is required for correct subtraction of the (time variable) sky background at near-infrared wavelengths. To adequately measure the LSF shape, we need a tunable frequency comb that covers the entire wavelength range of the instrument, from 450 nm to 2400 nm. The project will look at different possible designs for a Fabry-Perot based frequency comb, and determine the optimal design that best fits the instrument requirements. There will be an experimental component using commercial fibre / plate etalons to verify the comb’s operation.

Supervisor: ***Prof N Thatte***
Email: ***niranjan.thatte@physics.ox.ac.uk***

AS34 Detection of transiting exoplanets with the TESS space mission

The Transiting Exoplanet Survey Satellite, TESS, will commence operations in 2018, scanning almost the entire sky for planets transiting across bright stars. It will spend between one month and one year observing any given portion of the sky, with one observation every minute for the brightest 200000 stars. Simulations of TESS’s planet yield suggest it will discover thousands of new exoplanets, including several dozens of terrestrial planets. Here at Oxford we have developed tools to detect and model planetary transits in the context of previous space missions CoRoT and Kepler, which we are planning to use for TESS data. The project will consist in analysing the live stream of TESS data to detect new planet candidates, and liaising with our collaborators to arrange spectroscopic follow-up observations. Depending on progress, the project may lead to publications in refereed journals, which the student will be an author on. We are also planning to set up an online interface to enable the wider public to participate in the planet discovery effort, via the Zooniverse platform (see www.planethunters.org for an example of such a project on Kepler data), and there will be an opportunity to interact with the public through this if the student is interested.

The project will suit a student interested in exoplanets, with a good statistical background and programming skills (ideally some experience of Python). The student will work both with existing code (to detect and model transits) and write their own (to model individual planet candidates).

Supervisor: ***Prof S Aigrain***
Email: ***Suzanne.Aigrain@physics.ox.ac.uk***

AS35 Instrumentation on the Philip Wetton Telescope

The Philip Wetton telescope here in Oxford is used for a range of undergraduate projects, some research, and of course public outreach. The telescope is fully automated (robotic), and takes data for a range of projects every clear night. Currently, the only instrument available is a standard CCD camera with a range of colour filters. This project aims to expand the instrumentation capabilites of the observatory by developing some new instruments for spectroscopy or adaptive-optics. A range of possible options is listed below, but interested students are strongly recommended to discuss options with the supervisors before the application deadline -- there is scope to tailor the project to the student's aims. These projects would suit a student with an interest in the more practical side of astronomy.

Potential instrumentation projects include;

+ Automating the existing slit spectrograph to allow robotic operation

The observatory has an existing spectrograph, but it is little used as it is not compatible with robotic operation. This project will involve adding components (e.g. servo motors + controllers) to the spectrograph, and developing control software to allow it to be used remotely. Depending on how the project develops, we will also look at integrating the spectrograph into the existing observatory control software to allow fully robotic spectroscopy for the first time. This project should suit a student with an instrumentation and coding; exploiting the spectrograph to its full will require some significant code development.

+ Designing a new spectrograph for an integral field unit

We have an fibre integral field unit (to allow spectroscopy of extended objects such as planets or galaxies), which was built as an MPhys project several years ago. Unforuntately the existing spectrograph is not good enough work efficiently with the IFU, so we need to design a new more suitable spectrograph. This project will involve investigating different optical design options, and then developing a mechanical design around them. Depending on how the project develops, we will attempt to build a first version of the spectrograph in the lab. This project would suit a student with an interest in optical/mechanical design.

+ Characterising a new cheap fast camera for wavefront sensing

We have recently bought a small fast camera based on new CMOS technology, which seems to offer good potential as a wavefront sensing camera -- the first step in building a potential adaptive optics system for the PWT. This project will involve characterising the true performance of the camera in the lab and then on the telescope. Developing an AO system is beyond the scope of this project, but we will attempt to use the camera to characterise the atmosphere above Oxford as input to any future designs. This will involve developing some simple instrumentation and taking large runs of data with the camera. This project would suit a student with an interest in software and data processing/analysis.

Special Requirements

As the instrumentation projects are quite specialised, students must speak to the supervisors before applying for the projects. Code for the projects will be mainly based in Python, so experience in this is useful but not necessary. Some of the projects, particularly the wavefront sensing project, will require night-time working to take data.

Supervisor: ***Dr F Clarke***
Email: ***fraser.clarke@physics.ox.ac.uk***

AS36 High-redshift disk formation

Although unobserved as yet, galaxies in their infancy about 500 million years after the Big Bang are already being simulated by computational cosmologists. These early galaxies are predicted to form at the intersections of the cosmic web that grows out of the seed perturbations imprinted after the Big Bang. This project will study how gas streaming along filaments in the cosmic web can form rapidly rotating, dense, gaseous disks at their intersections in the high redshift Universe. In the simulations, these gaseous disks appear to be rotating as fast as the Milky Way but they are about a tenth of its size. Under such extreme conditions, a disk can become gravitationally unstable and fragment into massive gas "clumps" which could collapse into star clusters. Therefore understanding how these high redshift galaxies acquire their rapid rotation is crucial to making sense of high-redshift star formation.

The goal of this project, is to explain these rapidly rotating, small disks. This will involve converting outputs from ultra-high resolution hydrodynamical cosmological simulations into a format that is readable by a sophisticated three-dimensional visualization software, and then measuring the orientation of the filaments relative to the disk. From the geometrical information, and measurements of the gas velocities in the filaments, an explanation for the disk orientation and extreme rotational disk velocities will be constructed.

Good programming skills required.

Supervisors: ***Prof A Slyz*** and ***Dr J Devriendt***
Email: ***adrianne.slyz@physics.ox.ac.uk; julien.devriendt@physics.ox.ac.uk***

AS37 Dissecting galaxies using cosmic telescopes - strong gravitational lenses

Gravitational lenses are remarkable phenomena – a striking visual demonstration of Einstein's theory of General Relativity – where the light from a distant galaxy is bent by the gravity field of an intervening massive foreground galaxy or group of galaxies lying along the line of sight. This results in an amplified, magnified and distorted image of the distant background galaxy often resulting in multiple images or complete and partial rings. The separation and distortion of lensed images is entirely determined by the total matter distribution in the intervening 'lens', this includes both luminous (i.e. stars) and elusive dark matter. Therefore lensing is one of the only means to "weigh" galaxies, and to constrain dark matter providing one of the most direct pieces of evidence for its existence. However, finding gravitational lenses remains a difficult task with large numbers of false positives (configurations that mimic lenses) requiring significant effort in visually inspecting the candidates. Strong gravitational lenses have a variety of astrophysical and cosmological applications, including mapping dark matter and constraining cosmological parameters. In this MPhys project we focus on understanding the distribution of mass in the lenses, and the nature of the distant (high-redshift) lensed galaxies. The lenses studied in this project were discovered by citizen scientists taking part of the Galaxy Zoo and Space Warps (spacewarps.org) Zooniverse projects. The work will be centred on analysing spectroscopic data already in hand to determine the nature of the lens and place constraints on the lens model, mass and distribution of dark matter. The student will be guided through existing data reduction and analysis software packages. Therefore candidates should be comfortable with basic programming, and some experience with IRAF would be advantageous, but not essential. There will also be opportunity to liaise with lensing enthusiasts participating in Space Warps

More information

Aprajita Verma (aprajitaverma1@gmail.com, https://www2.physics.ox.ac.uk/contacts/people/verma)

Supervisor: ***Dr A Verma***
Email: ***aprajita.verma@physics.ox.ac.uk***

AS38 Measuring Galactic rotation with HI

Atomic hydrogen in our Galaxy (and elsewhere in the universe) emits a characteristic narrow radio emission line at a frequency of 1420 MHz.

The narrowness and precise rest frequency of this HI line means that it can be used to trace motion via the Doppler effect. HI measurements are widely used in astrophysics to measure rotation velocities, as well as a tracer of the overall expansion of the universe. In this project the student will use a small radio telescope on the roof of the DWB to map out the HI emission in the plane of our own Galaxy. The signal received from any given direction is the sum of multiple components along the line of sight with different projected velocities. By modelling the line shapes the student will determine the shape of the Galactic rotation curve and hence verify the existence of Dark Matter in the Galaxy.

Supervisors: ***Prof M Jones, Prof A Taylor*** and ***Dr J Leech***
Email: ***mike.jones@physics.ox.ac.uk***

AS39 Measuring the accelerating expansion of the Universe with distant Supernovae: Predicting the constraints the HARMONI instrument on the E-ELT will provide

The European Extremely Large Telescope, or E-ELT, is a revolutionary new ground-based telescope concept with a 39-metre main mirror and will be the largest optical/near-infrared telescope in the world: "the world's biggest eye on the sky".

The HARMONI integral field spectrograph is one of the first-light instruments for the E-ELT. The project is led by Prof Niranjan Thatte of Oxford, and will see first light on sky in about 8-9 years. It will be sensitive to wavelength between 0.5 and 2.5 µm

This project aims to simulate observations of Supernovae at redshift z=3-5 with HARMONI to measure the accelerated expansion of the universe over a wider redshift range. The student will create different input data cubes (different red-shifts, SN type, instrument settings) to feed into the 'hsim' pipeline, and analyse the output cubes produced by 'hsim', in order to establish how well HARMONI will be able to detect and characterise distant Supernova.

Special skills

As this project is computational, the student is expected to have sufficient computer and programming knowledge, and a basic knowledge of python. Further knowledge in data analysis, in any language, would be advantageous.

Supervisor: ***Dr M Tecza***
Email: ***matthias.tecza@physics.ox.ac.uk***

AS40 Radio telescope receiver systems

The physics department is setting up a radio astronomy lab for teaching and outreach, consisting of two small telescopes on the roof of the DWB.

This project is to develop a new control and receiver system for these telescopes, and to demonstrate the ability to make astronomical observations with it. The student will use a high-speed data acquisition system based on a Field-Programmable Gate Array to develop a digital backend that can be used to make broad-band spectral and continuum observations, and integrate this with the telescope control system so that the telescope can simultaneously track and take data. The performance of the system will be verified by observing astronomical sources. This project will require a reasonable level of computing skills as well as an inclination towards practical experimentation

Supervisors: ***Prof M Jones, Prof A Taylor, Dr J Leech, Dr K Zarb Adami***
Email: ***mike.jones@physics.ox.ac.uk***

AS41 Giant radio pulses from radio emitting neutron stars

Over the course of the last 2 years, we have been accumulating data using the Low Frequency Array (LOFAR) to search for new pulsars and fast radio bursts. In the process, we have accumulated data from a handful of known, extremely bright pulsars. These pulsars are seen to occasionally emit extremely bright individual pulses, a phenomenon referred to typically as giant pulse emission. The low radio frequency data of LOFAR are particularly prone to propagation effects, as the radio signals travel through the magneto-ionised interstellar space. In this project, we will investigate individual pulses from this population of pulsars, with the aim of characterising the interstellar medium and the intrinsic properties of giant pulse emission. These investigations will shed light on the radio emission process of pulsars at low radio frequencies (150 MHz) and help understand potential extreme propagation events in the Galaxy. Work will be supported by pulsar group members from Astrophysics and the OeRC.

Supervisor: ***Dr A Karastergiou***
Email: ***aris.karastergiou@gmail.com***

AS42 C-Band All Sky Survey project s(C-BASS)

Oxford is currently leading the C-Band All Sky Survey project (C-BASS) which is an experiment to measure the intensity and polarisation of the whole sky at 5 GHz. The primary aim of the experiment is to provide maps of and to understand the low frequency Galactic foreground emission that must be subtracted from current and future measurements of the CMB such that e.g the faint CMB B-mode signature may be detected. The experiment consists of two telescopes - one observing from California to map the northern sky and another in South Africa mapping the Southern sky. The northern survey is now complete and the Southern survey well underway. We are looking for MPhys students to work with us on a range of projects:

- Calibration and cross-calibration of the C-BASS surveys

- Detailed analysis of the Southern survey data to understand the systematics in the data

- Combined analysis of C-BASS data with WMAP and Planck

- Measurement of the variation of spectral index of Galactic Synchrotron across the whole sky in intensity and polarization

- Forecasting of requirements for a future low-frequency foreground experiment in support of up-coming ground-based and satellite CMB B-mode experiments.

All these projects will involve a large element of computing. Experience with either Matlab or python would be desirable.

More general information about the C-BASS project can be found at: http://www.astro.caltech.edu/cbass/

Supervisors: ***Prof M Jones, Prof A Taylor*** and ***Dr J Leech***
Email: ***mike.jones@physics.ox.ac.uk***

AS43 **tbc**

More details from the supervisor.

Supervisor: ***Prof C Terquem***
Email: ***caroline.terquem@physics.ox.ac.uk***

AS44 **tbc**

More details from the supervisor.

Supervisor: ***Prof S Balbus***
Email: ***steven.balbus@astro.ox.ac.uk***

AS45 **tbc**

More details from the supervisor.

Supervisor: ***Prof D Rigopoulou***
Email: ***dimitra.rigopoulou@physics.ox.ac.uk***

AS46 **tbc**

More details from the supervisor.

Supervisor: ***Prof M Bureau***
Email: ***martin.bureau@physics.ox.ac.uk***

AS47 **tbc**

More details from the supervisor.

Supervisor: ***Prof A Bunker***
Email: ***andy.bunker@physics.ox.ac.uk***

AS48 **tbc**

More details from the supervisor.

Supervisor: ***Prof P Ferreira***
Email: ***pedro.ferreira@physics.ox.ac.uk***

Biological Physics projects

BIO01 **Super-resolution imaging of pathogenic microbes**

Accurate localisation of single fluorescent molecules is at the heart of many methods that have recently shuttered the diffraction limit in optical microscopy, improving resolution from ~200 nm to ~10 nm; the potential of these methods was acknowledged by a Nobel Prize in 2014. We have been developing super-resolution fluorescence imaging and tracking methods for single biological cells, and applied them to many organisms ranging from living bacteria to mammalian cells; we are especially interested in pathogenic bacteria and viruses and their interactions with host cells. Our methods are both computational (involving image and time-series analysis) and experimental.

This project will focus on an aspect of super-resolution imaging and single-molecule tracking. Example projects: use experimental or machine-learning approaches to study the diffusion of DNA-processing machines inside bacterial cells; apply theoretical models to describe diffusion and interactions of molecules inside living bacteria; develop biosensors that probe the physiology of bacterial cells through physical descriptions of the cell interior (a novel method that can detect whether certain antibiotics are working or not).

All projects will involve wide-field imaging of cells and extensive image analysis, and can have an experimental, computational, or modelling focus. The students are encouraged to have a discussion with the supervisor regarding the focus of the project.

No prior knowledge of biophysics is necessary; experience in optics and programming (Python and/or MATLAB) would be an advantage. Introductory literature, as well as the relevant risk assessments for the specific experiment, will be provided.

Supervisor***: Prof A Kapanidis***
Website: **kapanidis.web.ox.ac.uk**
Email***: achillefs.kapanidis@physics.ox.ac.uk***

BIO02 **Time-series analysis of nanoscale motions and interactions in single-molecule biophysics**

To understand the mechanisms of protein machines that operate on DNA, our group is using single-molecule fluorescence methods that allow us to watch the nano-scale dynamics of DNA-processing machines (such as the RNA polymerase, the machine that copies DNA to RNA) in real-time; this work can identify new steps in genetic processes (such as transcription) that may serve as antibiotic targets, and can help us understand how existing and new antibiotics exert their function. These efforts depend on the ability to detect single protein molecules as they operate on DNA fragments that resemble segments of genomic material. We also develop methodologies that probe the existence of specific sequences in various contexts, either in purified systems or intact cells.

In all cases above, we need to apply, adapt or develop time-series analysis methods that analyse large data sets of time-series to identify the motions or interactions of the biological molecules involved. The project will focus on some aspect of time-series analysis of large data sets, e.g., machine-learning based classification of different kinetic behaviours for DNA-DNA or DNA-RNA interactions; and machine-learning-based classification of different single-molecule fluorescence-resonance-energy-transfer (smFRET) time series based on protein conformational changes occurring during transcription.

Projects will have mainly a computational focus. The students are encouraged to have a discussion with the supervisor regarding the project.

No prior knowledge of biophysics is necessary; experience in optics, programming (Python and/or MATLAB) and machine-learning would be an advantage. Introductory literature, as well as any relevant risk assessments for the specific experiment, will be provided.

Supervisors***: Prof A Kapanidis***
Website: **kapanidis.web.ox.ac.uk**
Email***: achillefs.kapanidis@physics.ox.ac.uk***

BIO03 **Machine learning for live cell super resolution imaging**

Super resolution imaging has revolutionised biological imaging by having the power to resolve structures down to a resolution of 20 nm, while maintaining functional information. Common methods separate the emission from site-specific labels on imaged structures stochastically or temporally to improve the resolution of images, and so have limited utility observing time-dependent events. Machine learning algorithms have previously been used to improve imaging speeds or to post-process images to improve their resolution, though have only been applied to general biological structures (microtubules, actin rings etc.). In the lab, we have been developing novel imaging, image processing and analysis tools to improve upon both the time and spatial resolutions of super resolution microscopy.

This project will extend previous super resolution developments in two possible ways: using post-processing to produce images trained from super-resolved dSTORM images, and applying machine learning networks to the analysis of more representative images, e.g., using fixed samples as a training dataset for a live-cell version of the same experiment. This will allow us to image structures that have not previously been imaged with high temporal and spatial resolution simultaneously.

No prior knowledge or experience of biophysics is necessary; experience in programming (Python/MATLAB) would be an advantage; basic knowledge or experience in machine learning is desirable but not necessary. Introductory literature will be provided.

Supervisor***: Dr N Robb***
Website: **https://www2.physics.ox.ac.uk/contacts/people/robb**
Email***: nicole.robb@physics.ox.ac.uk***

BIO04 Understanding diffusion and aggregation of virus particles

Many viruses (from the influenza virus to SARS-COV-2 which is responsible for the Covid-19 pandemic) can cause debilitating and deadly diseases, and their sensitive, specific and rapid detection is a major challenge in their identification and control. We have been developing novel detection methods (in part due to previous successful MPhys projects that have led to publications and patents) based on single-molecule fluorescence imaging, single-particle tracking and machine learning, to detect viruses. These measurements can be carried out on a compact microscope that can be used in clinical settings and detection can be completed in just a few minutes, significantly faster than existing assays that may take hours to return a result.

This project will extend the previously developed diffusion-based detection assay by characterising the type of diffusion of many different viral strains (e.g. anomalous), exploring dependencies on pH, virus concentration, isoelectric points, temperature and salt concentration, and studying their effect on viral aggregation. Analysis methods may include hidden Markov models, machine learning, simulations and the use of colloidal electrolyte theory.

No prior knowledge or experience of biophysics is necessary; experience in programming (particularly MATLAB or python libraries numpy, pandas, pytorch, tensorflow and matplotlib) would be an advantage. Introductory literature will be provided.

Supervisor***: Dr N Robb***
Website: **https://www2.physics.ox.ac.uk/contacts/people/robb**
Email***: nicole.robb@physics.ox.ac.uk***

BIO05 Gold nanorods as fast probes for measuring the rotation of molecular motors.

Nature has invented the wheel a number of times. In addition to the bacterial flagellar motor and ATP-synthase, and the extensive molecular machinery that winds its way around DNA, a number of new molecular structures in the last few years point to more natural biological rotary motors. These structures are beautiful and informative, and can often lead to predictions about the mechanism of the molecular machine. But to test predictions, an experimental probe of the motion of the machine is needed.

In this project, the student will investigate the use of gold nanorods as markers for molecular rotation. In the lab in Oxford we attach these to molecular motors and illuminate them with circularly polarized laser light in a light microscope. The intensity and polarization of light back-scattered by the rods depends on their orientation. The project may range from recovering rod orientation from the polarized scattering signals to analysis of the rotation of biological molecular motors, measured via nanorod scattering.

Supervisor: ***Prof R Berry***
Email: ***richard.berry@physics.ox.ac.uk***

BIO06 Structural, functional and computational studies of ion channels

The projects involve determining the relationship between the structure and function of ion channels found in the membranes of living cells. Ion channels regulate the 'bio-electricity' that control all forms of cellular electrical excitability. As a result they control or influence almost every process in the human body from the way our nerves and brain work, to the way our heart and kidneys function. We principally study K+ ion channels using a combination of techniques that includes electrophysiological recording of channel activity (including kinetic analysis of single channel behaviour), computational studies of channel structure and ion permeation (molecular dynamics simulations), plus various molecular biology and protein biochemistry approaches. There are options to suit almost every taste (https://biophysics.physics.ox.ac.uk/tucker/)

Requirement: Although no previous experience is required, some interest in biological systems is essential as there will be some background reading required.

Supervisor: ***Prof S Tucker***
Email: ***stephen.tucker@physics.ox.ac.uk***

BIO07 & BIO08 DNA Nanostructures

DNA is a wonderful material for nanometre-scale fabrication. Short lengths of DNA can be designed such that Watson-Crick hybridization between complementary sections leads to the self-assembly of complex nanostructures. Nanostructures can be used to deliver a payload into a cell, as a scaffold for protein crystallography or as both track and motor components of a molecular assembly line. The project will involve design, fabrication and characterization of a DNA nanostructure.

Supervisor***: Prof A Turberfield***
Email***: andrew.turberfield@physics.ox.ac.uk***

BIO09 Physics of cryopreservation of cell membranes

During cryopreservation cells (e.g. stem cells, sperm), tissues (ovarian tissues, umbilical cord), and even living organisms (bacteria, animal embryos) are preserved by cooling to sub-zero temperatures. A significant challenge of cryopreservation is to avoid damage caused by the formation of ice during freezing. It is known that when cells are frozen they undergo a ''cold shock'' which leads to mechanical damage to the plasma membrane and leakage of solutes across membranes. There is very little research about the physical aspects of the cell membrane freezing and thawing processes and in particular in the role of the membrane in the water structure during the freezing and thawing processes. This project aims at investigating the effect of freezing and thawing in lipid membrane models systems. It focuses in studying the role of the lipid phase/ordering on the water structure during freezing by atomic force microscopy.

Special skills: This is an experimental project but requires good data analysis skills (Matlab, python or equivalent) and willingness to pursue a multidisciplinary project.

Supervisor: ***Prof S Antoranz Contera***
Email: ***Sonia.AntoranzContera@physics.ox.ac.uk***

BIO10 **Mechanical and transport properties of biomaterials for tissue engineering and 3D cell cultures**

Hydrogels have applications in drug delivery, mechanical actuation and regenerative medicine. Applications in these fields require a robust characterisation of the mechanical and transport properties in their hydrated state. The most promising method for assessing mechanical properties is by nanoindentation, however there are unique challenges associated with testing hydrated materials, since they are at the same time poroelastic and viscoelastic, which requires that the fluid flow through the porous material is explicitly included in the interpretation of data. This project aims at implementing a new indentation scheme that can complete quantitative characterisation of hydrated hydrogels and analysing data using it.

Special skills: This is an experimental project but requires good data analysis skills (Matlab, python or equivalent) and willingness to pursue a multidisciplinary project.

Supervisor: ***Prof S Antoranz Contera***
Email: ***Sonia.AntoranzCo***

Condensed Matter Physics projects

CMP01 Quantum oscillations probing the Fermi surface of iron-based superconductors

Quantum oscillations is a well-established and powerful technique for the experimental characterisation of the Fermi surface at low temperatures. Due to the Landau quantisation of electronic states in an applied magnetic field, oscillations of various physical properties, periodic in inverse magnetic field, are observed. The frequency of oscillations relates directly to extremal areas of the Fermi surface, and the temperature-dependence of the amplitude of oscillations reveals the orbitally-averaged quasiparticle masses. The quasiparticle masses compared with band structure mass quantify the extend of electronic correlations inside different superconducting materials and they provide clue on how to enhance superconductivity.

This is a computational project that aims to establish the Fermi surface of novel superconducting materials using high magnetic fields and low temperatures. A suitable candidate should have a strong background in condensed matter physics and advanced computational skills (Matlab, Python) as well as interest to pursue further research in condensed matter physics. The student will compare existing experimental data with band structure calculations using Wien2k and make proposals of Fermi surface to describe the experimental data and estimate relevant parameters. For further questions please email amalia.coldea@physics.ox.ac.uk.

Further reading:

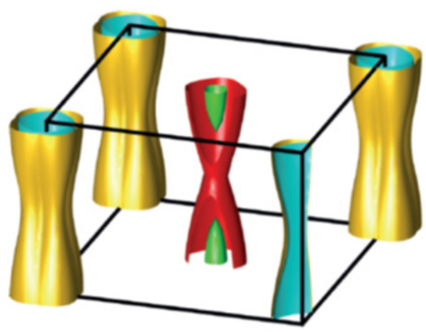
The key ingredients of the electronic structure of FeSe
Amalia I. Coldea, Matthew D. Watson
Annual Review of Condensed Matter Physics, Vol 9 (2018)
https://arxiv.org/abs/1706.00338

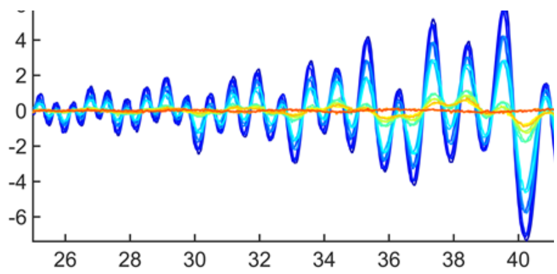
Quantum oscillations probe the Fermi surface topology of the nodal-line semimetal CaAgAs
Y. H. Kwan, P. Reiss, Y. Han, M. Bristow, D. Prabhakaran, D. Graf, A. McCollam, S. A. Parameswaran, A. I. Coldea
https://arxiv.org/abs/2001.02434

Linear magnetoresistance caused by mobility fluctuations in the n-doped Cd3As2
Phys. Rev. Lett. 114, 117201 (2015
https://arxiv.org/abs/1412.4105

Quantum oscillation studies of the Fermi surface of iron-pnictide superconductors, Reports on Progress in Physics, 74 124507, 2011, http://iopscience.iop.org/article/10.1088/0034-4885/74/12/124507

Wien2k; http://susi.theochem.tuwien.ac.at/





Fermi surface of an iron-based superconductor and an example of quantum oscillations in magnetic fields up to 45T and temperatures below 1.5K.

Supervisor: ***Prof A Coldea***
Email: ***amalia.coldea@physics.ox.ac.uk***

CMP02 Using uniaxial strain to detect nematic electronic states and tune superconductivity of iron-based superconductors

The iron-based superconductors represent new materials showing realistic potential towards their practical implementation. Among the different materials, FeSe, seems to be one of the simplest superconductor with intriguing electronic behaviour. Its superconducting properties can be enhanced either by applying hydrostatic pressure, by intercalating different alkali ions between its conducting layers or by the induced strain in its single-layer form towards 100K.

This project will investigate the response of iron-based superconductors to applied external strain. These materials display many electronic processes that occur simultaneously, which can be difficult to disentangle when looking at the unstressed system alone. One can gain much more information by understanding how elastic lattice distortion, applied through hydrostatic, biaxial, or uniaxial stress, affects the electronic properties of a material. For example, lattice strain may be used to suppress an electronic instability, or to enhance one or more of the processes in the material. Iron-based compounds display electronic nematicity, a form of electronic order which breaks rotational but not translational symmetries that may play an important role in high-temperature superconductivity. Uniaxial stress can be used to increase nematic polarisation in a material, by adding to the orthorhombic lattice distortion associated with nematic order.

This project is an experimental study focused on understanding the electrical resistivity and superconductivity under applied strain in iron-based superconductors. The experiment will consist in applying strain to different iron-based superconductors. A suitable candidate for this experimental project should have good knowledge of condensed matter courses, attention to detail and good experimental skills. A suitable candidate will perform experiments as function of strain, temperature and magnetic field. Good computational skills, such as Matlab and Python would be valuable for the project.

For further questions, please email amalia.coldea@physics.ox.ac.uk

Further reading:
Strain-tuning of nematicity and superconductivity in single crystals of FeSe
https://arxiv.org/abs/2102.11984

The relationship between transport anisotropy and nematicity in FeSe
https://arxiv.org/abs/2102.09212

The key ingredients of the electronic structure of FeSe
https://arxiv.org/pdf/1706.00338v1.pdf

Emergence of the nematic electronic state in FeSe,
https://arxiv.org/abs/1502.02917

Strong Peak in Tc of Sr2RuO4 Under Uniaxial Pressure
https://arxiv.org/ftp/arxiv/papers/1604/1604.06669.pdf

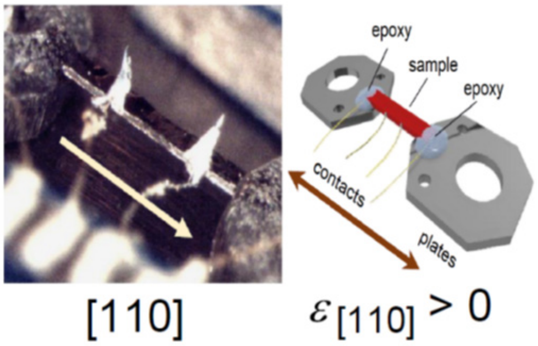
Transport properties of FeSe epitaxial thin films under in-plane strain https://iopscience.iop.org/article/10.1088/1742-6596/1054/1/012023

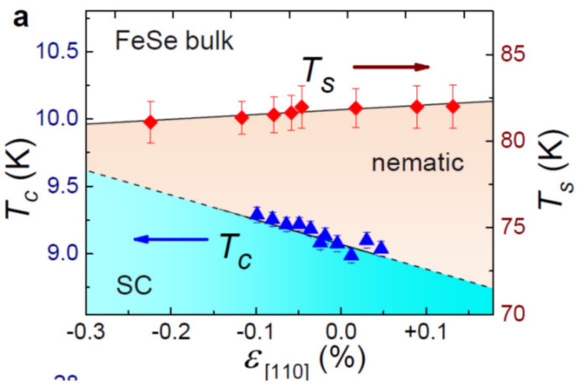
Divergent Nematic Susceptibility in an Iron Arsenide Superconductor

Science, Vol. 337, no. 6095 pp. 710 (2012), https://arxiv.org/abs/1203.3239

Measurement of the B1g and B2g components of the elastoresistivity tensor for tetragonal materials via transverse resistivity configurations,

Rev. Sci. Instrum. 87, 063902 (2016), https://arxiv.org/abs/1603.03537





Supervisor: ***Prof A Coldea***
Email: ***amalia.coldea@physics.ox.ac.uk***

CMP03 **Enhancing superconductivity by applied pressure in iron-based superconductors**

Applied hydrostatic pressure is an important tuning parameter that can induce and significantly enhance superconductivity as well as it can change the size of the unit cell, the electronic bandwidth as well as the strength of electronic interactions. FeSe is a unique high temperature superconductor in a monolayer form close to 100K. On the other hand, pressure applied to bulk single crystals of FeSe strongly enhances its superconductivity from 9K towards 40K.

This is an experimental project to perform pressure experiments under pressure using either transport or tunnel diode oscillator technique to probe the skin depth and penetration depth of novel materials. Tunnel diode oscillator based-technique is known to be sensitive to the London magnetic penetration depth in superconducting materials and can probe the transition temperature and the upper critical field. These experiments will be performed on high quality single crystals of FeSe-based superconductors and the superconducting phase diagrams under pressure will be constructed.

A suitable candidate should have a strong background in condensed matter physics and basic knowledge of electronics. Computational skills, such as using Matlab and Python would be useful and candidates are encouraged to consider PhD projects in condensed matter physics. To apply for this project please send your CV and a cover letter to justify your interest in the proposed topic to amalia.coldea@physics.ox.ac.uk.

For further questions please email amalia.coldea@physics.ox.ac.uk

For further reading consult:

Electronic nematic states tuned by isoelectronic substitution in bulk FeSe1−xSx

The key ingredients of the electronic structure of FeSe

Amalia I. Coldea, Matthew D. Watson

Annual Review of Condensed Matter Physics, Vol 9 (2018)

https://arxiv.org/abs/1706.00338

Quenched nematic criticality separating two superconducting domes in an iron-based superconductor under pressure
P. Reiss, D. Graf, A. A. Haghighirad, W. Knafo, L. Drigo, M. Bristow, A. J. Schofield, A. I. Coldea, Nature Physics (2019);
https://arxiv.org/abs/1902.11276;

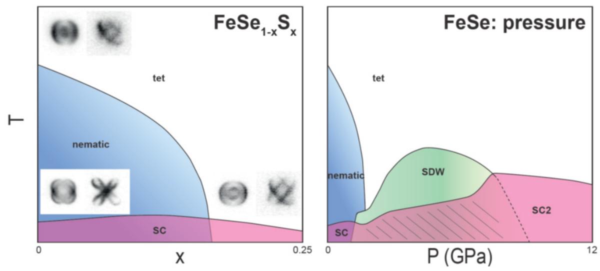
https://www.nature.com/articles/s41567-019-0694-2

Maximizing T c by tuning nematicity and magnetism in FeSe1−xSx superconductors,

K. Matsuura, Y. Mizukami, Y. Arai, Y. Sugimura, N. Maejima, A. Machida, T. Watanuki,

https://arxiv.org/abs/1704.02057

https://www.nature.com/articles/s41467-017-01277-x



Phase diagrams of FeSe tuned by chemical (using chemical substitution) and applied hydrostatic pressure. The components of a pressure cell are shown .

Supervisor: ***Prof A Coldea***
Email: ***amalia.coldea@physics.ox.ac.uk***

CMP04 Instrument control of low-temperature instrumentation to explore quantum matter in magnetic fields

Quantum materials at very low temperatures display unique collective phenomena such as superconductivity, spin-density or change waves and these states can be tuned by different parameters such as low temperature, applied magnetic fields and pressure. Establishing the phase boundaries of the nematic and other anisotropic phase transitions require complete experimental investigation along different crystallographic axes, beyond the single-axis rotation currently available and a full 3D angular dependence is necessary.

The aim of this project is to control accurately sample position in magnetic field using two-axis rotator and calibrate the instruments for different temperatures and magnetic fields. The student will implement and test new instrumentation in an existing Python code which controls experiments at low temperatures and high magnetic fields. This instrumentation will enable experiments on novel quantum materials to understand the effect of superconducting and resistivity anisotropy as well as quantum oscillations. The student will test the behaviour of Attocube rotators made from Titanium and CuBe which allow rotation of very small samples at low temperature and high magnetic fields. Two rotators can be coupled together to allow physical properties measurements as a function of orientation in magnetic field. A positioning controller permits the integration of different stepping module to finely control each rotator separately. After the implementation state, the instrument will be used for the angular dependent study of anisotropic superconductors.

We are looking for an enthusiastic student with good computational and electronics skills to implement this two-axis rotator in an existing Python software that already controls our low temperature experiments. The student will test the rotator as a function of temperature and magnetic field and test the anisotropy of a new material.

For further details, contact amalia.coldea@physics.ox.ac.uk.

For further reading please consult:

Thermodynamic evidence for a nematic phase transition at the onset of the pseudogap in YBa2Cu3Oy

Nature Physics volume 13, pages1074–1078(2017)

Thermodynamic evidence for nematic superconductivity in CuxBi2Se3

https://www.nature.com/articles/nphys3907

Attcoube information

https://www.attocube.com/en

Quantum oscillations probe the Fermi surface topology of the nodal-line semimetal CaAgAs

Y. H. Kwan, P. Reiss, Y. Han, M. Bristow, D. Prabhakaran, D. Graf, A. McCollam, S. A. Parameswaran, A. I. Coldea

https://arxiv.org/abs/2001.02434

Supervisor: ***Prof A Coldea***
Email: ***amalia.coldea@physics.ox.ac.uk***

CMP05 Modelling upper critical field and vortex dynamics inside novel superconductors in magnetic fields

This project aims to understand the complex vortex dynamic and the upper critical field of two-dimensional superconductors in the presence of different defects and impurities as well as a function of material-dependent parameters. The presence of the vortex state is crucial for the implementation of high-temperature superconductors in applications as the vortex pinning on defects help to maintain very large critical currents. Simulations will rely on time-dependent Ginzburg Landau theory, which is already implemented in the commercial software package COMSOL Multiphysics. In this project, the student will perform simulations of vortex lattice and relevant superconducting parameters using realistic parameters in order to understand the presence of large critical currents as well as upper critical field in novel iron-based superconductors. The student will use existing programs in COMSOL and Matlab and additionally will further develop computational tools optimize the calculations. This project will be performed in the new Oxford Centre for Applied Superconductivity (CfAS).

A suitable candidate should have a strong background in condensed matter physics and good computational skills, such as COMSOL, Matlab or Python. **For further queries** contact amalia.coldea@physics.ox.ac.uk.

For further reading see:

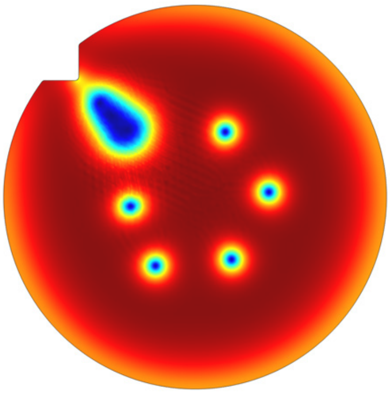
1. Competing pairing interactions responsible for the large upper critical field in a stoichiometric iron-based superconductor, CaKFe4As4, https://arxiv.org/abs/2003.02888

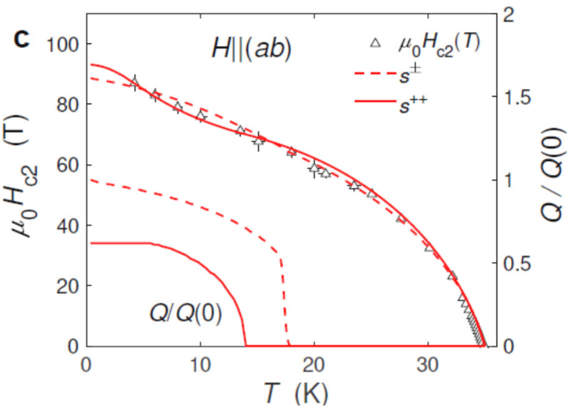
2. COMSOL Multiphysics https://www.comsol.com/comsol-multiphysics

3. https://www.comsol.com/blogs/modeling-superconductivity-ybco-wire/

4. Time-Dependent Ginzburg — Landau Simulations of the Critical Current in Superconducting Films and Junctions in Magnetic Fields;

5. See also the video of simulations on http://www.cfas.ox.ac.uk/discover





Supervisor: ***Prof A Coldea***
Email: ***amalia.coldea@physics.ox.ac.uk***

CMP06 **Doping of Semi-Transparent Conductive Single-Walled Carbon Nanotube:Polymer Films**

Making better flexible transparent or semi-transparent conductive films is crucial for future technologies like foldable or head-up displays, which offer exciting possibilities. Recently, carbon nanotube:polymer films using the polymer ethylene-vinyl acetate (EVA) have been shown to be a promising candidate for such applications [1]. Wrapping single-walled carbon nanotubes (SWNTs) with polymers, for whose development Oxford researchers played a key role, is by now a common technique to enable solubilisation of SWNTs in organic solvents. This is the foundation for further facile processing of SWNTs into thin films whilst simultaneously allowing to employ the outstanding physical properties of carbon nanotubes.

Electronic properties of semiconductors are in general tunable by doping. For SWNTs in particular doping with chloroauric acid has been shown to lead to a manifold decrease in sheet resistance in corresponding thin films [2].

In this project the student will investigate the effects of doping on SWNT:polymer transparent conductive films in more detail. The work will involve preparing the nanotube:polymer solution, depositing films by spray-coating and various optical and electrical experimental characterisation techniques to better understand the doping of our SWNT:EVA composite films and to reach new record values in their sheet resistance. If you would like to discuss project details, feel free to contact us:

[1] G. Mazzotta et al., ACS Appl. Mater. Interfaces 2019, 11, 1185–1191.

[2] A. Tsapenko et al., J. Phys. Chem. Lett 2019, 10, 14, 3961-3965.

Supervisors: ***Prof M Riede*** and ***Prof R Nicholas***
Email : ***moritz.riede@physics.ox.ac.uk*** and
robin.nicholas@physics.ox.ac.uk

CMP07 **Determining the mixing behaviour in Organic Solar Cell Heterojunctions”**

Differential Scanning Calorimetry (DSC) is a versatile tool used to probe the thermal behaviour in material systems by identifying key thermal transitions during heating and cooling cycles. This can be key in identifying different phases in material systems, as well as seeing how the behaviour of these phases change when blending different materials together. Organic solar cell devices often require thermal annealing and/or substrate heating to reach optimal performance, making this tool useful in understanding the optimal heating parameters to use for the mixture of two materials in the photovoltaic active layer.

This project will look at several small molecule systems and how they compare when prepared in thin film via vacuum deposition and in powder form. The student will have the option to prepare the vacuum deposited samples themselves and there might be the option to make use of the National Thin Film Cluster facility at Oxford. The student will be required to prepare the samples for DSC measurements, for which adequate supervision and instruction will be provided, and be expected to analyse the data sets using python. The DSC measurements themselves will not have to be done by the student. A theoretical understanding of DSC and phase behaviour of small molecule systems will be taught during the project, and the expectation is that this will be implemented in the analysis of the data.

Supervisors: ***Prof M Riede*** and ***Dr I Habib***
Email : ***moritz.riede@physics.ox.ac.uk*** and
irfan.habib@stx.ox.ac.uk

CMP08 The interaction between positive muons and quadrupolar nuclei.

The positively charged muon is widely used as a probe of condensed matter systems [1]. The muon interacts with electronic and nuclear magnetic moments inside the sample of interest. If the spin of any nucleus is > 1/2, there is the possibility of a quadrupole moment, which can interact with the electric-field gradient produced by the muon, contributing to the Hamiltonian. This project will explore this effect and simulate the effect of this quadrupolar coupling on the relaxation of the muon spin and of level crossing spectra.

Background reading:

[1] S. J. Blundell, Contemporary Physics 40, 175 (1999).

Supervisor*: **Prof S Blundell***
Email*: **stephen.blundell@physics.ox.ac.uk***

CMP09 **Stray field distributions, spin ice, and monopole motion**

When a magnetic field is applied to any material, a stray field is invariably produced. This arises because of demagnetization and is a function of sample shape [1,2]. Stray fields can be particularly significant in a material known as spin ice [3] which exhibits magnetic frustration and has excitations which can be described as magnetic monopoles. These stray fields can be used to understand the properties of spin ice in two dimensions (square ice) and three dimensions (the pyrochlore structure) and to study the fluctuations that arise due to magnetic monopole motion [4,5]. Calculations will be developed to understand the stray field in spin ice. Programs will be written using the Python computer language.

Background reading:

[1] J. A. Osborn, Phys. Rev. 67, 351 (1945).

[2] M. Beleggia, M. De Graef, J. Magn. Magn. Mater. 263, L1 (2003).

[3] S. J. Blundell, Phys. Rev. Lett. 108, 147601 (2012).

[4] F. K. K. Kirschner, F. Flicker, A. Yacoby, N. Y. Yao, and S. J. Blundell, Phys. Rev. B 97, 140402(R) (2018).

[5] R. Dusad, F. K. K. Kirschner, J. C. Hoke, B. R. Roberts, A. Eyal, F. Flicker, G. M. Luke, S. J. Blundell, J. C. S. Davis, Nature 571, 234 (2019).

Supervisor***: Prof S Blundell***
Email***: stephen.blundell@physics.ox.ac.uk***

CMP10 **High-throughput computational screening for stable ternary metal-halide semiconductors for optoelectronic application*s***

Organic-inorganic lead-halide perovskite are a remarkable novel family of heterogeneous semiconductors with excellent optoelectronic properties for applications such as photovoltaic devices or light emitting diodes. Their development has prompted tremendous efforts into understanding their fundamental properties, but also into further advancing the design and discovery of novel semiconductors with complex chemical heterogeneity. Among these efforts, the search for new lead-free metal-halide semiconductors led to the discovery of quaternary double perovskites based on alternating Bi-Ag, Sb-Ag and In-Ag [1,2,3].

In this project we would like to continue the search for novel metal-halide semiconductors by exploring stable ternary metal-halide compounds containing divalent metals. Expanding on the methodology developed in [4,5,6] we will establish a screening procedure that combines elements of the periodic table to form stable crystals, and select out only those materials with good semiconducting properties: direct band gap in the visible range, dispersive conduction and valence bands and non-toxic elemental composition.

As part of this MPhys project the student will have the opportunity to apply their basic Solid State Physics knowledge to understand electronic properties of state-of-the-art optoelectronic materials. The student will learn the basics of DFT, learn how to calculate electronic band structures using the Quantum Espresso DFT package [7] and high performance computers and learn how to interpret manipulate and interpret data on existing public databases such as the Materials Project [8]. A good command of Solid State Physics and Quantum Mechanics, as well as some basic coding or scripting skills would be desirable for undertaking this project.

[1] Volonakis, Filip, Haghighirad, Sakai, Wenger, Snaith & Giustino, J. Phys. Chem. Lett. 7, 7, 1254-1259 (2016).

[2] Filip, Hillman, Haghighirad, Snaith & Giustino, J. Phys. Chem. Lett. 7, 13, 2579-2585 (2016).

[3] Volonakis, Haghighirad, Milot, Sio, Filip, Wenger, Snaith & Giustino, J. Phys. Chem. Lett. 8, 4, 772-778 (2017).

[4] Filip & Giustino, J. Phys. Chem. C 120, 1, 166-173 (2016).

[5] Filip, Liu, Miglio, Hautier & Giustino, J. Phys. Chem. C, 1, 158-170 (2018).

[6] Filip & Giustino, Proc. Natl. Acad. Sci. 115, 21, 5397-5402 (2018).

[7] Gianozzi et al, J.Phys.: Condens.Matter 29, 465901 (2017) .

[8] https://materialsproject.org/

Supervisor***: Prof M Filip***
Email***: marina.filip@physics.ox.ac.uk***

CMP11 **From 3D to Q2D: Understanding Electronic Structure of Quasi-2D Halide Perovskites**

Organic-inorganic quasi-2D hybrid halide perovskites are a family of materials that has gained increasing interest for applications in optoelectronics, due to a great breadth of chemical variety, robust stability and tunability of optoelectronic properties [1]. However, unlike the closely related 3D metal halide perovskites, the structural chemical complexity of this family of semiconductors, the underlying fundamental optoelectronic properties of Q2D perovskites are not yet understood.

In this project, we will aim to study the electronic structure Q2D perovskites starting from model systems derived from their 3D counterparts, using a combination of first principles density functional theory (DFT) calculations and tight binding modeling. We will use and develop upon previously established understanding of the optoelectronic properties of 3D lead halide perovskites

[2] and tight binding frameworks [3] to rationalize structure property relations in Q2D perovskites.

As part of this MPhys project the student will have the opportunity to apply their basic Solid State Physics knowledge to understand electronic properties of state-of-the-art optoelectronic materials. The student will learn the basics of DFT, learn how to calculate electronic band structures using the Quantum Espresso DFT package [2] and high performance computers and learn how to interpret computational modeling data with the help of standard tight binding models. A good command of Solid State Physics and Quantum Mechanics, as well as some basic coding or scripting skills would be desirable for undertaking this project.

[1] Smith, Crace, Jaffe & Karunadasa, Annu. Rev. Mater. Res. 48, 111-136 (2018).

[2] Filip, Eperon, Snaith & Giustino, Nat. Commun. 5, 5757 (2014).

[3] Slavney, Connor, Leppert & Karunadasa, Chem. Sci. 10, 11041-11053 (2019).

[4] Gianozzi et al, J.Phys.: Condens.Matter 29, 465901 (2017) .

Supervisor***: Prof M Filip***
Email***: marina.filip@physics.ox.ac.uk***

CMP12 Machine learning and optical microscopy on 2D materials (2Ds)

The mechanical exfoliation of graphite into graphene flakes was the starting point of an extremely vibrant field of research. As it turned out, there is a wide range of two-dimensional materials with very similar properties in terms of exfoliation, yet spanning the entire range of optical, electronic, and magnetic properties. By stacking them up into heterostructures, there are sheer endless possibilities of tailoring functional materials. This stacking approach is not possible with 'ordinary' thin films as most of them are not compatible with one another. In contrast, in 2D materials, where the bonding forces between adjacent layers are weak, van der Waals heterostructures can be assembled using an exfoliation, search, and stacking strategy. This process involves tedious and time-consuming optical microscopy work and this project aims at automating the process by using machine learning to first identify suitable flakes on a substrate, then picking them up and finally stacking them up into heterostructures.

As part of this programming project, you will use machine learning to analyze optical microscopy images in search for suitable monolayer-thin flakes. By interfacing with the motor controls of the xyz stage, you will help to automate the pick-and-place process for the preparation of large heterostructures.

Reading list:

1. A. Geim and I. Grigorieva, Van der Waals heterostructures, Nature 499, 419 (2013). https://doi.org/10.1038/nature12385

2. Junkai Jiang, Kamyar Parto, Wei Cao, and Kaustav Banerjee, Ultimate Monolithic-3D Integration With 2D Materials: Rationale, Prospects, and Challenges, IEEE Journal of the Electron Devices Society 7, 878 (2019). https://doi.org/10.1109/JEDS.2019.2925150

3. Or watch https://www.youtube.com/watch?v=ISst1jhY0Eo

Special skills required:

For this project, a solid knowledge of machining learning is required.

Supervisors***: Prof T Hesjedal*** and ***Dr R Fujita***
Email***: thorsten.hesjedal@physics.ox.ac.uk***

CMP13 Sputtering of Magnetically Doped Thin Film Quantum Materials

The elegant mathematical concept of topology generally describes a system's protected symmetry, which cannot be explained by established symmetry-breaking theories. Among the topologically protected materials, topological insulators (TIs) have captured the imagination of physicists as they promise dissipation-free, spin-polarized carrier transport at room temperature. From an application standpoint, TIs are extremely interesting due to their ability to efficiently convert charge into spin currents, which has been observed by spin pumping from a ferromagnetic (FM) to a TI layer, and their ability to generate large spin-transfer torques (STTs). The large figure-of-merit of charge-to-spin density conversion, quantified by the spin Hall angle, is a direct consequence of spin-momentum locking and it can be further enhanced by the spin Hall effect and the interfacial Rashba effect. As for all device applications, the growth of thin film materials stands at the beginning of the journey, and this project aims to explore the magnetic doping of the prototypical TI Bi2Te3.

As part of this experimental project, you will learn to deposit thin films by magnetron sputtering, you will determine their structural properties by x-ray diffraction, and their magnetic properties by SQUID magnetometry and magnetotransport measurements.

Reading list:

1. Xiao-Liang Qi and Shou-Cheng Zhang, The quantum spin Hall effect and topological insulators, Physics Today 63, 33 (2010). https://doi.org/10.1063/1.3293411

2. Desheng Kong and Yi Cui, Opportunities in chemistry and materials science for topological insulators and their nanostructures, Nature Chemistry 3,845 (2011). https://doi.org/10.1038/nchem.1171

3. Recent group publications: https://www2.physics.ox.ac.uk/research/thin-film-quantum-materials/publications

Special skills required:

For this project, dedication and a real passion for experimental lab work is required. Further, programming skills are helpful for data analysis and interpretation.

Supervisors***: Prof T Hesjedal*** and ***Dr A Frisk***
Email***: thorsten.hesjedal@physics.ox.ac.uk*** and ***andreas.frisk@diamond.ac.uk***

CMP14 Growth and analysis of magnetic skyrmions in thin films

Magnetic skyrmions – swirls of magnetic moments – have unique topological properties that make them promising candidates for the next generation of computer storage devices. This experimental project is dedicated to the exploration and study of novel, low-dimensional skyrmion-carrying materials. It is part of the UK-wide, EPSRC-funded national research program into Skyrmionics, designed to achieve a step-change in our understanding of skyrmions in magnetic materials and engineer them towards application. A detailed description of the research topics and institutions involved can be found at http://www.skyrmions.ac.uk. The goal of the project is to synthesise novel, skyrmion-carrying thin film materials. The thin films will be grown by magnetron sputtering, structurally characterised by x-ray diffraction, and magnetically by SQUID magnetometry.

As part of this experimental project, you will learn to deposit thin films by magnetron sputtering, you will determine their structural properties by x-ray diffraction, and their magnetic properties by SQUID magnetometry and magnetotransport measurements.

Reading list:

1. https://tinyurl.com/7aznva7a

2. Recent group publications: https://www2.physics.ox.ac.uk/research/thin-film-quantum-materials/publications

Special skills required:

For this project, dedication and a ***real passion for experimental lab work*** is required, and an interest in thin films, magnetism, and crystallography. Further, programming skills are helpful for data analysis and interpretation.

Supervisors***: Prof T Hesjedal*** and ***Dr B Achinuq***
Email***: thorsten.hesjedal@physics.ox.ac.uk*** and ***barat.achinuq@physics.ox.ac.uk***

CMP15 Probing long-range order in 2D with tensor networks

The Mermin-Wagner theorem proves that two-dimensional systems with continuous degrees of freedom cannot show long-range order in the thermodynamic limit. In practice, however, ordered two-dimensional materials (such as graphene) exist, since the length scales at which ordering is destroyed is beyond experimental relevance. The same mechanism makes establishing the true thermodynamic properties of many simple 2D models very difficult using traditional means, such as Monte Carlo simulation.

As a case in point, this project would explore the thermodynamics of the classical Heisenberg model on the square lattice, using tensor network techniques to access larger system sizes than it is possible for direct sampling. You would learn about tensor networks and their applications for classical thermodynamical systems, and develop approaches to deal with continuous degrees of freedom.

Good computational skills (programming in Python, familiarising yourself with new libraries), good mathematical ability, and a strong foundation in thermodynamics are essential for this project.

Supervisor***: Dr A Szabó***
Email***: attila.szabo@physics.ox.ac.uk***

CMP16 Neural network density matrices for many-body quantum mechanics

Finding the ground states of strongly interacting many-body quantum systems computationally, and representing them efficiently, are major challenges of modern condensed matter physics. Neural networks have recently been proposed as ansätze for many-body wave functions, capitalising on their ability to represent complicated multivariate probability distributions in conventional machine-learning tasks. In many important systems, however, competing interactions result in destructive interferences and a complicated pattern of positive and negative wave function amplitudes in the ground state, which neural networks struggle to capture.

This project proposes to get around this problem by representing ground-state or low-energy density matrices, rather than wave functions. Using a representation of density matrices in terms of strictly nonnegative measurement outcomes, the problem of finding ground states maps exactly on finding a probability distribution, the traditional forte of neural networks. You would learn about neural network quantum states, develop neural network density matrix ansätze, and apply them to challenging quantum spin liquid phases of matter to assess their ability to represent ground states qualitatively and quantitatively. We may also extend the approach to open quantum systems, where a handle on density matrices becomes even more important.

Excellent computational skills (programming in Python, familiarising yourself with new libraries), good analytical and mathematical ability, and a strong foundation in condensed matter physics are essential for the project. Experience with machine learning (ideally using PyTorch or JAX) is useful.

Supervisor***: Dr A Szabó***
Email***: attila.szabo@physics.ox.ac.uk***

CMP17 Probing the Evolution of the Microstructure in the active layer of Organic Solar Cells

Differential Scanning Calorimetry (DSC) is a versatile tool Organic semiconductors have the potential to enable inexpensive and ubiquitous optoelectronic devices with highly tailored functionality, from solar modules to wearable sensing devices. However, many organic semiconductors remain susceptible to degradation when subjected to elevated temperature or ambient gases. The goal of the project is to better understand the role of microstructural re-organization during thin film exposure to these various stimuli. The results of this investigation will be of high relevance for the next generation of electronic devices based on organic semiconductors.

The MPhys student will use in-situ x-ray diffraction to assess the impact of temperature and trace gas concentration on small-molecule thin films relevant to organic photovoltaics and gas sensor devices.

The student should have a strong interest in solid state physics. The project will also provide an opportunity to learn thermal deposition techniques for organic electronics and device physics, based on the student's own interests. If you would like to discuss project details, feel free to contact me.

Supervisor: ***Prof M Riede***
Email : ***moritz.riede@physics.ox.ac.uk;***

CMP18 Multi-Million Atom Molecular Dynamics Simulations of Matter under Planetary Core Conditions

Recent advances in high power optical and x-ray laser technology allow us to compress solid-state matter to pressures comparable to those within planetary cores, and to study the material via femtosecond X-ray diffraction However, we can only keep matter under these conditions for a few nanoseconds. We simulate the results of these experiments with molecular dynamics (MD) - knowing an empirical form for the potential between atoms we can track the structure and temperature of the matter as it is compressed, and as it rarefies upon release. Whilst these simulations have been highly successful, there are several outstanding pieces of basic physics that remain poorly understood, and which could be successfully addressed during the course of an MPhys project. These include developing a better understanding of the physics of the huge number of defects (dislocations) that get generated in our crystals as we compress them to millions of atmospheres within a few nanoseconds, and issues such as the 'thermoelastic anomaly', which is a poorly-understood discrepancy in how a sample cools when the pressure is finally released. In this project the student will undertake multi-million atom MD simulations to address the issues mentioned above. Whilst a detailed knowledge of coding is not strictly required, a good familiarity with C/C++ would be advantageous.

Reading

Wehrenberg et al, Nature 550, 496 (2017)

Sliwa et al, Phys. Rev. Lett. 120, 265502 (2018)

Heighway et al, Phys. Rev. Lett. 123, 245501 (2019)

Supervisors: ***Prof J Wark and Dr P Heighway***
Email: ***justin.wark@physics.ox.ac.uk*** and ***patrick.heighway@st-hughs.ox.ac.uk***

CMP19 Improving quantum logic gates in superconducting quantum circuits

Superconducting electric circuits are proving to be a strong candidate for building the world's first useful universal quantum computer within the next decade. We have developed a new architecture based on coaxial circuit elements and 3D wiring with promising quantum coherence and scaling potential. An important current topic in the field is to understand the long-term stability of qubit properties such as their transition energies, energy relaxation and coherence times, which are found to fluctuate in time, leading to difficulty in using them for the exquisitely fragile process of quantum computation. In this project you will explore this topic by measuring and analysing the statistical correlations of these qubit properties, both between each other (e.g. correlations between coherence of different qubits) and also with environmental parameters such as the temperatures of key components in the measurement setup. Success in this project could lead to crucial improvements in performance of quantum logic gates. The project will likely mostly involve computer programming, measurements, data analysis, numerical simulation and understanding of related physics, but may also involve more hands-on lab work. Note that this and other projects in the group are subject to change due to the rapid rate of progress in research. We will always endeavour to find a project that is interesting, new and a good match for your particular interests & skills.

Supervisor: ***Prof P J Leek***
Email: ***peter.leek@physics.ox.ac.uk***

CMP20 High-fidelity multiplexed readout of qubits in circuit QED

One of the key requirements for operation of a quantum computer is to be able to carry out high fidelity (trustworthy) measurements of the states of the qubits at the end of quantum algorithms, or during, to enable reliable error correction. In superconducting circuits, this is commonly achieved by coupling LC resonators to qubits and observing how their frequencies shift as the qubit state changes. In recent MPhys projects on this topic, we have shown that we can improve this readout by optimising signal filtering and making use of the higher excited qubit states. In this project you will experimentally investigate methods to extend the readout to operate on multiple qubits simultaneously using signal 'multiplexing' via specially designed filters. Successfully achieving this will be very important for scaling our circuits up for quantum computing. The project will likely involve circuit design and simulation, computer programming, measurements, data analysis, and understanding of related physics, but may also involve more hands-on lab work. Note that this and other projects in the group are subject to change due to the rapid rate of progress in research. We will always endeavour to find a project that is interesting, new and a good match for your particular interests & skills.

Supervisor: ***Prof P J Leek***
Email: ***peter.leek@physics.ox.ac.uk***

CMP21 Decoding the science of ultimate performance in perovskite solar cells: the beauty of interfacial engineering

Following an unprecedented rise in power conversion efficiencies within the past few years, metal halide perovskites (MHPs) have surged as a new class of photovoltaic materials and hold great promise to revolutionise the solar industry in the next decade. However, many studies have suggested severe non-radiative recombination that exists at the imperfect interfaces between perovskite light absorbers and charge collection layers could hinder photo-carrier collection, hence limiting the ultimate photovoltaic performance using MHPs in solar energy harvesting applications. Taking these basic understanding forward, it seems natural to ask whether the photo-carriers dissociated within MHPs could be effectively collected through engineering preferential interface properties. This question provides the springboard for this project.

The specific approach that will be used here is to integrate various types of polymer electrets (i.e. dielectric polymers) in-between charge-collection layers and perovskite light absorbers. This work demands good experimental (solar cell fabrication) and electrical-characterisation (J-V measurement) skills. The main activities include that 1) understanding how the dipole-induced built-in electric-fields in polymeric materials could reduce non-radiative recombination losses; and 2) implementing selected polymer electrets into MHP cell structures, hence decoding what limits the ultimate cell performance both theoretically and experimentally.

Supervisors: ***Dr Y Lin*** and ***Prof H Snaith***
Email: ***yen-hung.lin@physics.ox.ac.uk***; ***henry.snaith@physics.ox.ac.uk***

CMP22 "There's Plenty of Room at the Bottom" – Nanostructure-assembly towards high-performance perovskite solar cells

Commenting on the possibility of directly manipulating individual atoms, more than half a century ago Nobel laureate Richard Feynman gave a lecture in Caltech, called "There's Plenty of Room at the Bottom". The idea conveyed in this lecture is believed to be the very first conceptual origin in the field of nanotechnology. In fact, the ability to control each individual photo-induced carrier in nanoscale/molecular-scale is particularly important for the applications of metal-halide perovskites (MHPs) in photovoltaics. This is because the non-radiative recombination loss that takes place at the interfaces between MHP and charge-collection layers plays a major role that limits perovskite solar cells (PSCs) from reaching their theoretical efficiency.

In this project, we will carry out our research in a nanoworld. The specific approach will be used is to integrate various types of organic molecules into charge-collection layers through the means of nano-assembly. This project demands good experimental (solar cell fabrication) and electrical-characterisation (J-V measurement) skills. The main activities are to identify potential organic nanostructures that can facilitate charge transport as well as to design the processing routes to nano-assembling feasible organic molecules into PSCs, hence unlocking PSC's theoretical performance.

Supervisor: ***Dr Y Lin*** and ***Prof H Snaith***
Email: ***yen-hung.lin@physics.ox.ac.uk***;
henry.snaith@physics.ox.ac.uk

CMP23 **Developing a pulsed electron spin resonance spectrometer with arbitrary pulse shaping capability**

Pulsed electron spin resonance (pESR) is a technique for manipulating quantum spins coherently with microwave pulses and has versatile applications in physics, chemistry, biology and quantum information. Conventional pESR experiments are conducted by simply switching the microwave signal between on and off to form square excitation pulses. In recent years, the development of high-frequency arbitrary waveform generators (AWG) has introduced the possibility of engineering pulse shapes (including amplitude and frequency) to gain much greater control over the spins.

In this project, the student will design and build a pESR spectrometer with AWG pulse shaping options that will match (and potentially exceed) the performance of the state-of-the-art commercial pESR spectrometers. This involves programming the AWG to generate required waveforms and use them to modulate high frequency (~ 10 GHz) microwave signals. The student will also perform pESR experiments with molecular nanomagnets to test the performance the spectrometer. The project demands good programming skills (in Python) and basic microwave electrical engineering knowledge.

Supervisors***: Dr J Liu*** and ***Prof A Ardavan***
Email***: junjie.liu@physics.ox.ac.uk***

CMP24 **Preparation and physical properties of a new candidate Weyl semi-metal**

In recent years there has been great interest in materials whose electronic structure has topologically non-trivial features. Weyl semi-metals have two linearly dispersing electron bands which cross at points called Weyl nodes which lie at the Fermi energy. The electronic quasiparticles are massless chiral fermions, similar to those in graphene, but in Weyl semi-metals the nodes are robust against small perturbations in the structure. Only a small handful of real materials are known to behave as Weyl semi-metals. In this project you will investigate a new phase, TaIrTe4, which has been predicted to be a new type of Weyl semi-metal. You will perform measurements on single crystals of TaIrTe4 to establish its physical properties. You will also synthesize a series of related compounds RIrTe4, where R = a rare-earth ion. The R ions have a magnetic moment, and you will explore whether the moments order at low temperature. Magnetic order would perturb the Weyl fermions and could influence the electrical properties. The measurements as a function of temperature will be performed with a SQUID magnetometer and an electrical transport probe.

Supervisors: ***Dr D Prabhakaran*** and ***Prof A Boothroyd***
Email: ***dharmalingam.prabhakaran@physics.ox.ac.uk, andrew.Bbothroyd@physics.ox.ac.uk***

CMP25 **Investigation of the phase diagrams of doped spin ice**

A spin ice is compound with many possible ground states having almost the same energy, which owing to its crystal structure is analogous to the arrangement of hydrogen atoms in water ice. The best known examples are Dy2Ti2O7 and Ho2Ti2O7. Spin ices have very interesting statistical mechanics. In particular, there are low energy excited states that behave like magnetic monopoles. The statistical properties are changed when different ions are substituted randomly for Dy or Ti, and this has been the subject on recent interest. In this project you will investigate what happens when some of the Ti4+ is replaced by Sc3+. The different charge states of these ions results in changes in the local structure and magnetism and, eventually, a change in the global crystal structure. This is an experimental project in which you will synthesize samples of Sc-doped Dy2Ti2O7 and Ho2Ti2O7 and make a systematic study of their crystal structure and magnetization as a function of Sc concentration by X-ray diffraction and SQUID magnetometry. There will also be an opportunity to perform electrostatic calculations of the crystal field in order to model the magnetic data.

Supervisors: ***Dr D Prabhakaran*** and ***Prof A Boothroyd***
Email: ***dharmalingam.prabhakaran@physics.ox.ac.uk, andrew.boothroyd@physics.ox.ac.uk***

CMP26 Simulation of spin dynamics for Dirac and Weyl magnons

This is a combined theory/computational project to simulate/visualize the spin oscillations in interacting spin systems, as part of the broader research effort in the quantum magnetism group to explore experimentally using inelastic neutron scattering the spin dynamics of magnets with strong spin-orbit coupling. Of particular interest are magnetic materials that can support linear touching points between spin-wave bands, analogous to the electron band touchings in a single honeycomb layer of carbon atoms (graphene) where electrons behave like Dirac particles with a relativistic dispersion (linear in momentum) near the touching points. We are interested in magnetic analogues of such physics, where dispersive bands of collective spin oscillations (spin waves) can display touching points, leading to Dirac (in two dimensions) and Weyl magnons (in three dimensions) [1]. The aim of the project is to develop computer code to simulate/visualize how the spins oscillate near the band-touching points, and understand the effects of spin-orbit coupling and externally applied magnetic fields, which can shift the bands and in certain circumstances open gaps. The project will require theoretical derivations of „normal modes" of spin oscillations and coding to create movies of the time-evolution of the spins. Support can be offered for coding in matlab. The project will benefit from existing numerical code to determine the eigevector of normal spin-wave modes for a multi-sublattice system.

[1] S.A. Owerre, Journal of Physics: Condensed Matter 28, 386001 (2016). https://iopscience.iop.org/article/10.1088/0953-8984/28/38/386001/meta

This project would require the ability to learn independently from books and papers and a very keen interest and experience in programming (suitable for 1 student taking the C6 Theory or C3 CMP option).

Supervisor: ***Prof R Coldea***
Email: ***radu.coldea@physics.ox.ac.uk***

CMP27 **tbc**

More details from the supervisor.

Supervisor: ***Prof M Johnston***
Email: ***michael.johnston@physics.ox.ac.uk***

CMP28 **tbc**

More details from the supervisor.

Supervisor: ***Prof Y Chen***
Email: ***yulin.chen@physics.ox.ac.uk***

CMP29 **tbc**

More details from the supervisor.

Supervisor: ***Prof L Herz***
Email: ***laura.herz@physics.ox.ac.uk***

CMP30 **tbc**

More details from the supervisor.

Supervisor: ***Prof P Radaelli***
Email: ***paolo.radaelli@physics.ox.ac.ukk***

Interdisciplinary projects

INT01 & INT02 An Electronics Project

Design, build and test a piece of electronic equipment of your choice. The project will take place on the Practical Course electronics laboratory.

These projects can only be undertaken in-person.

Suggested Reading:

Horowitz and Hill

Any book on electronics.

Supervisor***: Prof R Nickerson***
Email**: *richard.nickerson@physics.ox.ac.uk***

NT03 & INT04 Very-high-energy gamma-ray astrophysics with the Cherenkov Telescope Array

Very high-energy gamma-ray astrophysics is an exciting field spanning high-energy particle physics and extreme processes in astronomy. Our investigations range from the nature and variety of particle acceleration around supernovae and black holes, to physics beyond the Standard Model including dark matter, axion-like particles and Lorentz invariance violation.

The group in Oxford works on both experiment and theory. We are members of the High Energy Stereoscopic System (H.E.S.S.) in Namibia, presently the world's largest gamma-ray observatory, and the next-generation gamma-ray observatory, the Cherenkov Telescope Array (CTA). CTA will consist of up to one hundred telescopes using state-of-the-art photomultiplier detectors and high-speed digital signal processing to detect and characterize the electromagnetic air shower caused when an astrophysical gamma-ray enters the Earth's atmosphere. The telescope prototypes are under construction, and deployment to the observatory sites at Paranal, Chile, and La Palma, Canary Islands, will commence in 2020.

M.Phys. students will have an opportunity to choose their project from a variety of our activities. On the experimental side of the prgramme, we are leading efforts to develop advanced analysis techniques for the large volumes of data that will be generated when CTA becomes operational, including co-ordination of the CTA Machine Learning Task Force. On the theoretical/observational side, we have recently developed a new class of models for the broad-spectrum emission from relativistic jets in active galaxies, which let us use the gamma-ray to investigate the physical properties of the jet and the black hole at its base. We now propose to extend these models to look in particular at the entrainment of heavy particles as the jets propagate through their host galaxy, the resulting possibility of hadronic particle processes within the jets, and propagation effects in intergalactic space that may provide evidence for axion-like particles or Lorentz invariance violation.

These projects are particularly suited to students who are taking astrophysics or particle physics major options.

For more information please contact Professor Garret Cotter.

Supervisor: ***Prof G Cotter***
Email: ***garret.cotter@physics.ox.ac.uk***

INT05 Building a model Memristor

Memristors are a predicted class of electronic component with applications in future generation computing that complete the matrix of charge/current/flux/voltage relationships exhibited by conventional electronic components. The project aim is to design, construct and characterise a model Memristor using electronic or spintronic components.

Supervisor: ***Prof J Gregg***
Email: ***john.gregg@physics.ox.ac.uk***

INT06 Towards radiofrequency intelligent tomography of conductive surfaces

This is a practical project involving the design of part of a prototype instrument which combines (1) high-resolution textural mapping and (2) compositional analysis of electrically conducting materials. Such an instrument has important applications in the study and identification of — among other things — ancient coins and other metal objects.

Two projects are offered in connection with this work. One involves the construction of the electronic and mechanical part of the instrument (using an existing circuit design and pre-manufactured mechanical components), the other focuses on the construction of a software-based tool for data capture and analysis.

Supervisor: ***Dr A Karenowska***
Email: ***alexy.karenowska@physics.ox.ac.uk***

INT07 Low-temperature measurements of the inverse spin Hall effect. Investigating the spin pumping and inverse spin Hall effects at low temperatures

The field of magnonics is the area of magnetics dedicated to the science of quasi-particles known as magnons. In certain magnetic systems, magnons are able to play the role of microscopic tokens which can carry 'spin' — the quantum mechanical currency of magnetism — over relatively long distances (up to centimetres), and at high speed (many tens of kilometres per second). Our group develops low-temperature microwave magnetic circuits to probe the physics of magnonic systems at the quantum level.

This project will involve designing and carrying out a low-temperature experiment to make an inverse spin Hall effect based measurement of a magnon-driven spin current pumped through a magnetic insulator/non-magnetic metal interface. Measurements will be made in a dilution refrigerator. The work will contribute to our group's investigations into how magnons — the quasi-particles associated with excitations of the electronic spin-lattices of ferro- and ferrimagnetically ordered materials — might be used in new types of quantum measurement and information processing device. This is a project suitable for anyone who enjoys challenging practical work and has a strong interest in magnetic dynamics and low-temperature experimental techniques.

Supervisor: ***Dr A Karenowska***
Email: ***alexy.karenowska@physics.ox.ac.uk***

INT08 Investigating the physics of coupled magnonic resonators at millikelvin temperatures

The field of magnonics is the area of magnetics dedicated to the science of quasi-particles known as magnons. In certain magnetic systems, magnons are able to play the role of microscopic tokens which can carry 'spin' — the quantum mechanical currency of magnetism — over relatively long distances (up to centimetres), and at high speed (many tens of kilometres per second). Our group develops low-temperature microwave magnetic circuits to probe the physics of magnonic systems at the quantum level.

This project will involve designing and carrying out an experiment in which microwave-frequency magnon modes in two lumped magnetic samples are controllably coupled. Measurements will be made in a dilution refrigerator. The work will contribute to our group's investigations into how magnons — the quasi-particles associated with excitations of the electronic spin-lattices of ferro- and ferrimagnetically ordered materials — might be used in new types of quantum measurement and information processing device. This is a project suitable for anyone who enjoys challenging practical work and has a strong interest in magnetic dynamics and low-temperature experimental techniques.

Supervisor: ***Dr A Karenowska***
Email: ***alexy.karenowska@physics.ox.ac.uk***

INT09 X-ray based tools for reading ancient texts

Over the last decade, tremendous progress has been made in "reading the unreadable" — deciphering ancient texts which are inaccessible to the human eye. A key step here has been the development of methodologies for the digital unwrapping of ancient paper, papyrus, and parchment documents which are too fragile to be manually unwrapped or unrolled. In collaboration with the leading group in this area — that of Prof. Brent Seales at the University of Kentucky —and colleagues at the Diamond Light Source, this project will contribute to the development of new X-ray based tools which, through their ability to detect ancient inks which are invisible to existing techniques, will significantly broaden the range of ancient texts which can be accessed using these methods.

Supervisor: ***Dr A Karenowska***
Email: ***alexy.karenowska@physics.ox.ac.uk***

INT10 Portable Reflectance Transformation Imaging (RTI) apparatus for mapping the surface textures of ancient objects and inscriptions

Reflectance Transformation Imaging is a well-established tool for investigation of ancient materials. RTI is used to uncover eroded inscriptions or fine surface textures that cannot be easily seen with the human eye. Though easy to optimize in a laboratory setting, traditional RTI hardware does not lend itself to use in the field — particularly in environments where space is limited or lighting conditions are difficult to control.

This project, which is extremely practical in nature, will involve completing an existing design of a fully portable RTI apparatus, constructing it, and evaluating its performance.

Supervisor: ***Dr A Karenowska***
Email: ***alexy.karenowska@physics.ox.ac.uk***

INT11 Ultra Sensitive Noise Temperature Measurement of a Superconducting Quantum Mixer

Superconductor-Insulator-Superconductor (SIS) mixers are the most sensitive quantum detectors for astronomical observations below 1 THz. They are now routinely used in various millimetre and sub-millimetre telescopes that require quantum-limited sensitivity for detection of weak spectral lines emitted by astronomical sources. The sensitivity of an SIS mixer is experimentally determined, in the laboratory, by measuring its equivalent noise temperature. This is done by comparing the difference in output power, when the mixer is illuminated by either a hot (room temperature) or a cold (liquid nitrogen) load.

The aim of this project is to design, build and test a setup that can measure the sensitivity of an SIS device rapidly and accurately. This involves replacing the manually operating hot/cold system used in our laboratory by an automatic system comprising a chopping wheel, and an electronic/ software interface that syncs the timing of load changes with the readout system to measure the noise temperature instantaneously. The student will start by learning how to use a cryogenic system to test a 230 GHz SIS mixer using an existing system before working on the design of the automatic system. The new setup can then be used to test the same mixer for comparison.

The project is suitable for students who are interested in experimental works, and also requires some programming skills e.g., LabView code to sync the chopping wheel and the readout system. The student will be working in a team including the supervisors, an experienced technician and a D.Phil student who is investigating the performance of a 230 GHz SIS mixer..

Supervisors: ***Prof G Yassin*** and ***Dr B Tan***
Email :***ghassan.yassin@physics.ox.ac.uk***

INT12 A Horn-Reflector Feed for Superconducting Detectors.

Superconductor-Insulator-Superconductor (SIS) mixers are the most sensitive quantum coherent detectors for astronomical observations below 1 THz.

The principle of detection is based on down-converting the high frequency of the incoming signal (RF) into a much lower *intermediate* frequency (IF) which can be amplified and detected by standard electronics. Frequency down-conversion is obtained when the mixer is fed by both the astronomical signal of frequency ν_S and another high frequency signal that is generated by a Local Oscillator in the receiver (LO) of frequency ν_{LO}. An output signal is then generated at an intermediate frequency $\nu_{IF} = \nu_{LO}-\nu_S$ which can be handled by standard electronics. The non-linear device responsible for the frequency conversion is the superconducting tunnel junction which has an area of approximately $1\mu m^2$ fabricated in a planar circuit chip mounted in a block which is cooled below the transition temperature of the tunnel junction material (4 Kin our case). The electromagnetic signals (RF signal and LO signals) are received by an electromagnetic horn, mounted on the detector block and then coupled to the planar chip via a waveguide.

For efficient power coupling we aim to match the curvature of the wave-front of the local oscillator to the wave-front curvature of the signal that can potentially be emitted or received by the detector block horn. This is usually done by designing an optical system consisting of several curved mirrors between the local oscillator source and the detector. A much more compact system is obtained however if the detector block horn is replaced by a horn-reflector combination (H-R antenna) which is fabricated as a single optical unit that is optimized to receive (of emit) plane waves. In that case only a single curved mirror would be needed between the detector horn and the local oscillator horn. The aim of this project therefore is to design and test a Horn-Reflector antenna that is optimized to receive plane waves efficiently at 700 GHz. The horn is a conical section that emits spherical waves originating at the "phase centre" located at the axis of the cone. If the cone is mounted in such a way that the phase centre coincides with the focal pint of an offset parabolic reflector, the emerging wave will have a plane wave-front.

To calculate the fields at the aperture of the horn the student will use commercial electromagnetic software that simulates guided waves propagation. To calculate the radiated waves in the near and far field, the student will use a commercial "Physical Optics" software package called "GRASP" which is used in most modern optical designs in astronomy. The design can then be fabricated at Oxford Physics workshop and tested in one of our cryogenic systems.

The project will suit a student who likes to be involved in both experimental and computational work. There is also a scope for theoretical work as the student may choose to calculate the field at the aperture of the antenna analytically. The Oxford "THz Detectors" group has many years experience in the development of quantum limited detectors and optical components for astronomical receives at millimetre and submillimetre wavelengths. The student will have access to a state of the art detector laboratory, commercial and local software and powerful computing cluster.

Supervisors: ***Prof G Yassin*** and ***Dr B Tan***
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Particle and Nuclear Physics projects

PP01 Bell-inequality violation in top quark decays at the Large Hadron Collider

Quantum systems exhibit non-classical engagement, which has been measured in photons and atoms through violation of the Bell inequality. Similar entanglement is predicted to occur at the high energies of the LHC, but has not yet been measured. A recent proposal (arXiv:2102.11883) suggests a method by which violation of the Bell inequality could be measured using the decays of entangled top quarks at the Large Hadron Collider. This project aims to determine whether it's possible to make those measurements with analysis of existing or upcoming LHC data. The project will make use of Monte Carlo simulations of LHC collisions, and the LHC Open Data sets.

The project requires good understanding of quantum mechanics, and analytical or programming skills in c++ or python.

Supervisor: ***Prof A Barr***
Email: **alan.barr@physics.ox.ac.uk**

PP02 Analysis definition and optimisation with differentiable programmins

There is currently a substantial effort in the HEP-software community towards a differentiable analysis paradigm. The student will investigate the advantages and disadvantages of this method using Monte Carlo. The analysis under study will be the decays of the Higgs boson to b quarks. The student will be required to develop a simple analysis, which will be then optimized by explicitly asking the analysis sensitivity to be maximal. The project could also involve a study of how feasible this approach is in the presence of systematics. A variation or extension of this project could look at and compare different performance metrics to define the selection criteria such as sensitivity to the SM Higgs vs. sensitivity to Effective Field Theory deformations.

The project is computer based only and requires knowledge of Python

Supervisors: ***Prof D Bortoletto***; ***Dr E Schopf*** and ***Dr P Windischhofer***
Email: Daniela.Bortoletto@physics.ox.ac.uk

PP03 Optimization of the Higgs to Charm Quarks Analysis Using Machine Learning

The measurement of the decay of the Higgs boson to charm quarks provides a direct probe of the Higgs coupling to second-generation quarks, which is fundamental to understand the structure of the Higgs Yukawa couplings. Unfortunately, the Higgs to charm quarks decay is very rare and it is also challenging to distinguish it from the more copious decay of the Higgs boson to b-quarks. The student will study Higgs bosons produced in association with vector (V) bosons (W or Z bosons) and develop machine learning techniques to optimally define the VH(bb) and VH(cc) phase spaces. The project is computer based only and requires knowledge of Python.

Supervisors: ***Prof D Bortoletto; Dr P Windischhofer*** and ***Dr Miranova***
Email: ***Daniela.Bortoletto@physics.ox.ac.uk***

PP04 B_s and B Meson Lifetimes

The B_s^0 meson is the bound state of the bottom quark and the anti-strange quark. This meson is produced at the Fermilab Tevatron in generous amounts. This particle is expected to exist in two states called 'Heavy' and 'Light' which are the quantum mechanical mixture of the BS meson and it's antiparticle partner. The two states should have different lifetimes. A measurement of the B_s lifetime is the first step towards finding out if, in the data, there are in fact $B_s$mesons decaying with two different time signatures.

Part of the challenge to understanding this data is the fact that, in order to find the B_s meson, a trigger on the decay $J/\psi \rightarrow \mu^+ \mu^-$ is used. The student will try to find and fit a B_s lifetime in the CDF detector data at the Tevatron along with Monte Carlo simulations. Time permitting (but unlikely), the student will attempt to find any lifetime difference in CP even and CP odd parts of the decay $B_s \rightarrow J/\psi\phi$

Knowledge of Computer programming required: Yes, C++ programming is best.

Suggested Reading:

See the MPHYS section of Dr. Huffman's web site at: http://www-pnp.physics.ox.ac.uk/~huffman/ for a reference about B mesons at CDF.

The following references on mixing though are not as related to this project, but do provide backstory on why the B lifetimes themselves might be interesting.

Introduction to Elementary Particles, by David Griffiths, section 4.8 gives a very good explanation of mixing in the kaon system. Apart from the fact that the BS meson has a much shorter lifetime, the arguments are identical. The original Kaon paper is referred to here and that too is recommended.

Collider Physics, by Barger and Phillips. In particular the sections on B meson physics and B meson mixing.

F. Abe et. al. (The CDF Collaboration), Phys. Rev. D60, 072003; The first page and its references give an overview of mixing but this is a very advanced paper.

Supervisor: ***Prof T Huffman***
E-mail: ***todd.huffman@physics.ox.ac.uk***

PP05 ATLAS Physics

The world's highest energy particle accelerator, the Large Hadron Collider (LHC) at CERN, started operation at the high-energy frontier in 2009. Constructed in a 27 km long circular tunnel, 100 meters underground, it accelerates two counter-rotating proton beams and brings them into collision at center-of-mass energies of up to 14 TeV. By pushing the energy frontier by an order of magnitude above that previously accessible, it offers unprecedented opportunities to explore the fundamental constituents of the universe.

The ATLAS and CMS experiments have observed a new boson, and this opens up a new research area with the aim of understanding if this particle is a Higgs boson and, if so, whether it a Standard Model (SM) Higgs boson or a more exotic version. Studies can be carried out with the existing data to begin to address these issues, such as determining the spin of the boson. Even if the new particle turns out to be compatible with a SM Higgs, there are many remaining problems in the SM, many of which point to the existence of exotic physics in the LHC energy range. Hence a primary goal of ATLAS is to explore SM physics in new energy regimes and to discover new physics signatures beyond the SM. Possibilities include Supersymmetry (SUSY) as well as models which posit the existence of additional spatial dimensions beyond our normal experience.

In addition, the LHC is a “factory” for W and Z bosons and top quarks, enabling not only systematic studies of their properties but also their use as precision tools to probe the deep structure of the proton and to guide searches for physics beyond the Standard Model.

PP0501 Tagging B hadrons in High energy jets

The B hadron is the bound state of the bottom quark and one or more of the other, lighter quarks in the Particle Physics pantheon. It is often a “gateway drug” into more exotic areas of Physics because both top quarks and higgs bosons predominately decay into b quarks which will eventually produce a B hadron within a jet of particles.

All B hadrons have a substantial lifetime of around 1.5 ps. This is sufficient to permit a slew of jet identification methods for the ATLAS experiment at the Large Hadron Collider. When a B hadron candidate is found within a jet of particles it is then labeled a b-jet, or the jet is said to have been “b-tagged”.

The ATLAS experiment uses many different methods of tagging and wraps them all up using a feed forward neural network called “DL1r” to generate a “score” which is used to determine if a jet is a b-jet, a light-jet, or a jet containing a charm quark progenitor. But this tagger tends to lose efficiency for b-jets, and has trouble rejecting light-jets, when the jet energies because large.

One reason for this is that the B-hadron’s lifetime is long enough, and the ATLAS energy is high enough, that Lorentz factors in excess of 100 are now not uncommon. Such B hadrons would suvive long enough to decay within the detector itself. Further their energies would be so high that the hits in the pixel detector would cluster tightly. This property makes it difficult for all traditional methods of detecting b-jets.

The possibility that the hit numbers would “jump” from one layer to the next, because of a B decay, or that the hit clusters would be unique for B decays might well be a method that the neural network could employ to recover light-quark jet rejection and b-jet identification with the highest energy jets produced by the CERN Large Hadron Collider in the ATLAS experiment. This project seeks to study these effects by studying hit-based variables and then applying them to the DL1r neural network in order to uncover whether there is merit in this idea for b-jet tagging in the ATLAS experiment.

The project is entirely computer based and uses Monte Carlo simulations of the data and the ATLAS detector for both training and testing DL1r. The student would need to mainly know or learn the Python code language and we will be using the Keras package which is based on Tensor Flow during the course of the year. The data set already exists in a ROOT Ntuple based format and will need to have training and test samples constructed from it with the variables of interest. Initial studies, without using a Neural network, can also be done using the ROOT framework and an existing code framework in C++.

Knowledge of Computer programming required: Yes, Python programing essential, C++ programming desires.

Suggested Reading:

<work in progress – need to find a good reference for Keras and pyhf >

Good set of Machine learning tutorials from scratch: https://victorzhou.com/blog/intro-to-neural-networks/

Supervisor: ***Prof T Huffman***
E-mail: ***todd.huffman@physics.ox.ac.uk***

PP0502 Hunting matter-antimatter asymmetry in Higgs boson decays

The standard model of cosmology requres at least one unknown source of asymmetry between matter and antimatter in the fundamental interactions, and the discovery of the Higgs boson opens up a new set of interactions to probe for such a source. This project will investigate the sensitivity of the LHC to a matter-antimatter asymmetry in Higgs-boson decays to tau leptons, b-quarks, and c-quarks. The potential sensitivity of future colliders will also be explored.
Supervisor: ***Dr C Hays***
Email: ***chris.hays@physics.ox.ac.uk***

PP06 Investigation of bleed trails in LSST camera data

The LSST survey is a next generation optical survey which will be carried out at the currently in-construction Vera Rubin Observatory. One of its scientific aims is to constrain our knowledge about dark energy through weak lensing measurements of galaxies. These weak lensing methods involve precise measurements of the shapes of galaxies which can be subject to large systematic errors both astronomical and instrumental, which must be well understood and characterised.”bleed trails” are one of the phenomena inherent in CCD imagers as used by the LSST camera. They occur where a very bright object causes the pixels to become oversaturated. Despite their ubiquity, and important role in affecting measurements, no major effort has been directed to fully understand the details of the physics behind the formation of bleed trails, though the basic mechanisms are of course known.

Using a combination of experimental data from the Oxford OPMD lab, and on-sky data from the LSST camera auxilliary telescope, accompanied by device simulation results, the student will investigate the physics of bleed trails in CCD sensors. There will be opportunities for the student to be involved in the design of the OPMD lab experiments and this will involve working with optical and electronic components. Previous experience of programming (python) would be advantageous. This would ideally suit a student who is interested in working with (sometimes temperamental) experimental data.

Supervisors: ***Prof I Shipsey*** and ***Dr D Weatherill***
Email: ***daniel.weatherill@physics.ox.ac.uk***

PP07 Direct oversampled PSF measurements on LSST sensors

The LSST survey is a next generation optical survey which will be carried out at the currently in-construction Vera Rubin Observatory. One of its scientific aims is to constrain our knowledge about dark energy through weak lensing measurements of galaxies. These weak lensing methods involve precise measurements of the shapes of galaxies which can be subject to large systematic errors both astronomical and instrumental, which must be well understood and characterised.

It is crucially important to understand the point spread function (PSF) of the instrument, which has contributions from the atmosphere, the telescope optics and the detector. We are concentrating on measuring the detector PSF, and are working on developing new and novel methods to directly measure an oversampled detector PSF in the Oxford OPMD lab using an interferometric method.

The student will contribute to the design and build of one of these experiments, and hopefully carry out the first single pixel direct oversampled PSF measurements on sensors used for the LSST camera. This will involve hands on lab work with optical and electronic components. Some programming experience in the python language will be highly beneficial.

Supervisors: ***Prof I Shipsey*** and ***Dr D Weatherill***
Email: ***daniel.weatherill@physics.ox.ac.uk***

PP08 Search for neutrinoless double beta decay at SNO+

SNO+ is an experiment designed to look for neutrinoless double beta decay, which would indicate that neutrinos are their own anti-particles, could help explain why neutrino masses are so small, and shed light on possible dark matter candidates and other non-Standard Model physics. The experiment will use about a tonne of Tellurium dispersed in 1000 tonnes of liquid scintillator in order to pick up faint traces of light which result from this decay. Possible specific projects include the refinement of algorithms to recognize these faint traces, and to investigate the effect of low energy radioactive backgrounds on the experiment's sensitivity. Some familiarity with C++ and Linux would be an advantage.

Supervisors: ***Prof S Biller*** and ***Prof J Tseng***
Email: ***Steven.Biller@physics.ox.ac.uk, Jeff.Tseng@physics.ox.ac.uk***

PP09 Effective field theories and nuclear uncertainties in WIMP dark matter

A more complete description of the potential interactions that WIMP particle dark matter may have with a nucleus is given by effective field theories that rely upon nuclear response functions of various target nuclei. These calculations are often truncated with unknown uncertainties. This project will study the impact of nuclear uncertainties on final limits or detection uncertainties in dark matter experiments. We will utilize Fortran code which is run with a python wrapper(no Fortran is needed) to calculate the WIMP-nucleus interaction spectra, and likelihood calculations in C++ through the ROOStats package.

Supervisor: ***Prof K Palladino***
Email: ***kimberly.palladino@physics.ox.ac.uk***

PP10 Simulations for the Ricochet experiment

Coherent neutrino-nuclear scattering was the last standard model process to be observed, and it is still being measured with different target nuclei. Additionally, as it offers a flavor independent interaction for neutrinos, scattering allows for investigating new physics in the neutrino sector such as searching for sterile neutrinos or a neutrino magnetic moment.

The Ricochet experiment plans to deploy semiconducting germanium and superconducting zinc cryogenic crystals for detecting nuclear recoils near the ILL reactor near Grenoble. An assary of such detectors will use transition edge sensors with a microwave multiplexing readout. Simulations of backgrounds are currently done with the Geant4 package. This project will continue working on simulating the electronics response of the system to go from Geant4 energy deposits to waveforms that appear like the data that will be taken by this forthcoming experiment. Coding will be primarily in C++ with some python.

Supervisor: ***Prof K Palladino***
Email: ***kimberly.palladino@physics.ox.ac.uk***

PP11 Simulation of background sources in dark matter detectors

Dark matter detectors rely on environments that are as free as possible of radioactive contaminants, at a level several orders of magnitude better than natural radioactivity. This project will build a model (in GEANT) of a simple dark matter detector and explore the effects various types of radioactive impurities in materials have on the final result. Experience in GEANT4 would be useful, but can be acquired quickly with sufficient background in C++ programming.

Supervisor: ***Prof H Kraus***
Email: ***hans.kraus@physics.ox.ac.uk***

PP12 Event reconstruction from single photon detection

The use of scintillators with photo multiplier readout is popular in a large number of particle physics experiments. One such example is the search for dark matter candidates, another the adaptation of the technique to the determination of sample temperature in protein crystallography. This project looks at developing realistic simulations of the electronic response of photo multiplier tubes and algorithms to extract relevant physics information from the digitized signals recorded by the data acquisition system. This is a software project where knowledge of C++ is essential and familiarity with ROOT desirable.

Supervisor: ***Prof H Kraus***
Email: ***hans.kraus@physics.ox.ac.uk***

PP13 Early high-voltage breakdown warning system for dark matter detectors

Dark matter detectors have progressed to unprecedented sensitivity in probing dark matter particle models. The challenge is the identification of any signal that is not associated with the interaction of dark matter but is caused by natural backgrounds or spurious electronics effects so that one can be sure that whatever is left after having removed (vetoed) all such possible contributions to the signal can be attributed to dark matter interaction. The detectors probing the smallest WIMP-nucleon interaction cross sections, and thus exhibiting the highest sensitivity are based on large time projection chambers filled with liquefied noble gases. Their operation involves the presence of high voltage in the detector and thus a detector system is necessary that is capable of identifying local or partial temporary discharges or breakdowns at a level that would not be detected by the existing safety systems but could still cause spurious signals in the detector's data. This project involves the modelling of an existing loop antenna system and its electronic readout system with the aim of maximizing its sensitivity. A thorough understanding of electromagnetism and circuits will be required as well as programming skills in C/C++.

Supervisor: ***Prof H Kraus***
Email: ***hans.kraus@physics.ox.ac.uk***

PP14 Identification and classification of acoustic signals:

Dark matter detectors aim to detect extremely rare events and thus have to operate in an environment that avoids accidental signals that could be confused with a dark matter interaction in the detector. One of the veto systems planned for these very sensitive dark matter detectors is an acoustic sensor system that records sound. The project is focussed on the analysis of data from such a veto system. The analysis algorithms to be developed within this project should achieve high efficiency in classifying events recorded in the data. The project is computational but there exists also an opportunity to record sound with the existing hardware in order to generate acoustic samples that the algorithm analyses. Good familiarity with programming, preferably in C++ is essential. As an extension to the project (not mandatory), there is further the opportunity for implementing trigger algorithms directly into the FPGA of the hardware. Familiarity with VHDL would be required for this optional part.

Supervisor: ***Prof H Kraus***
Email: ***hans.kraus@physics.ox.ac.uk***

PP15 A new method for measuring the CKM angle gamma

During the last decade, the LHCb experiment has collected large samples of charmed D meson decays as well as B meson decays. These heavy, flavoured mesons are characterised by relatively long lifetimes before decaying via the weak force. Detailed studies of these mesons permit exploration of quark interaction with the weak force. Of particular interest is the generation of CP violation via the CKM matrix parameter, gamma.

The Masters project will be an excellent opportunity to become involved with a cutting-edge analysis, to understand the detail of meson decays and to contribute towards a publication. The work will focus on modelling a four-particle D meson decay and performing a sensitivity optimisation. The kinematics of this particle decay is fully described in a 5D space, which needs to be chopped up into 'bins' for the data analysis. The binning is to be defined by the Masters student by applying adaptive binning algorithms (or anything else the student wishes to explore), taking into account the details of the D decay, which is currently under study by the LHCb group. The coding should be mainly in python using widely-used packages but prior experience is not expected.

The project is entirely software based and can be carried out remotely, or in an office in the DWB assuming restrictions are lifted.

Supervisor: ***Prof M John***
Email: ***malcolm.john@physics.ox.ac.uk***

PP16 *Phenomenology of neutrino pion production*

Accelerator neutrino experiments are searching for the signature of leptonic CP violation (LCPV) which is beyond the Standard Model of particle physics. Neutrino interaction plays an important role in this discovery, whereby pion production is one of the critical interaction mechanisms in current and future experiments. Precise theoretical description of these processes is of high demand by the progressing experimental sensitivity.

In this project, the student will explore the state-of-the-art event generators of neutrino interactions, examine the crucial theoretical framework for pion productions, and address their impact on the discovery potential of LCPV in future experiments. The project demands good programming skills in C/C++ and proficiency on Linux operating system.

Supervisor: ***Dr X Lu***
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PP17 PaMIr+: Interferometry on fast targets

PaMIr is short for Phase Modulation Interferometry. The PaMIr group is developing a novel method to interferometrically measure rapid displacements with high accuracy and time resolution as well as low latency. PaMIr+ will extend this scope towards absolute distance measurements, which have abundant applications in large-scale science experiments. Among the highlight scientific applications so far are the alignment of the crab cavities in the upgrade HL-LHC, control of undulators at LCLS-II, relative positioning of the primary and secondary mirrors of several next generation telescopes (GMT, EELT, KECK), as well as future measurements of deployable space antennae on satellites.

PaMIr is a plug-compatible extension of an absolute distance interferometry technology (FSI, Frequency Scanning Interferometry) previously developed by Oxford Physics. This FSI technology is now used in its commercial form (Absolute Multiline™) in many scientific projects in accelerator science, particle physics, astrophysics but also in many industrial settings. The high speed, continuous differential measurements from PaMIr can be used in dynamic control loops to measure rapidly time variable positions continuously over long periods. These are needed in many of the above science problems and in the control of robots and CNC production machines in industry.

The PaMIr project is funded through an innovation partnership grant, which has inputs from STFC and from our two industrial partners, VadaTech Plc and Etalon GmBH. The student will be a member of the PaMIr group, which currently has five permanent members at Oxford. Prof Armin Reichold is the group leader, Dr Peter Qui is a PDRA, Dr Jubin Mitra is the groups FPGA engineer, Mr Mark Jones and Mr Johan Fopma are two further electronics engineers working part time on PaMIr. We have enjoyed input from four summer students and an MPhys student. Seven further part time team members are working on the project in our partner organisations.

This project student opportunity offers a wide range of possible engagements with the PaMIr project. The range of activities suitable for an MPhys project are:

1. Measurement of fast moving targets with PaMIr interferometers

a. Testing multiple modulation and demodulation techniques

b. Experimentally verify some of the demodulation algorithms in their real time form in an FPGA in collaboration with out FPGA engineer Jubin Mitra.

c. Develop PaMIr offline analysis algorithms in collaboration with our post-doc, Peter Qiu.

2. Comparison of PaMIr measurements to those made by our own and a commercial reference interferometer.

a. Test PaMIr at critical distances

b. Measure performance as a function of laser power

3. Evaluate new frequency stabilised lasers for PaMIr

a. Stabilise our own fibre lasers to gas absorption cells

b. Test a new commercial fibre laser in PaMIr algorithms and fully characterise it.

4. Analysis of Absorption spectra of gas-cells using frequency comb measurements which can contain.

a. Fitting the beat signals of the scanning lasers with the comb to obtain a highly precise frequency axis.

b. Fitting the positions and widths of the peaks in the absorption spectra with Voigt functions instead of the simpler Gaussian functions used so far.

c. Potentially performing the fits from 2. using a total chi-squared method in which errors in both axes can be considered.

d. Comparing the results of the above fits to see how accurately the Gaussian fraction of the width of the peaks can be fit and hence how accurately the pressure of the gas cell can be determined.

e. Comparing the results of the above fits to measure the relative spacing of the gas cell peaks

f. Using these results to improve the distance measurement results.

The skills that would be useful for all of the above projects would be an interest and some experience with programming in Matlab and/or C/C++ as well as skills in optics and lasers.

Interested applicants can discuss project options with Prof Armin Reichold (armin.reichold@physics.ox.ac.uk).

Supervisor: ***Prof A Reichold***
Email: ***armin.reichold@physics.ox.ac.uk***

PP18 Improved understanding of proton structure

The Large Hadron Collider (LHC) is the world's highest energy particle collider. Following the discovery of the Higgs boson, the machine continues to collect a wealth of data. Among the primary physics goals of the machine are to search directly for new, high mass particles, as well as to precisely measure the properties of the Higgs, which may also reveal evidence of as-yet unknown physics. One of the dominant uncertainties, which can limit the ability to discover new physics, is an imprecise knowledge of the structure of the proton. This project will investigate the prospects to improve our knowledge of proton structure, using either existing LHC data, or by looking at simulated data from possible future colliders. A set of proton parton distribution functions (PDFs) will be determined, and the impact of any improvements on the prospects for new physics discovery or Higgs properties will be investigated. This is a computing project. Some prior experience of C++ would be an advantage.

Supervisor: ***Prof C Gwenlan***
Email: ***claire.gwenlan@physics.ox.ac.uk***

PP19 Search for neutrinoless double beta decay at SNO+

SNO+ is an experiment designed to look for neutrinoless double beta decay, which would indicate that neutrinos are their own anti-particles, could help explain why neutrino masses are so small, and shed light on possible dark matter candidates and other non-Standard Model physics. The experiment will use about a tonne of Tellurium dispersed in 1000 tonnes of liquid scintillator in order to pick up faint traces of light which result from this decay. Possible specific projects include the refinement of algorithms to recognize these faint traces, and to investigate the effect of low energy radioactive backgrounds on the experiment's sensitivity. Some familiarity with C++ and Linux would be an advantage.

Supervisors: ***Prof S Biller*** and ***Prof J Tseng***
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PP20 Constraining atmospheric neutrino flux predictions for the SuperKamiokande Experiment using cosmic-ray muon data.

Neutrino oscillation was first seen in neutrinos that had been produced in the atmosphere from cosmic rays by comparing the rates of neutrinos from different directions in the SuperKamiokande experiment. The different directions translate into different oscillation distances. SuperKamiokande has continued to collect data and now has a formidable amount of statistics, and has recently undergone an upgrade that will allow Gadolinium to be introduced into the water in the near future. The Gadolinium will allow neutrons from the neutrino interactions to be detected by delayed emission of gamma rays after the neutrons are captured by the Gadolinium nuclei.

The flux predictions are made by Monte-Carlo simulation of the atmospheric interactions, and we are involved in a programme to substantially improve them. The simulation involves a whole chain of processes: Generating primary protons and other nuclei according to measured primary fluxes from balloons and satellites, including effects of solar wind and geomagnetic field, generating hadronic interactions when the primaries collide with nuclei in the atmosphere, propagating the resulting particles through the rest of the atmosphere. The simple neutrino-counting argument of the decay of a pion to a muon and neutrino and then the muon to two more neutrinos is insightful for understanding the oscillation phenomena, but because of the variations of the fluxes with energy, this much more detailed simulation approach is necessary for the data analysis.

The main difficulty is that because the strong interaction is unsuitable for calculation with perturbation theory, the hadronic interactions are not possible to predict, and so data from accelerator experiments is used to govern the Monte-Carlo generation instead. While SuperKamiokande has been running, the quality of experimental data on hadron production has increased significantly, and we are in the process of inserting them into the Monte-Carlo calculations. This will produce significantly improved calculations that can be used with the new data from SuperK. By using weighting techniques, it will also be possible to vary the assumptions from the hadron production modelling and provide uncertainties (as has been done before), and to use tuning techniques to apply different forms of input data as constraints. We are intending to use accelerator hadron production data, data from the T2K long-baseline accelerator experiment and from cosmic ray muon data.

The aim of the project is to tackle the application of constraints from the cosmic ray muon data, which has not been attempted by our simulation group before. Independent predictions of the fluxes were carried out in the early days, and the other major flux calculation does include these constraints. We will try to parameterise how both the muon flux and neutrino fluxes vary when the assumptions about hadron production are changed, and then apply the muon data as a constraint using a fitting procedure which we will devise. One of the investigations will be to understand whether all of the phase space for neutrinos is constrained by the muons, it is likely that it isn't, but there may be ways we can investigate to overcome this.

The project is computer based and will involve extensive use of either C++ or python programming (to make histograms)

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PP22 **tbc**

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PP25 **tbc**

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Supervisor: ***Prof D Wark***
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Theoretical Physics projects

TP01 Modelling dwarf galaxies using contaminated data

The dwarf galaxies that orbit the Milky Way are some of the most dark matter dominated stellar systems that we know, and are invaluable laboratories for the study of dark-matter physics. To understand these systems it is essential that we know their current dynamical states. However, the task of determining these dynamical states is hampered by the presence of binary stars (which cause us to over-estimate these systems' intrinsic velocity dispersions) and by the contamination of our data by halo stars.

The student will develop dynamical models of dwarf galaxies based on an underlying phase-space distribution function that accounts for stellar binarity. They will use synthetic data to test the precision and accuracy of their models, testing how well they can recover the internal state of simulated galaxies and how the recovered models are affected by contamination by interloping halo stars. Having done this, they will then fit their models to observational data, and compare their results to the best existing models.

The project requires good programming skills (ideally C, C++, or Python).

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TP02 Mapping orbits around galactic dics

How do galactic discs respond to perturbations? New surveys of the Milky Way have stimulated new work on this long-standing problem. To date, most of the effort has focused on understanding the in-plane response of the disc, mostly because we don't have a reliable scheme for assigning good, canonical labels to out-of-plane orbits.

There are two limits in which this labelling problem has good solutions. Close to the plane of a razor-thin disc the vertical oscillation timescale is much shorter than the radial one and, by adiabatic invariance, the vertical action $J_z=E_z/\omega_z$ becomes a good label. In the other limit, orbits that plunge quickly through the disc experience the disc as an (approximately) impulsive perturbation, which can be used to construct an approximate analogue to the vertical action. The purpose of this project is to develop a more general orbit-mapping scheme that joins these two solutions (and corrects the flaws in the second).

The project involves laptop-scale computation. You would need to be (or become) familiar with the material covered in the short option course on classical mechanics.

Supervisor: ***Prof J Magorrian***
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TP03 Particle Physics phenomenology from String Theory models

The student will explore a simple class of String Theory models and analyse their implications for Particle Physics phenomenology. Familiarity with the Standard Model of Particle Physics as well as the basic ideas of supersymmetry will prove useful for tackling this project.

Supervisor: ***Dr A Constantin***
Email: ***andrei.constantin@mansfield.ox.ac.uk***

TP04 Physics and Machine Learning

In recent years Machine Learning has become a tool of increasing influence in Theoretical Physics. Machine Learning can be useful not only for numerics, but also for rigorous exact results, such as conjecture generation and the discernment of mathematical structures in physical data. With ML, the discernment of analytic patters out of empirical data that has been at the core of Physics research for centuries is brought to a new level. The student will have the opportunity to explore this side of ML in various contexts, ranging from data generated in pure mathematics research to experimental data.

Supervisor: ***Dr A Constantin***
Email: ***andrei.constantin@mansfield.ox.ac.uk***

TP05 N-body simulations of tidal dynamics in stellar systems

Gravitational tides play an important role in planetary and stellar systems. Whereas tides have been explored extensively in the Solar System, there still remains a lot to be explored for dense stellar systems, such as open clusters.

The student will study the influence of gravitational tides in few-body stellar systems. Processes such as stellar deformations, spin accelerations and onset of spin synchronization will be investigated. To this end, the student will use the newly developed N-body code TIDYMESS developed by the supervisor. This code solves for the complex interplay between orbital, spin, and shape evolution of self-gravitating bodies.

The project will consist of a literature research, constructing initial conditions, running and managing an extensive suite of N-body simulations, and data analysis. The project demands good programming skills (C++, Python, Linux, CPU clusters) and a strong interest in N-body dynamics within an astrophysical context.

Supervisors: ***Dr T Boekholt*** and ***Prof B Kocsis***
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TP06 Topological defects in bacterial layers

Very recently scientists have found it useful to model layers of bacteria as active nematics; essentially as dense assemblies of self-propelled rods. Topological defects have been identified and shown to have an effect on the dynamics of the bacterial colonies. In this project we will investigate mixtures of different types of bacteria using self-propelled rod models. We are interested in whether the activity leads to spontaneous separation of the different bacterial species and the properties of topological defects in the mixtures.

This is a simulation project based on codes written in Matlab.

Meacock et al., Bacteria solve the problem of crowding by moving slowly, Nature Physics 17, 205 (2021)

Copenhagen et al., Topological defects induce layer formation in Myxococcus xanthus colonies, Nature Physics 17, 211 (2021)

Supervisors: ***Prof J M Yeomans*** and ***Dr M Nejad***
Email: ***julia.Yeomans@physics.ox.ac.uk***

TP07 Surface flows in active systems

Active materials such as bacteria, molecular motors and self-propelled colloids are Nature's engines. They extract energy from their surroundings at a single particle level and use this to do work. Active matter is becoming an increasingly popular area of research because it provides a testing ground for the ideas of non-equilibrium statistical physics, because of its relevance to the collective behaviour of living creatures, from cells to starlings, and because of its potential in designing nanomachines.

Active hydrodynamic forces depend on activity gradients so forces and flows specific to boundaries appear at the edges of active materials. The aim of the project is to investigate these in a more detailed and joined up way building on recent developments and experiments. This will be a primarily analytical project, but simulations will provide a useful check.

Doostmohammadi et al., Active Nematics, Nature Communications 9 1 (2018).

Thijssen et al., Submersed Micropatterned Structures Control Active Nematic Flow, Topology and Concentration, https://arxiv.org/abs/2102.10184

Supervisors: ***Prof J M Yeomans*** and ***Dr S Bhattacharyya***
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TP08 Topological Quantum Computing

One typically learns in quantum mechanics books that identical particles must be either bosons or fermions. While this statement is true in our three dimensional world, if we lived in two dimensions, more general types of particles known as "anyons" could exist. While this sounds like just a mathematical flight of fancy, in fact, when we restrict particles to move only within two dimensions, such exotic particles can (and sometimes do) emerge as low energy excitations of condensed matter systems, and various experiments have claimed to observe this behavior. It has been proposed that such anyons could be uniquely suited for building a so-called "quantum computer" — a computer that could in principle use the unique properties of quantum mechanics to perform certain types of calculations exponen- tially faster than any computer built to date.

The first objective of this project is to learn about the properties of anyons, where these particles exist, and how these particles might be used to build a computing device. A few toy model calculations will start the student in the direction of modern research.

The project is suitable for a mathematically strong student taking the Theoretical Physics option. This work will involve analytical calculations, abstract mathematics, and probably some computing based on Matlab or Mathematica.

Some background reading: Wikipedia Article on Anyons; Wikipedia Article on Topological Quantum Computing; Steven Simon (2010) "Physics World: Quantum Computing with a Twist" (see my home page for link); Ady Stern (2008), "Anyons and the quantum Hall effect

— A pedagogical review". Annals of Physics 323: 204; Chetan Nayak, Steven Simon, Ady Stern, Michael Freedman, Sankar Das Sarma (2008), "Non-Abelian anyons and topological quantum computation," Reviews of Modern Physics 80 (3): 1083.

Supervisor: ***Prof S Simon***
Email: ***steven.simon@physics.ox.ac.uk***

TP09 Topological Insulators and Surface States

Over the last decade, a revolution has occurred in condensed matter physics. We now think of materials in terms of topological classes --- placing two materials in the same class if one Hamiltonian can be smoothly deformed into the other. This new was of classifying materials has led us to discover new materials and new, previously hidden, properties. The simplest example of the power of this type of thinking is given by what is known as a "topological insulator". For many purposes these materials appears like any non-interacting electron band insulator (a filled valence band and an empty conduction band), but on closer inspection they turn out to have fundamentally different properties --- such as protected surface modes. The first part of this project will be to understand this idea topological classification. The remainder of the project will be to explore the physics of protected surface states, using the framework of Fermi liquid theory. This project is suitable for a student who is mathematically very strong and is taking the C6 theory option. Some amount of computation will be required (almost any computer language would be acceptable).

Reference: M. Z. Hasan and C. L. Kane, Rev. Mod. Phys. 82, 3045 (2010).

Supervisor: ***Prof S Simon***
Email: ***steven.simon@physics.ox.ac.uk***

TP10 Topological Statistical Mechanics

Exactly solvable models have taught us an enormous amount about statistical physics and phase transitions. A new class of (classical) stat-mech models was recently proposed which can be solved exactly due to their having a special "crossing" symmetry. The simplest example of such a problem is counting the number of nets (branching tree structures) without ends on the honeycomb.

The objective of this project is to use the exact solvabiltiy of these models as a stepping off point for the analysis of models which are nearly, but not exactly, solvable. I.e., we will perturb these models with small terms that slightly ruin the crossing symmetry. We will use several tools to come to an understanding on the statistical physics of these systems — these tools include numerical simulation of several types, analytical perturbation theory, and renormalization group approaches.

The project is suitable for a mathematically strong student taking the Theoretical Physics option. This work will involve analytical calculations, and a large component of computer programming. Working knowledge of a computational programming language such as C, C++, or fortran will be required.

Some background reading: Steven H. Simon, Paul Fendley; J. Phys. A 46, 105002 (2013). M. Hermanns and S. Trebst http://arxiv.org/abs/1309.3793.

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TP11 Topics in Geometry, Number Theory and Gauge/ String Theory

We present the student with a manageable (appropriate for a mathematically and theoretically inclined fourth-year), self-contained project in a specific problem in the realm of the interaction of geometry, number theory and gauge/ string theory.

Topics in the past have included finite graphs and field theory, Calabi-Yau manifolds and compactification, as well as modern geometrical aspects of the standard model from string theory.

The project will provide an opportunity for the student to some rudiments of, for example, differential/algebraic geometry, quantum field theory, supersymmetry, as well as number theory and advanced algebra. More recently, there has been much interaction of these fields also with machine-learning and data science, so those interested in computational aspects can also explore this direction.

Programming experience (with C and mathematica/maple) most welcome.

Supervisor: ***Prof Y-H He***
Email: ***hey@maths.ox.ac.uk***

TP12 Micro-stability of plasma immersed in 3D magnetic fields

Ionized gas, called plasma, generates and responds to electromagnetic fields and demonstrates collective behavior including unstable modes of oscillation that result in turbulence. In the context of magnetic confinement fusion — where strong magnetic fields are used to confine a hot, fusing plasma — this turbulence is problematic: It leads to mixing of the hot and cold regions of the plasma, thus limiting confinement. Understanding and subsequently limiting the plasma turbulence is thus a crucial challenge for controlled fusion.

In this project, the student will investigate the influence of the confining magnetic field geometry on the micro-stability of the plasma. This will involve conducting linear stability simulations for the plasma, analysing the resulting data, and seeking approximate analytical solutions to the underlying equations. A firm grasp of kinetic theory, fluid mechanics, and electrodynamics would be useful, as would some prior experience with or enthusiasm for programming.

Supervisor: ***Prof M Barnes***
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TP13 Anderson localisation of a Dirac particle in a random magnetic field

In a condensed matter physics course, students learn that quantum particles (such as electrons) propagate through a periodic potential (such as the potential in a perfect crystal) without scattering. In an imperfect crystal, surprising things can happen: if the potential is sufficiently disordered, quantum particles may be unable to propagate long distances, being instead trapped in microscopic regions. This phenomenon is known as Anderson Localisation and has been studied very extensively. While many aspects of the field are well understood, it was shown in late 2019 that standard beliefs about one type of Anderson localisation problem are almost certainly wrong. The aim of this project is to test and extend our understanding of this new direction.

The project is best suited to an ambitious student who is considering a PhD in theo- retical condensed matter physics. The project will involve digesting ideas from the current research literature, developing physical understanding with pen and paper, and doing some computational simulations. Although the project will not make direct use of material cov- ered in the C6 option, an appetite for theoretical approaches is necessary. Since the project involves the Dirac equation, there is some benefit in having done the Advanced Quantum Mechanics option, but this is not essential because the necessary background can be learnt quite quickly.

More specifically, the Anderson localisation problem for which established ideas have turned out to be wrong is one involving a massless relativistic quantum particle moving in two dimensions, in a magnetic field that varies randomly with position. This can be de- scribed using the Dirac equation. Although at first sight the problem may seem an entirely artificial construct, it in fact represents the situation on the surfaces of materials known as topological insulators, which are currently under intensive experimental investigation.

References:

[1] The paper reporting the new discovery is https://arxiv.org/pdf/1912.06748.pdf published as Phys. Rev. X 10, 021025 (2020). However, it is not an easy read, and not recommended as a basis for choosing a project.

[2] Two good articles giving an overview of the phenomenon of Anderson localisation are: Physics Today 62, 8, 24 (2009), doi: 10.1063/1.3206091; and Physics Today 41, 12, 36 (1988), doi: 10.1063/1.881139.

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TP14 tbc

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TP15 tbc

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