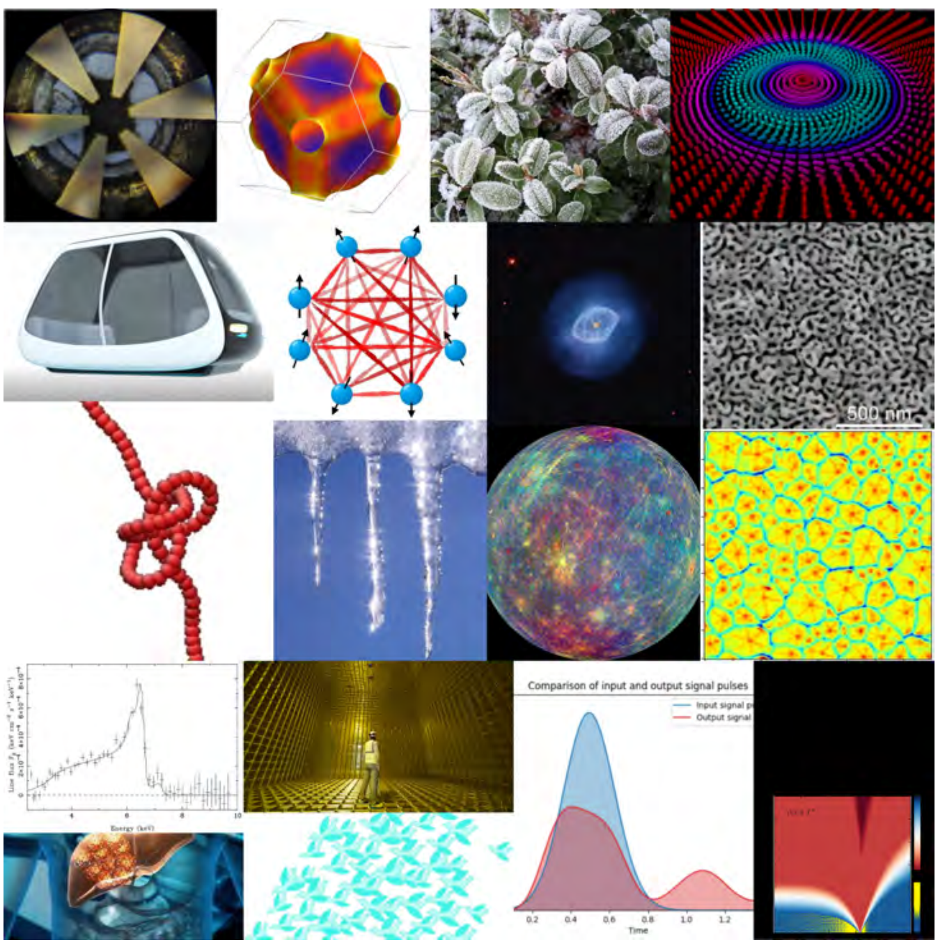
University of BRISTOL

School of Physics

PROJECT PROPOSALS

for Final Year MSci students

2023/2024



March 2023

INTRODUCTION

It is probably fair to say that not many of you have a very clear picture about the way the research environment of the H.H. Wills Physics Laboratory operates. You have come across staff as tutors, lecturers or in laboratory classes and don't see us working on our research. Yet for most of us this is a vital part of our activity and one that we find not just fulfilling, but exciting and has often been the primary reason we choose this career path.

As you embark on a final year project you are coming close to the research side of our work and it is very important to make the right choice as your research project is the single most important contributor to your final degree grade. To help you to make the most effective choice of project this booklet has been arranged by research groups.

Many students judge their projects to be the high point of their university experience and it is an important part of your training, and it is also important to us. We depend on motivated, original researchers to enable our research groups to flourish and the work you do, if it is well done, may well be publishable. Moreover we often recruit PhD students internally and students who enjoy their projects frequently wish to continue in that line of research.

ESSENTIAL INFORMATION FOR ALL STUDENTS

Project proposals

The 60CP proposals are suitable for those on the following courses:

- MSci Physics
- MSci Physics with Astrophysics
- MSci Physics with Study in Continental Europe
- MSci Physics with Industrial Experience
- MSci Physics with international Experience

The 30 CP proposals are suitable for those on the following courses:

- MSci Maths & Physics
- MSci Physics and Philosophy
- MSci Theoretical Physics

The allocation of MSci projects will be made by the end of week 23, the first week of teaching after the Easter vacation.

Students with Study in Continental Europe

You should try to make your selection at the same time as students staying in Bristol if possible, but it is appreciated that this is not always feasible; if you need more time, email phys-ug@bristol.ac.uk to let them know. As a student abroad you will not be able to commence your project in June in the same way as home-based students, so make contact with your supervisor to make sure you have reading lists and preparatory material so that a prompt start can be made in the new academic year.

MSci Students in Industrial Placements

MSci students on the Year in Industry should make their selection at the same time as students staying in Bristol if possible; if you need more time, email phys-ug@bristol.ac.uk to let them know. You should make contact with your supervisor before the end of the summer term to make sure you have reading lists and preparatory material so that a prompt start can be made in the new academic year.

Joint Honours students

Joint Physics and Philosophy: MSci students must do their project in physics as it counts towards their credit points in the physics component of the degree programme. Students wishing to do experimental projects are advised that their experimental partner must also be taking a 30cp project. Students who are having difficulty finding a partner can contact Prof. Rademacker, who may be able to make suggestions.

Joint Maths and Physics: MSci students will usually do a 30cp physics project chosen from this booklet. It may also be possible to do an alternative or additional project run by the School of Mathematics. Please speak to the math-physics programme coordinators (Dr Short and Dr Muller) if you are interested in this possibility.

Selection of Project Preferences

This project proposal book contains more than 100 different project proposals, grouped by Bristol Physics research theme. For each Theme there is a brief description of the research carried out within the Theme, followed by a description of each project. In most Themes there are projects which involve experimental work, theoretical / computational work or a mix of the two.

You must make 6 choices and rank these in order of preference.

Physics with Astrophysics students must carry out their project work with the Astrophysics or the Particle Physics Themes. If you would like to take a project outside of these areas, you should transfer off of the Physics with Astrophysics programme at the start of the new academic year. Astrophysics students will get preference on the available Astrophysics projects. Non-Astro students can also select Astro projects as one or more of their preferences, however, as availability is limited, you are advised to also include some non-Astro projects in your preference list.

Physics with Scientific Computing students are expected to carry out a project containing a substantial computing element. These projects will involve a significant amount of coding and not just using a pre-built package such as a CAD package. Suitable projects are available within many research groups and are flagged in the 'Skills' section as involving computer coding. If you are unsure whether a project qualifies as a Physics with Scientific Computing project, please check with your prospective supervisor or with the Physics with Scientific Computing programme director, Dr. Hanna.

Selection of partner

Projects are normally done in pairs. Try to find a project partner yourself and indicate this name on the project preferences form. You should agree on your selection of the 6 preferences, so these should be the same for both of you. If you cannot find a suitable partner, do not worry, we will pair you with someone else who has submitted similar project preferences.

Q: The project I want to do is available at both 30 and 60 credit points, can I do this project with a partner who wants to do it for a different number of credit points?
A: No, partners need to be completing a project for the same number of credit points.

Q: Do partners need to be on the same course type (I.e MSci/BSc) where projects are available as both MSci and BSc projects?
A: Yes, they do.

ASTROPHYSICS (AP)

The research interests of the group cover topics in galactic astronomy, extragalactic astronomy, cosmology, planet formation, exoplanets, sunspots, and astrophysics. This work uses a wide range of ground and space-based telescopes to observe over the entire electromagnetic spectrum and involves theoretical and computational studies of the phenomena that these observations reveal.

Galactic astronomy

Much observing time on the Isaac Newton Telescope on La Palma and the VST in Chile has been devoted to an H imaging campaign to cover the Galactic plane. These surveys (IPHAS and VPHAS) have brought about the discovery of a host of new planetary nebulae and line-emitting stars and will lead to a better understanding of the photo-excited component of the interstellar medium.

External galaxies

We study galaxy populations and their evolution using optical surveys of nearby clusters to look for previously undetected low surface brightness and dwarf galaxies, and observations of more distant clusters to follow the evolution of their galaxy content. This led to the discovery of a new class of compact galaxy, on which follow-up optical imaging and spectroscopy are being done. Alongside this there is work in observational large-scale structure in the Universe.

Active galactic nuclei

We study active galactic nuclei (AGN) using radio, infra-red, optical, and X-ray techniques both to understand the underlying physics that causes them to be so luminous and to use them as pointers to large-scale structures in the distant Universe. Current work is providing new information about the relationships between AGN and their environments, the properties of the various classes of AGN, and the extent to which all types of AGN are different aspects of the same structures in galaxies the so-called ‘Unified Schemes’.

Intracluster plasma

We also use X-ray observations to study the masses and hot gas content of galaxy clusters. The numbers of distant galaxy clusters of different temperatures, and the evolution of this distribution relative to nearby clusters, is very sensitive to underlying cosmological parameters.

The cosmic microwave background radiation and the structure of the Universe We measure the scattering of the cosmic microwave background (CMB) by hot atmospheres in clusters of galaxies. These measurements are combined with X-ray data to study the matter contents of clusters, but they can also be used to determine the value of the Hubble constant and to trace the development of gravitational structures in the Universe. We also study CMB structures caused by general-relativistic effects and scatterings in the early Universe.

Black Holes

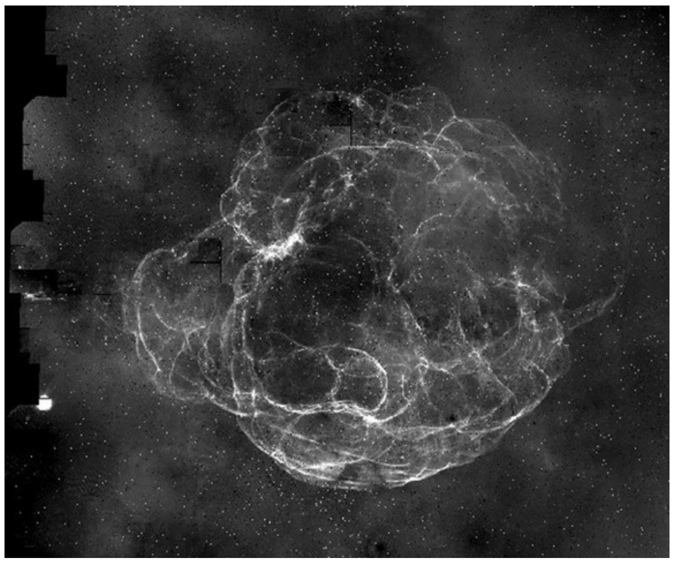
Gas falling towards a super-massive black hole can produce tremendous quantities of radiation (often outshining an entire galaxy) and can also produce very high velocity outflows such as relativistic jets. We study the astrophysics and spacetime close to the black hole, the feedback between inflowing gas and outflowing jets and radiation which plays an important role in regulating galaxy and galaxy cluster formation and evolution.

Planet formation

Planet formation is common, with a Jupiter mass planet in close orbit around at least 1% of all main sequence stars. The systems that are observed are surprisingly diverse and very different from our solar system. We are currently developing a state-of-the-art numerical method which is able to evolve newly formed planetesimals all the way through to planets.

Exoplanet Atmospheres

Using space-based telescopes like Hubble, and the James Webb Space Telescope we can measure the composition, temperature, and dynamics of exoplanet atmospheres to help understand the formation, evolution, and interaction with their present-day environment. We study the spectrum of the planet's atmosphere in absorption, reflection, and emission to piece together a better understanding of the planet's nature and of our solar system's place in a galaxy where planets far outnumber the stars.



A Galactic Supernova Remnant imaged in H-alpha, showing the ionized gas distribution.

Data Intensive Astronomy

Next generation surveys are due to produce very large catalogues of astronomical sources. We use multiwavelength photometric and spectroscopic datasets to first classify astronomical sources into stars, galaxies and AGN/QSO and later estimate their physical properties (distance, star formation rate). To achieve this, we use traditional data analysis methods, and we develop machine-learning models. We have leading positions in the Euclid Collaboration, a space telescope due to launch in July 2023. Euclid will map 15,000 square degrees in the optical and near-infrared, delivering impeccable imaging.

Stellar Structure and Nucleosynthesis

Stars are responsible for the production of (almost all) the elements in the Periodic Table. Some elements are formed during the quiescent phases of nuclear fusion that happen during a star's life. Others form in the violent processes that mark the demise of more massive stars. Which stars form which elements, and how those elements form, is what stellar evolution and nucleosynthesis aims to understand. In particular, we study the formation of elements by neutron capture and how these can be used to understand the behaviour of binary star systems.

Diatomic Molecules in sunspots

Sunspots are regions of intense magnetic flux on the Sun's surface: these relatively cooler regions allow for the formation and existence of diatomic molecules. We combine high-level quantum chemistry calculations with laboratory measurements of molecular spectra to produce high-accuracy and extensive molecular line lists (lists of wavelengths with corresponding intensities). We are interested in modelling the spectra of molecules in sunspots to test if they could be used as probes of pressure, temperature, and magnetic field strength.

Next Generation Radio Astronomy

The global astronomy community is collaborating on building the next large radio telescope interferometer, called the Square Kilometre Array Observatory (SKAO). With one telescope located across southern Africa, and another in Western Australia, these facilities represent the next generation of radio telescopes, enabling observations and discoveries not possible with existing instruments. The operational headquarters are in Jodrell Bank, near Manchester, so the UK is a core partner in the SKAO project. By using existing telescopes for our research, such as MeerKAT, we will build expertise in advance of the start of SKAO operations in the coming decade and be ready for the science the SKAO will enable.

Artist's impression of the SKAO mid-frequency array across Southern Africa


Mark Birkinshaw: active galaxies, radio astronomy


Malcolm Bremer: clusters of galaxies


Sotiria Fotopoulou: active galaxies, data-intensive astronomy


Maire Gorman: atmospheric chemistry

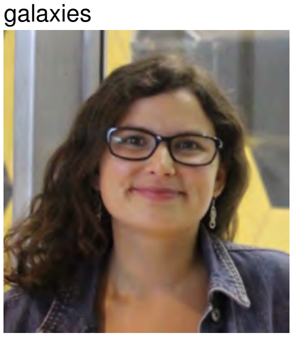

Zoë Leinhardt: planet formation and collisional evolution


Natasha Maddox: radio astronomy, active galaxies


Ben Maughan: Clusters of galaxies


Rhys Morris: galactic line emission


Richard Stancliffe: stellar evolution and nucleosynthesis


Hannah Wakeford: exoplanet atmospheres


Andrew Young: black holes, active galaxies

AP-M1 : The dark matter halo spin parameter of HI-rich galaxies

Supervisor: Dr Natasha Maddox (Astro)

MSci
60/30

Description

Neutral hydrogen (HI) is the fundamental building block for forming stars in galaxies. The HI content of galaxies can tell us about the current and future star formation, past interactions, and is a good probe of the dark matter haloes in which galaxies reside. Large observing campaigns using the most powerful radio telescopes have assembled observations of the HI content of samples of galaxies, so we can now use the data to understand how galaxies form and evolve. Meanwhile, observations with optical telescopes give information about the stellar content of galaxies, also a fundamental measurement.
You will use existing HI and optical data from ALFALFA and the Sloan Digital Sky Survey to create a sample of 30,000 galaxies for which we have data for both the HI and stellar content. You will then investigate correlations between the HI and optical properties of the galaxies, such as mass and star formation rate. By combining information from both HI and optical observations, information about the galaxy dark matter haloes will be derived. The large sample can then be subdivided by other properties, such as galaxy group membership. The correlations will be discussed in the context of galaxy evolution.

Key References

1. N. Maddox et al, MNRAS, Volume 447, Issue 2, p.1610-1617 (2015)
   https://doi.org/10.48550/arXiv.1412.0852
2. M. Haynes et al, ApJ, Volume 861, Issue 1, article id. 49, 19 pp. (2018)
   https://doi.org/10.48550/arXiv.1805.11499
3. K. Abazajian et al, ApJS, Volume 182, Issue 2, pp. 543-558 (2009)
   https://doi.org/10.48550/arXiv.0812.0649

Skills

- SQL to extract data from databases
- Handling large datasets
- Optical photometry

AP-M2 : Rotation Measure synthesis

Supervisor: Prof. Mark Birkinshaw (Astro)

MSci
60/30

Description

This project will construct models of mixed gas and magnetic fields that can both emit synchrotron radiation and modify the polarisation of that radiation via Faraday rotation. Numerical experiments will then be run to calculate how precisely Rotation Measure (RM) studies of the polarised radio emission can reconstruct the models. Early work on Faraday rotation in radio astronomy (Burn 1966) described how mixed thermal plasma and magnetic field cause the plane of polarisation of radio emission to rotate, and much work has been done to measure RMs towards radio sources to investigate the magnetic field of the Galaxy, or the influences of radio sources on their environments. Recently a number of new methods have been developed for extracting RMs from low signal/noise data, in preparation for large-scale RM surveys. This project will use several methods to investigate their reliability and the practical signal/noise limits for their use, in the presence of noise with realistic properties and allowing for beam averaging.

Key References

1. *On the depolarisation of discrete radio sources by Faraday dispersion*, Burn, B.J., 1966. MNRAS **133**, 67.
   https://doi.org/10.1093/mnras/133.1.67
2. *Faraday rotation measure synthesis*, Brentjens, M.A., de Bruyn, A.G, 2005. A&A **441**, 1217.
   https://doi.org/10.1051/0004-6361:20052990
3. *The intergalactic magnetic field probed by a giant radio galaxy*, O'Sullivan, S.P. *et al.*, 2019. A&A, **622**, 16.
   https://doi.org/10.1051/0004-6361/201833832
4. *Observing interstellar and intergalactic magnetic fields*, Han, J.L., 2017. ARAA **55**, 111.
   https://doi.org/10.1146/annurev-astro-0916-055221
5. *Broadband polarimetry with the Square Kilometre Array:a unique astrophysical probe*, Gaensler, B. *et al.*, 2015. Proceedings of *Advancing Astrophysics with the Square Kilometre Array*.
   https://doi.org/10.22323/1.215.0103

Skills

- Python computing skills.
- Understand QU fitting, Fourier synthesis, and other methods for measuring polarisation.
- Physical modelling of magnetic field distributions.

AP-M3 : Relativistic boosting

Supervisor: Prof. Mark Birkinshaw (Astro) | MSci 60/30

Description

This project will create simulations showing the effect of special relativistic boosting on the appearance of the jets emitted from an active galactic nucleus, taking account of aberration effects and allowing for precession of the jet emission direction, time-dependent Lorentz factors, and (perhaps) spectral evolution of the emitting regions. The resulting curves and movies will help in the interpretation of Very Long Baseline imaging of active galactic nuclei (as in the MOJAVE programme) and show the uncertainties involved in using radio to X-ray emission ratios to extract the bulk properties of jet flows.

Key References

1. *Retardation magnification and the appearance of relativistic jets*, Jester, S., 2008. MNRAS **389**, 1507.
   https://doi.org/10.1111/j.1365-2966.2008.13673.x

2. *An analysis of the proper motions of the SS 433 radio jets*, Hjellming, R.M., Johnston, K.J., 1981. ApJ **245**, L141.
   https://doi.org/10.1086/183571

3. *MOJAVE. XV. VLBA 15 GHz total intensity and polarisation maps of 437 parsec-scale AGN jets from 1996 to 2017*, Lister, M.L. *et al.*, 2018. ApJS **234**, 12.
   https://doi.org/10.3847/1538-4365/aa9c44

Skills

- Python computing skills.
- Understand interplay of Lorentz boosts and relativistic aberration.
- Making simple movies of physics simulations.

AP-M4 : Which molecules should be most abundant in sunspots?

Supervisor: Dr Maire Gorman (Astro)

MSci (60/30)

Description

To date there are ∼60 diatomic molecules which have been detected in sunspots which include water, CrH, FeH and a range of funky fluoride and chloride containing molecules. These detections have been done mostly on an ad hoc basis and have been biased by the availability of experimental data for particular molecules. This availability is in turn dependent upon ease of measuring spectra in a particular wavelength region and generating a stable gaseous form of the molecule in a safe manner within a laboratory. Hence some molecules have arguably had a disproportionate amount of scientific attention at the expense of others. Could there be other molecules which could be explored as possible pressure, temperature and magnetic field probes? Sunpot activity is intrinsically linked to violent space weather events such as solar flares and coronal mass ejections so hence probing these environments is of global importance.

The aim of this project is to compute which molecules are theoretically expected to be most abundant in sunspots. This is an important step in prioritising future experimental, theoretical and observational work.

To do this, you will explore theoretical models of how temperature and pressure vary within sunspots and hence construct T-p grids as input for calculations using the "TEA" code. The "TEA" code is used within exoplanet studies to predict relative abundances of molecules: it does this by minimsing "Gibbs" thermodynamic potential. The overarching challenge in this project is to run a suite of systemtic calculations for different sunspot environments and draw conclusions from all the data generated.

Key References

1. Wohl (1971), On molecules in sunspots, Solar Physics, 16
2. J. Blecic et al. (2016), TEA: a code calculating thermochemical equilibrium abundances, The Astrophysical Journal Supplement Series, 225 (1)
3. Matthew et al. (2003), Thermal-magnetic relation in a sunspot and a map of its Wilson depression, Astronomy & Astrophysics, 422 (2)
4. Rempel & Schlichenmaier (2011), Sunspot Modeling: From Simplified Models to Radiative MHD Simulations, Living Reviews in Solar Physics, 8 (3).

Skills

- Critique and synthesis of theoretical models
- Planning of suite of simulation calculations.
- Batch calculation running.
- Analysis of multi-variate data.

AP-M5 : Simulating the Zeeman effect in diatomic molecules

Supervisor: Dr Maire Gorman (Astro)

MSci (60/30)

Description

An exotic range of quirky diatomic molecules have been found in a range of astrophysical environments including cold ISM clouds, brown dwarfs, exoplanets and sunspots. These molecules include hydrides, fluorides, chlorides and elements spanning the periodic table. Many astrophysical environments have inherent and complex magnetic fields: observing and modelling (by means of computer simulation) these fields can give valuable insights into formation and evolution of such environments.

At present, within sunspots, atomic species are commonly used as probes of magnetic field strength. However spectra of these atomic species are often blended by unidentified molecular spectra. Sunspots are regions of enhanced magnetic field flux: probing these complex magnetic field environments is crucial for space-weather forecasting as future "Carrington" events will threaten global electrical grids and communication networks.

The purpose of this project is to use existing open-source code to simulate how a magnetic field changes the spectra of select diatomic molecules and hence investigate if any molecular species could be utilised as magnetic field diagnostic. For example, is there a systematic shift in spectra which we could exploit?

Molecular spectra are very rich and much more dense compared to atomic spectra as it incorporates rotational and vibrational modes on top of electronic configurations. This complexity increases with temperature as the individual probabilities for occupying higher energy levels increases. Hence the overall strategy is to start at low temperatures and weak fields (i.e. ISM type environments) and then systematically increase to higher temperature applications (i.e. sunspots).

Key References

1. Tennyson et al. (2020), The 2020 release of the ExoMol database: Molecular line lists for exoplanet and other hot atmospheres, Journal of Quantitative Spectroscopy and Radiative Transfer, 255.
2. Wohl (1971), On molecules in sunspots, Solar Physics, 16
3. Berdyugina & Solanki (2002), The molecular Zeeman effect and diagnostics of solar and stellar magnetic fields, A&A 385, 701-715 (2002).
4. Semenov et al. (2016), Predicted Lande g-factors for open shell diatomic molecules, Journal of Molecular Spectroscopy, Volume 330, December 2016, Pages 57-62

Skills

- Planning of suite of simulation calculations.
- Batch calculation running.
- Analysis of multi-variate data.

AP-M6 : Heavy element nucleosynthesis via the intermediate neutron capture process?

Supervisor: Dr. Richard J. Stancliffe (Astro)

MSci
60/30

Description

Heavy elements are typically produced by the capture of neutrons. For a long time, it was thought that only two processes occurred, dubbed the slow and rapid processes, with the range of elements being produced being dependent on the neutron density. However, a certain class of low-metallicity star has odd abundance patterns that cannot be described by either process. In this project, you will look at how variations in neutron density affect element production, and determine what conditions are able to reproduce stellar abundances.

This project requires the use of python as a programming language.

Key References

1. Cowan J., Rose W., 1977, ApJ, 212, 149
2. Hampel M., et al., 2016, ApJ, 831, 171
3. Hampel M., et al., 2019, ApJ, 887, 11

Skills

- Programming – Python
- Data analysis

AP-M7 : Explaining the abundance patterns of barium stars

Supervisor: Dr. Richard J. Stancliffe (Astro)

MSci
60/30

Description

Barium stars are the result of mass accretion in binary star systems. A barium star's surface abundances is the direct result of nucleosynthesis that took place in a long-dead companion star. As the companion reached the end of its life, it underwent an asymptotic giant branch phase where it was able to produce a wide variety of heavy elements by the slow neutron capture process. We are now able to observe this pattern of abundances in the barium star, giving us a window onto how these elements can be produced. In this project, you will investigate how predictions of stellar nucleosynthesis can be combined to with detailed binary stellar modelling to understand how binary star systems evolve.

This project requires the use of python as a programming language.

Key References

1. Stancliffe, R.J., 2021, MNRAS, 505, 5554
2. Escorza, A., et al., 2017, A&A, 680, 100
3. de Castro, D.B., et al., 2016, MNRAS, 459, 4299

Skills

- Programming – Fortran/Python
- Data analysis

AP-M8 : Can the Moon survive another giant impact on the Earth?

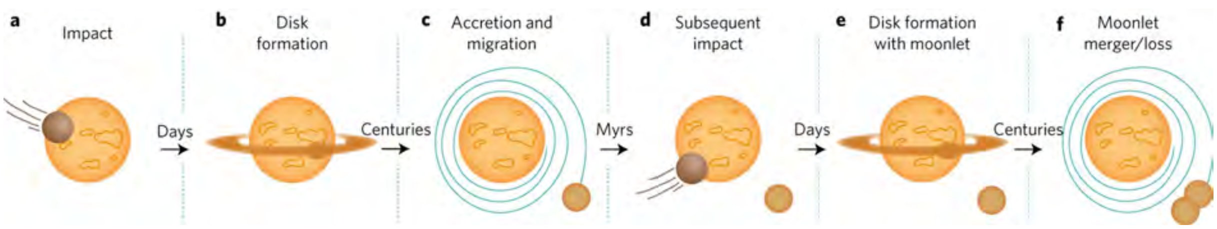
Supervisor: Dr. Zoë Leinhardt (Astro)
Co-supervisor: Dr. Philip Carter

MSci (60)

Description

The final stage of formation of terrestrial planets is known as the giant impact stage. During this period rocky protoplanets undergo one to 10s of collisions with other protoplanets – giant impacts (e.g. Quintana et al., 2016). It is widely accepted that the proto-Earth underwent at least one giant impact that resulted in the formation of Earth's Moon (e.g. Canup & Asphaug, 2001). This giant impact must also explain the surprising compositional similarity between the Earth and the Moon. It is generally believed that this was the final giant impact onto the proto-Earth, however, this may not necessarily be the case.

One theory for the formation of the Moon involves a series of smaller giant impacts each one producing a Moon-let that merges with Moon-lets from previous impacts (Rufu et al., 2017). In this scenario the proto-Moon necessarily must survive these smaller giant impacts with the Earth, so how large of an impact onto the Earth can the Moon survive? The goal of this project is to model such giant impacts and determine their effects on an existing Moon: does the Moon survive on a stable orbit? How much material from impactor and Earth are deposited on the Moon?



Lunar formation in the multiple-impact scenario. From Rufu et al., (2017)

Key References

1. Canup, R., Asphaug, E., Nature **412**, 708–712 (2001).
   https://doi.org/10.1038/35089010
2. Rufu, R., Aharonson, O. & Perets, H., Nature Geoscience **10**, 89–94 (2017).
   https://doi.org/10.1038/ngeo2866
3. Quintana, E. V. et al., Astrophysical Journal **821** 126 (2016).
   https://doi.org/10.3847/0004-637X/821/2/126

Skills

- Set up and run astrophysical hydrodynamic simulations
- Write code to read and process simulation results
- Analyse numerical simulations

AP-M9 : Would a mighty smack tilt Uranus?

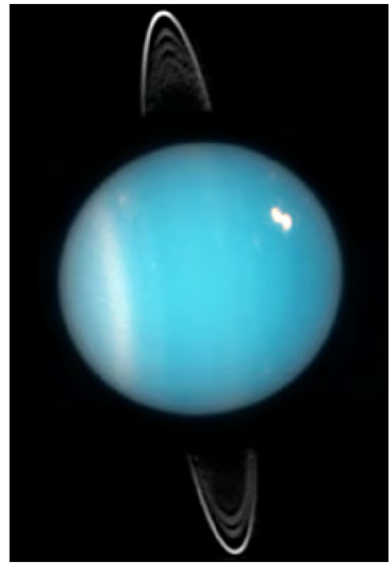
Supervisor: Dr. Zoë Leinhardt (Astro)
Co-supervisor: Dr. Philip Carter

MSci (60)

Description

Uranus is the seventh planet in our solar system. It orbits the Sun once every 84 years. It is an ice giant with an atmosphere of hydrogen and helium and an interior consisting of volatile rich ices like methane and ammonia and a rock-rich central core. Uranus is about 14 times as massive as the Earth and about four times the size. Uranus also has a ring system with several distinct and well defined rings. All of these characteristics are consistent with the other large planets in our solar system. The one thing that is not is Uranus' axial tilt. This ice giant lies on its side with its spin axis parallel to the orbital plane of the solar system.

Given Uranus' size and mass it is quite difficult to come up with plausible hypotheses for how the planet has ended up on its side. The two leading theories are a strange complex resonance or a large impact after the planet was fully formed. In this project we will investigate what type of impact is needed to knock a giant planet on its side using numerical simulations and determine whether such an impact would have been possible during the formation of the solar system. This project will involve using the University of Bristol's high performance super-computer BlueCrystal to run collision simulations using the hydrodynamical code SWIFT.



Uranus and rings - image from HST (2005)

Key References

1. Kegerreis, J. A. et al. The Astrophysical Journal **861** (2018)
   https://doi.org/10.3847/1538-4357/aac725

2. Rogoszinski Z., Hamilton D. P., The Planetary Science Journal, **2**, 78 (2021)
   https://doi.org/10.3847/PSJ/abec4e

3. Rufu R., Canup R. M., The Astrophysical Journal, **928**, 123 (2022)
   https://doi.org/10.3847/1538-4357/ac525a

Skills

- Set up and run astrophysical hydrodynamic simulations
- Write code to read and process simulation results
- Analyse numerical simulations

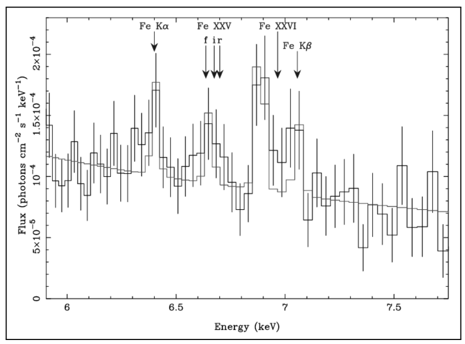
AP-M10 : Inefficient Accretion

Supervisor: Dr Andrew Young (Astro)

MSci
60/30

Radiatively Inefficient Optically Thin Accretion Flows Onto Supermassive Black Holes

The goal of this project is to construct a computer model of the X-ray emission from optically thin, hot accretion flows onto supermassive black holes at the centres of galaxies. Examples of these flows include Sgr A* at the centre of our galaxy, M87* at the centre of the Virgo cluster, and M81* at the centre of a nearby spiral galaxy. M81* is close enough and bright enough that high-resolution X-ray spectroscopy can be performed with the *Chandra* X-ray observatory [1] and, in the near future, the *XRISM* observatory. You will use our general relativistic ray tracing software `Gradus` [2] to take into account all of the relativistic effects close to the black hole that will modify the spectrum of thermal emission from hot plasma [3]. Your high-resolution spectra can be compared with observational data to learn about the physics of the accretion flow close to the black hole.



The Chandra High Energy Transmission Grating Spectrometer X-ray spectrum of the low-luminosity active galactic nucleus M81 [1]. Emission lines can be seen from neutral Fe Kα to almost completely ionised H-like Fe XXVI. Some of these lines are significantly Doppler shifted.*

Key References

1. A. J. Young, et al., ApJ **669**, 830 (2007)
   https://doi.org/10.1086/521778
2. `Gradus` general relativistic ray tracing package (2023)
   https://github.com/astro-group-bristol/Gradus.jl
3. A. F. Foster et al., ApJ **756**, 128 (2012)
   https://doi.org/10.1088/0004-637X/756/2/128

Skills

- Introduction to Linux
- Introduction to X-ray data analysis and modelling software
- Use of ADS to access astronomical literature
- Computer modelling

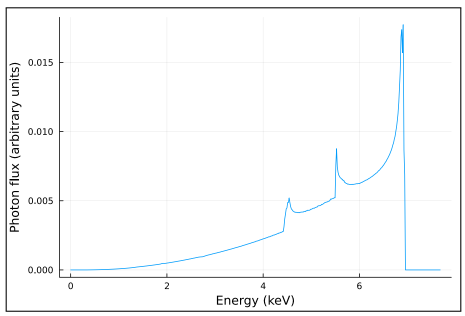
AP-M11 : Testing General Relativity

Supervisor: Dr Andrew Young (Astro)

MSci
60/30

Testing General Relativity With High Resolution X-ray Spectroscopy of Accreting Black Holes

The goal of this project is to investigate how high-resolution X-ray spectroscopy with a new generation of X-ray observatories can be used to test general relativity in the strong field regime. Accretion flows around supermassive black holes are powerful sources of X-rays which illuminate the accretion disc producing a back-scattered spectrum with a prominent iron fluorescence line. This line is broadened and skewed by Doppler and relativistic effects. The precise shape of the line depends on the illumination of the disc, the inclination angle of the system, and the nature of the spacetime, e.g., if the black hole is spinning. You will use our `Gradus` ray tracing package [2] to produce synthetic line profiles for a range of different scenarios, including warped discs, corrugated discs (e.g., with spiral density waves), discs with hot spots, and perturbations to standard spacetimes (e.g., if there is any deviation from general relativity). You will produce a catalogue of line profiles for different scenarios that can be compared with future data. New observatories such as *XRISM* will have the next generation of X-ray detectors with significantly improved X-ray resolution, going beyond what has been possible to date (e.g., seee references [1] and [3]).



Model of X-ray iron line from an accretion disc around a black hole. Two bright annuli on the disc produce the peaks between 4 and 5 keV. The detailed shape depends on the disc and spacetime.

Key References

1. A. J. Young et al., ApJ, **631**, 733 (2005)
   https://doi.org/10.1086/432607
2. `Gradus` general relativistic ray tracing package (2023)
   https://github.com/astro-group-bristol/Gradus.jl
3. J. T. Turner, et al., ApJ **574**, L123 (2002)
   https://doi.org/10.1086/342504

Skills

- Introduction to Linux
- Use of ADS to access astronomical literature
- Computer modelling

AP-M12 : Probing the Main Sequence of star forming galaxies

Supervisor: Dr. Sotiria Fotopoulou (Astro)

MSci (60/30)

Description

Galaxies are largely categorised as star-forming or quiescent, according to the rate of formation of new stars. Quiescent galaxies have depleted their gas reservoir, and as such they have lost the capacity to form stars at large rates.

If we plot the star formation rate of a large sample of galaxies versus their mass, we see a prominent correlation. The goal of this project is to use a large sample of galaxies using the deepest available data from the VIDEO fields, to model precisely the multiwavelength emission of galaxies and estimate their star formation rate, and stellar mass. Finally, you will examine trends on the star-formation main sequence, such as evolution with redshift, and large scale structure environment.

Key References

1. Code Investigating GALaxy Emission (CIGALE) https://cigale.lam.fr/
2. Speagle J. S., Steinhardt C. L., Capak P. L., Silverman J. D., 2014, ApJS, 214, 15. doi:10.1088/0067-0049/214/2/15
3. Somerville R. S., Davé R., 2015, ARA&A, 53, 51. https://arxiv.org/abs/1412.2712
4. Kennicutt R. C., 1998, ARA&A, 36, 189. https://arxiv.org/abs/astro-ph/9807187

Skills

- Model multiwavelength emission of galaxies
- Write Python scripts to visualise and present your results
- Work in the Linux environment

AP-M13 : The location of active galaxies on the main sequence

Supervisor: Dr. Sotiria Fotopoulou (Astro)
Co-supervisor: Prof. Malcolm Bremer

MSci (60/30)

Description

Active galaxies (active galactic nuclei, AGN) are a special category among the normal galaxy population. The supermassive black hole located in their centres is accreting matter which, in some cases, is able to outshine the entire galaxy. We believe that active galaxies are a special phase during the life time of any galaxy.

With this work, you will use a sample of active galaxies with multiwavelength photometric data to model the emission processes that govern the observed light, originating from the galaxy and the active region around the black hole. You will measure the rate of star formation, the stellar mass, and the fraction of AGN.

Finally, you will compare your results with the literature and discuss possible reasons for the discrepancies found in the literature that might place AGN lower, en par, or higher than the main sequence of normal star forming galaxies.

Key References

1. Code Investigating GALaxy Emission (CIGALE) https://cigale.lam.fr/
2. Ciesla L., Charmandaris V., Georgakakis A., Bernhard E., Mitchell P. D., Buat V., Elbaz D., et al., 2015, A&A, 576, A10. doi:10.1051/0004-6361/201425252
3. Speagle J. S., Steinhardt C. L., Capak P. L., Silverman J. D., 2014, ApJS, 214, 15. doi:10.1088/0067-0049/214/2/15
4. Somerville R. S., Davé R., 2015, ARA&A, 53, 51. https://arxiv.org/abs/1412.2712
5. Kennicutt R. C., 1998, ARA&A, 36, 189. https://arxiv.org/abs/astro-ph/9807187

Skills

- Model multiwavelength emission of AGN
- Write Python scripts to visualise and present your results
- Work in the Linux environment

AP-M14: Weighing clusters of galaxies

Supervisor: Prof. Ben Maughan (Astro)

MSci
60/30

Description

Clusters of galaxies are important cosmological probes and cosmic laboratories with which to study astrophysical feedback loops and the evolution of galaxies. The defining characteristic of a galaxy cluster is its mass, and uncertainty on a cluster's mass is often the limiting factor in cosmological and astrophysical studies. However, measuring the mass of a cluster is challenging as they are $\sim 90\%$ dark matter.

Recent work has led to claims that the X-ray luminosity of some galaxy clusters is much lower than would be expected given their mass (these are called "underluminous" clusters). If true, this would have important implications for our understanding of the feedback processes that affect the X-ray emitting plasma in clusters, and also our ability to use them for cosmological probes. However, it is possible the these claims are incorrect due to uncertainties on the masses of the clusters.

In this project you will investigate this claim by employing different techniques to measure the masses of galaxy clusters. These will be based initially on using the velocities of the member galaxies, but could extend to techniques based on your analysis of X-ray observations of the clusters. This will enable you to confirm or refute the existence of underluminous clusters of galaxies.

Key References

1. S. Andreon et al., Astronomy and Astrophysics, 585, A147 (2016)
   http://adsabs.harvard.edu/abs/2016A%26A...585A.147A
2. J. P. Willis et al., MNRAS, 503, 5624 (2021)
   https://ui.adsabs.harvard.edu/abs/2021MNRAS.503.5624W

Skills

- Coding skills for data analysis and model fitting
- Advanced statistical techniques

AP-M15: Searching for new clusters of galaxies

Supervisor: Prof. Ben Maughan (Astro)

MSci
60/30

Description

Clusters of galaxies are important cosmological probes and cosmic laboratories with which to study astrophysical feedback loops and the evolution of galaxies. Clusters are luminous X-ray sources due to the emission from the hot plasma that makes up $\sim 10\%$ of their mass, and so X-ray surveys of the sky are a powerful way to discover new clusters of galaxies.

The eROSITA telescope is currently performing the first X-ray survey of the entire sky in thirty years, with orders of magnitude greater sensitivity than previous surveys. This will lead to the discovery of $\sim 10^5$ clusters of galaxies. The first survey data from eROSITA will be released in summer 2023, and in this project you will use this data to search for clusters of galaxies. The aim of the project will be to test different methods for detecting clusters in X-ray images, and understand the impact of the selection method on the statistical properties of the samples of clusters that are discovered.

This will be a data-driven project, using a mixture of standard analysis tools and your own code to perform source detection and analysis in large volumes of survey data.

Key References

1. A. Liu et al., Astronomy and Astrophysics, 666, 25 (2022)
   https://ui.adsabs.harvard.edu/abs/2021arXiv210614518L
2. K. Borm et al., Astronomy and Astrophysics, 567, A65 (2014)
   http://adsabs.harvard.edu/abs/2014A%26A...567A..65B

Skills

- Coding skills for data analysis and model fitting
- Advanced statistical techniques
- Image analysis and source detection

AP-M16 :Differences in galaxy cluster populations

Supervisor: Prof. Malcolm Bremer (Astro)
Co-supervisor:

MSci 60

Description

Samples of galaxy clusters can be selected using a range of wavelength-dependent techniques. Each of these can potentially bias the properties of the clusters so selected, potentially biasing our understanding of these systems in subtle (and sometimes quite unsubtle) ways. Recently, samples of clusters have been independently selected using optical/near-IR methods (focussing on galaxy overdensities on the sky), X-ray observations (selected for the strength of the emission from the hot gas trapped in the cluster gravitational potential) and through the Sunyaev-Zel'dovich effect (linked to the total mass of the systems). By comparing the properties of the samples selected in these different ways, the project will explore how the selection techniques bias the properties of the different samples.

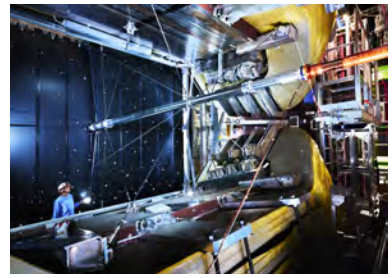
Key References

1. Adami et al., https://arxiv.org/abs/1810.03849
2. Hilton et al., https://arxiv.org/abs/2009.11043
3. Zou et al., https://arxiv.org/abs/2101.12340

Skills

- Astrophysics software
- Python scripting
- Image analysis techniques

Particle Physics (PP)



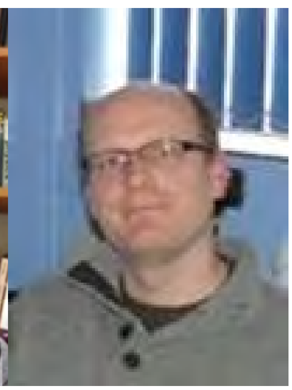
The particle physics group constructs and operates experiments to explore the most basic constituents of matter and their interactions. We are involved in the CMS and LHCb experiments at the CERN LHC, which use complementary approaches to study the current 'standard model' of particle physics and to look for phenomena beyond it. Following on from the discovery of the Higgs boson in 2012, LHC experiments have provided the most stringent tests of the standard model, revealing tantalising hints for new physics. The analysis of the latest data from the LHC is underway, as well as the preparation for new runs at higher intensity in the future.

We are also involved in non-LHC projects. The LZ experiment is designed to directly detect dark matter particles passing through the earth. Its preliminary run in 2022 produced the tightest limits to-date on particle-like dark matter, and new data is currently being taken. The NA62 experiment looks for rare of kaons.

The group also carries out R&D on new upcoming experiments and detector technologies which, among other things, will search for ultra-rare lepton-flavour-violating muon decays and perform precision measurements of the properties of neutrinos. Finally, the particle physics group applies established particle physics techniques in new areas. These include medical physics, security, and environmental risk management.

Projects offered generally cover all of these areas. Our emphasis is on the inclusion of project students into real ongoing research projects (including the analysis of LHC data), offering the best possible experience of a working scientific environment. The projects will often require you to learn new skills (e.g. statistical data analysis, electronics), and most require some ability in software and computing - all useful skills both in particle physics and other careers.

Jim Brooke: DUNE and CMS



Jonas Rademacker: LHCb and DUNE

Joel Goldstein: Mu3e and CMS

Helen Heath: NA62 and CMS

Henning Flaecher: LZ and CMS

Sudan Paramesvaran: CMS and DUNE

Kostas Petridis: LHCb

Jaap Vetlhuis: Detector R&D

PP-M1 : Exploring Strange Decays at CERN

Supervisor: Prof. Helen Heath (Particle)

MSci
60/30

Description

The NA62 experiment at CERN measures the decays of kaons. Although the energies are much lower than the energies at the Large Hadron Collider the precision measurements at NA62 can be compared to very precise theoretical predictions and could therefore find flaws in the standard model of particle physics. The NA62 experiment has been taking data since 2015 and this means that the basic software used for analysing the data is stable and performs well. There are a range of different types of measurement that can be made from improving the understanding of common kaon decay modes to searching for very rare processes such as those that violate lepton flavour conservation. This project would select a potentially interesting decay and either perform a search (in the case of very rare decays) or a measurement of the decay branching ratio (how often the decay occurs). The aim would be to select a topic from those identified by the experiment as interesting but where no-one is currently working meaning that you might be performing an analysis that is unique to you.

The experiment has developed analysis and simulation packages so the task involves considering what features of the signal events would distinguish them from common backgrounds and developing algorithms based on those features. You will be running well-defined software packages but tuning them to select events of interest and reject backgrounds. The code is written in C++ so you will gain experience of this language. You will be able to start from standard analyzers and understand how an analysis works by building on standard code rather than writing software from scratch. Large samples of simulated backgrounds are available to test whether the algorithm successfully rejects events that are not of interest.

Key References

Rare Kaon Decays, Augusto Ceccucci, Annual Review of Nuclear and Particle Science, Vol. 71:113-137, URL
The beam and detector of the NA62 experiment at CERN, E. Cortina Gil et al 2017 JINST 12 P05025, URL

Skills

- Developing computer based analysis as part of a large framework.
- Working as part of an international collaboration
- Computational Coding Skills

PP-M2 : Modelling DNA damage for ^{225}Ac therapy

Supervisor: Prof. Jaap Velthuis (Particle)
Co-supervisor: Dr. Chiara De Sio

MSci 60

Description

A novel trend in radiotherapy is the use of α particles. α particles deposit a lot of dose, and thus do a lot of damage, in a limited volume. This spares the healthy tissue. In our group we are studying the radiation damage at the DNA level using advanced Monte Carlo modelling using Geant4-DNA together with colleagues in Japan and Australia. Our studies include damage studies of implanted α sources, in particular DaRT. In DaRT seeds containing ^{224}Ra are implanted. The ^{224}Ra decays, which leads to a cascade of α emissions. The daughters of each decay diffuse a bit through the cells leading to a reasonable treatment volume. We have calculated the DNA damage to the cells in DaRT using Geant4-DNA. There is a second suitable decay chain for treatment like this. That cascade starts with ^{225}Ac. In this project you will modify the existing simulations for DaRT sources to simulate the damage of ^{225}Ac and compare the two treatment methods.

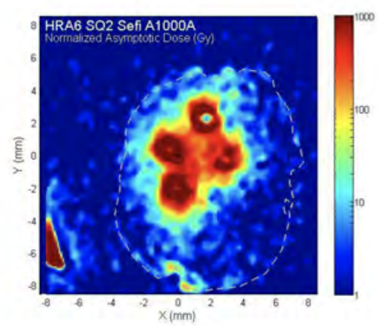


Figure shows a dose distribution calculated for 4 DaRT seeds.

Key References

1. Scheinberg DA, McDevitt MR. Actinium-225 in targeted alpha-particle therapeutic applications. Curr Radiopharm. 2011 Oct;4(4):306-20
   https://doi.org/10.2174/1874471011104040306

2. A. Popovtzer et al, Initial Safety and Tumor Control Results From a First-in-Human Multicenter Prospective Trial Evaluating a Novel Alpha-Emitting Radionuclide for the Treatment of Locally Advanced Recurrent Squamous Cell Carcinomas of the Skin and Head and Neck, Int J Radiation Oncol Biol Phys, Vol. 106, No. 3, pp. 571e578, 2020
   https://doi.org/10.1016/j.ijrobp.2019.10.048

Skills

- Monte Carlo techniques
- Data analysis
- Computational coding skills required

PP-M3 : Modelling DNA damage for Helium ion beam therapy

Supervisor: Prof. Jaap Velthuis (Particle)
Co-supervisor: Dr. Chiara De Sio

MSci 60

Description

Helium ion beam therapy is a re-emerging radiotherapy modality for the treatment of cancer. Most patients receive radiation treatment with X-rays. However, proton therapy has been shown to be much more effective in certain cases due to the Bragg peak phenomenon. This allows to deposit most of the energy in the tumour. Since the start of proton therapy, many different ion beam treatments are under investigation. Helium ion beams are one of them. The provide a narrower Bragg peak and are cheaper to provide than heavier ion beams. Studying the damage to the DNA due to radiation is a scientifically hot topic.

In our group we are studying the radiation damage at the DNA level using advanced Monte Carlo modelling using Geant4-DNA together with colleagues in Japan and Australia. Our studies include damage studies of implanted α sources. In this project you will modify the existing simulations for implanted α sources to simulate the damage of Helium ion beams. You will then compare the results with the damage from implanted α sources and proton beams to come to treatment recommendations.

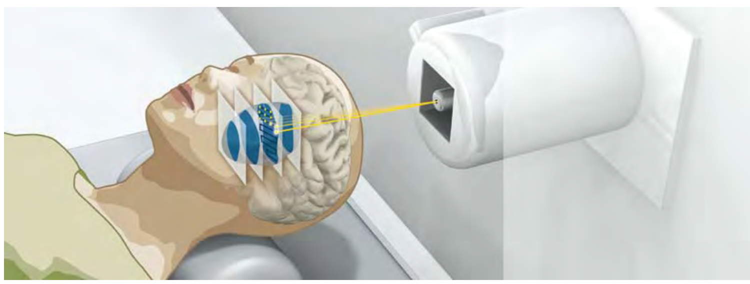


Figure shows a schematic treatment.

Key References

1. Mairani A, et al. Roadmap: helium ion therapy. Phys Med Biol. 2022 Aug 5;67(15) https://doi.org/10.1088/1361-6560/ac65d3

2. Tessonnier, T., Mairani, A., Chen, W. et al. Proton and helium ion radiotherapy for meningioma tumors: a Monte Carlo-based treatment planning comparison. Radiat Oncol 13, 2 (2018) https://doi.org/10.1186/s13014-017-0944-3

Skills

- Monte Carlo techniques
- Data analysis
- Computational coding skills required

PP-M4 : Analysing Data From ProtoDUNE at CERN

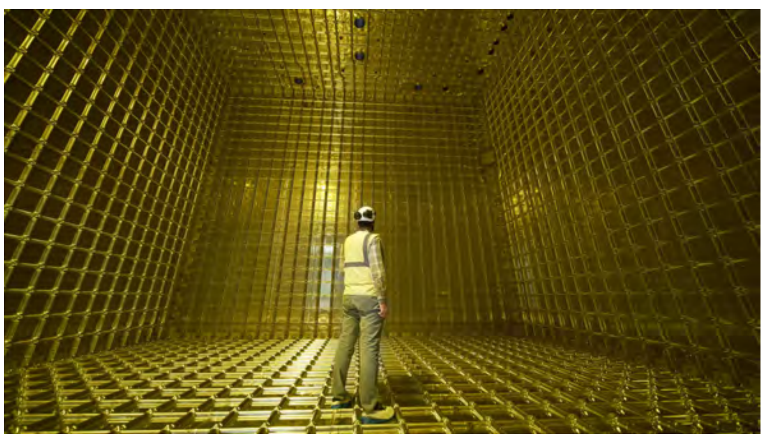
Supervisor: Dr. Jim Brooke (Particle)
Co-supervisor: Dr. Stoyan Trilov

MSci
60/30

Description

The Deep Underground Neutrino Experiment (DUNE) is a $Bn leading edge international experiment under construction in the USA [1]. The goal is to measure neutrino oscillations to world-leading precision, resolve the neutrino mass hierarchy, discover CP violation in the lepton sector (potentially explaining the matter/anti-matter asymmetry in the Universe), and hopefully to observe neutrinos produced in Supernovae [2]. The experiment involves producing a neutrino beam at Fermilab (nr Chicago), and measuring it at a Far Detector, located 1300km away in South Dakota, at a depth of 1.5km undergound. The Far Detector comprises 70,000 tonnes of liquid Ar, which acts as a target for the neutrinos, and as a time projection chamber to measure ν-Ar interactions with exquisite precision. ProtoDUNE is a 10% scale prototype of the DUNE Far Detector, which was constructed at CERN in 2018. It received beams from the CERN SPS ($p^+, \pi^+, K^+, \mu^+, e^+$) during Run 1 in 2019 [3]. The detector design and electronics is currently being updated to the final DUNE specifications, and it will receive beam again during Run 2 in Spring 2024, while this project is ongoing.

In this project we will develop techniques for identifying and measuring the properties of particles produced in collisions of the SPS beams with Ar nuclei. Such interactions will produce a variety of different particle species, which can be detected using a variety of different reconstruction techniques. These studies may lead to more sophisticated analyses such as measurement of interaction cross-sections (eg. $\sigma(K^+ \mathrm{Ar} \to X)$). Data analysis techniques will be developed initially using existing Monte-Carlo simulation and datasets from ProtoDUNE Run 1. Later in the project, analysis will move on to ProtoDUNE Run 2 datasets.



Interior of the protoDUNE cryostat before detector installation and filling with liquid Argon.

Key References

1. https://www.dunescience.org/
2. DUNE Collaboration, *JINST* **15**, T08008 (2020) URL
3. DUNE Collaboration, *JINST* **15**, P12004 (2020) URL

Skills

- Data analysis
- Python programming

PP-M5 : Detecting Neutrinos (and Dark Matter) with Liquid Argon at the Large Hadron Collider

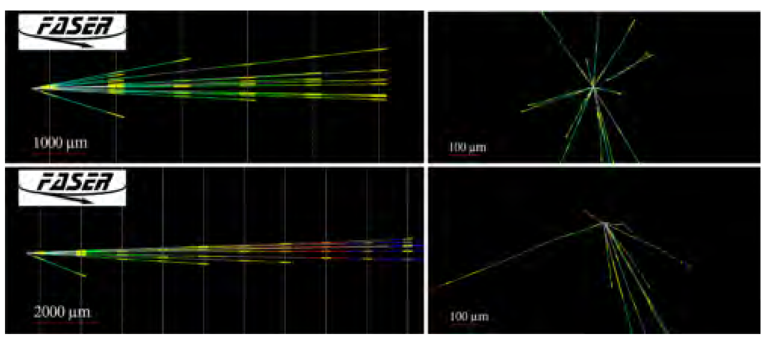
Supervisor: Dr. Jim Brooke (Particle)

MSci 60

Description

Neutrinos are the least well measured particles in the Standard Model, due to the experimental challenges brought about by their tiny mass and weak couplings to other particles. Neutrino experiments typically rely on nuclear reactors, or on delivering high intensity beams to solid targets. Although neutrinos are also produced in colliders such as the Large Hadron Collider (LHC) at CERN, they will pass through the detectors without interacting. Their presence generally has to be inferred from a momentum imbalance of the other particles in an event. Recently, however, a detector placed on the axis of the LHC colliding beams, far downstream of the collision point, was able to make the first direct detection of neutrino production at a collider [1]. A ”Forward Physics Facility” (FPF) has been proposed in which multiple experiments in a similar location would perform searches for dark matter, and other physics beyond the Standard Model, as well as measure neutrino properties [2]. The FLArE detector is a proposed liquid Argon time projection chamber for the FPF, capable of detecting neutrinos and dark matter [3]. A program to develop the conceptual designs of FLArE and other FPF detectors is now underway, with the goal of constructing them before LHC Run 4, starting in 2030.

In this project, you will simulate the proposed FLArE detector at the LHC and the physics to which it is sensitive. The initial goal will be to characterise the main physics processes which will be observed, and estimate event rates, in order to specify requirements for the FLArE data-acquisition system. This may lead to design of a ”trigger” strategy, ie. real-time event analysis and selection, to ensure events of interest are stored. Further extensions are possible, including studies of the experimental sensitivity to neutrinos, or dark matter.



Candidate neutrino events produced by the LHC and detected by the FASER experiment (taken from [1]).

Key References

1. FASER Collaboration, *Phys. Rev. D* **104**, L091101 (2021) URL
2. J. L. Feng et. al., *J. Phys. G: Nucl. Part. Phys.* **50** 030501 (2023) URL
3. B. Batell, J. L. Feng, and S. Trojanowski, *Phys. Rev. D* **103**, 075023 (2021) URL

Skills

- Data analysis
- Monte-Carlo simulation
- Python programming

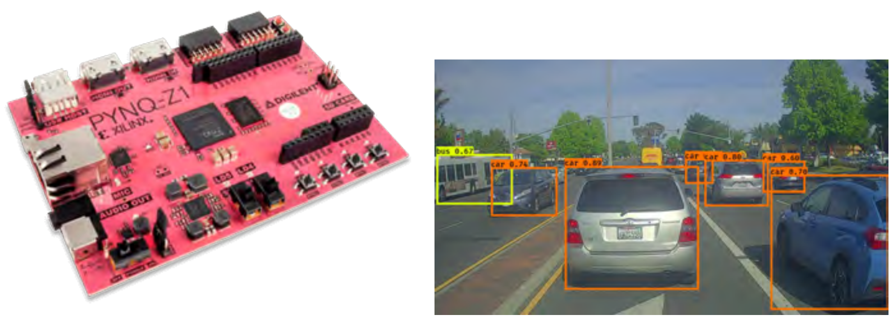
PP-M6 : Computer Vision for Particle Detectors

Supervisor: Dr. Jim Brooke (Particle)

MSci 60

Description

Image recognition techniques based on machine learning - aka computer vision - are increasingly ubiquitous. Particle physics applications have been studied for fast data selection in the context of large experiments, for example at the LHC [1]. These applications rely on arrays of high specification computers or custom electronics at high cost. However, applications may arise associated with smaller scale detectors, which can be run on embedded computers or cheap commercial electronics cards. For example, applications associated with medical sensors, radiation detectors, etc.
The goal of this project is to demonstrate image recognition on alow cost System-on-Chip (SoC) device. SUch devices are available which combine FPGA (Field Programmable Gate Array) fabric with a lower power embedded CPU. Although the CPU is not capable of running sophisticated ML network itself, these functions can be offloaded to the programmable FPGA part of the device. The project will involve training a CNN (or more sophisticated YOLO - You Only Look Once - network [2]) on a selection of images from different potential applications and studying its performance. You will then proceed to implement the network on a PYNQ development board [3] to demonstrate its capability to detect images of interest in a realistic environment.



(1) The PYNQ development board. (2) Car detection using YOLO (from https://github.com/shambhavimalik/Autonomous-Driving-Car-Detection)

Key References

1. J. Duarte et. al., *JINST* **13** P07027 (2018) https://doi.org/10.1088/1748-0221/13/07/P07027
2. J. Redmon et. al., You Only Look Once: Unified, Real-Time Object Detection https://doi.org/10.48550/arXiv.1506.02640
3. http://www.pynq.io/

Skills

- Python programming
- Machine learning
- Embedded systems

PP-M7 : Identifying Higgs Bosons with Machine Learning at the LHC.

Supervisor: Dr Sudan Paramesvaran (Particle)
Co-supervisor: Dr. Emyr Clement

MSci
60/30

Description

The CMS detector has been operating at the Large Hadron Collider for a decade, resulting in a wide range of ground-breaking measurements, including the discovery of the Higgs boson. The volume of data produced by CMS is enormous, at 40TB/s, far in excess of what can be recorded on disk. A “trigger” system is therefore required, which analyses and selects proton collisions as they are produced, to ensure crucial physics is stored for later analysis. An upgrade of the system is currently underway, which will increase the processing power of the system by over an order of magnitude. The system must cope with the huge increase in data expected from the high-luminosity LHC, which begins operation in 2029.This project will focus on developing Machine Learning algorithms for the future CMS trigger system, assessing their performance using simulations, as well as real data already recorded by CMS. These algorithms may have a significant impact on the physics programme of the high-luminosity LHC. In particular, our recent work indicates a significant improvement in selecting events containing two Higgs bosons, which both decay to b-quarks. Such events allow the measurement of the Higgs self-coupling, which is a direct probe of the Higgs potential. This is one of the headline measurements of the HL-LHC, so an improvement in sensitivity will be of great scientific interest.This project can be tailored more to using Machine Learning in Python/C++ but can also involve FPGA (Field Programmable Gate Arrays) programming if there is interest. FPGAs are cutting edge silicon chips which house the algorithms used in the CMS trigger, there are several in the in-house electronics particle physics lab here at Bristol for use in this project.

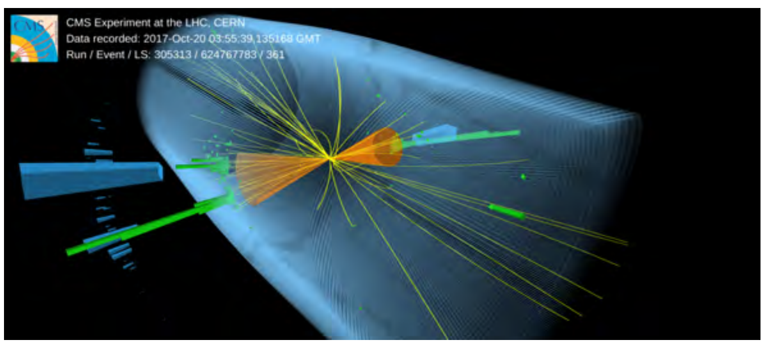


Figure shows a dandidate event in which a Higgs boson produced at large transverse momentum decays into a collimated bottom quark-antiquark pair

Key References

1. Bass, S.D., De Roeck, A. & Kado, M. The Higgs boson implications and prospects for future discoveries. Nat Rev Phys 3, 608–624 (2021)
   https://doi.org/10.1038/s42254-021-00341-2

2. Bologna S. Overview of the HL-LHC Upgrade for the CMS Level-1 Trigger. PoS TWEPP2019 (2020) 147
   http://cds.cern.ch/record/2718197

Skills

- Programming in C++/Python
- Experimental Particle Physics knowledge
- Optional: FPGA Programming with VHDL/HLS

PP-M8 : Using Machine Learning to identify double Higgs boson production at the LHC.

Supervisor: Dr Sudan Paramesvaran (Particle)
Co-supervisor: Dr. Florian Bury

MSci
60/30

Description

The CMS detector has been operating at the Large Hadron Collider (LHC) for a decade, resulting in a wide range of ground-breaking measurements within the standard model (SM), most notably the discovery of the Higgs boson (H) ten years ago. While a major success, half a century after its prediction, several important questions are left unanswered by the SM. The study of the Higgs boson is one of the most promising path towards a deeper understanding of spontaneous symmetry breaking. Its self-interaction, through the simultaneous production of a pair of Higgs bosons (HH), has yet to be measured and any deviation from its SM prediction could be a sign of new physics. The search for HH production in the proton collisions of the LHC is made challenging by the rarity of the process and the multiplicity of the decay channels.
The bbWW decay channel is of particular interest and major gains in sensitivity have recently been obtained by enlarging the search region to cases where one W boson decays hadronically. The combinatorial challenge that represents the jet-parton assignment (JPA), namely to correctly assign each reconstructed jet to the correct mother particle (H or W boson), is not fully resolved by the current method. This project will focus on improving the JPA, notably by using modern Machine Learning (ML) methods in Python and more specifically Deep Neural Networks (DNN), and possibly with more cutting-edge methods such as Graph Neural Networks (GNN) and adversarial training. The method will be tested within a real analysis framework and its performance compared with the current sensitivity of the CMS analysis on Run-2 data.

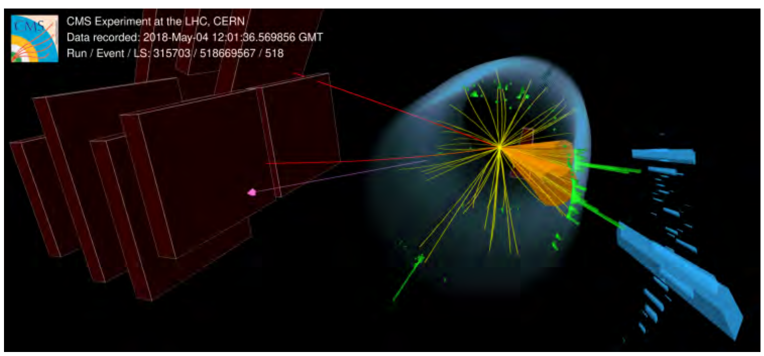


Figure shows a HH candidate event in which two muons (red) and missing momentum (pink) could represent the signature of the decay of a Higgs boson to a pair of W bosons, and the two b-jets (orange) the signature of the decay of a Higgs boson to a pair of bottom quarks.

Key References

1. The CMS Collaboration. A portrait of the Higgs boson by the CMS experiment ten years after the discovery. Nature 607, 60–68 (2022)
https://doi.org/10.1038/s41586-022-04892-x

2. Di Micco, B. et al. Higgs boson potential at colliders: status and perspectives. Reviews in Physics 5, 100045 (2020),
https://doi.org/10.1016/j.revip.2020.100045

Skills

- Programming in Python (C++)
- Experimental Particle Physics knowledge
- Machine Learning knowledge

PP-M9 TORCH pattern recognition

Supervisor: Prof. Jonas Rademacker (Bristol Particle Physics
Co-supervisor: Dr. Marco Adinolfi

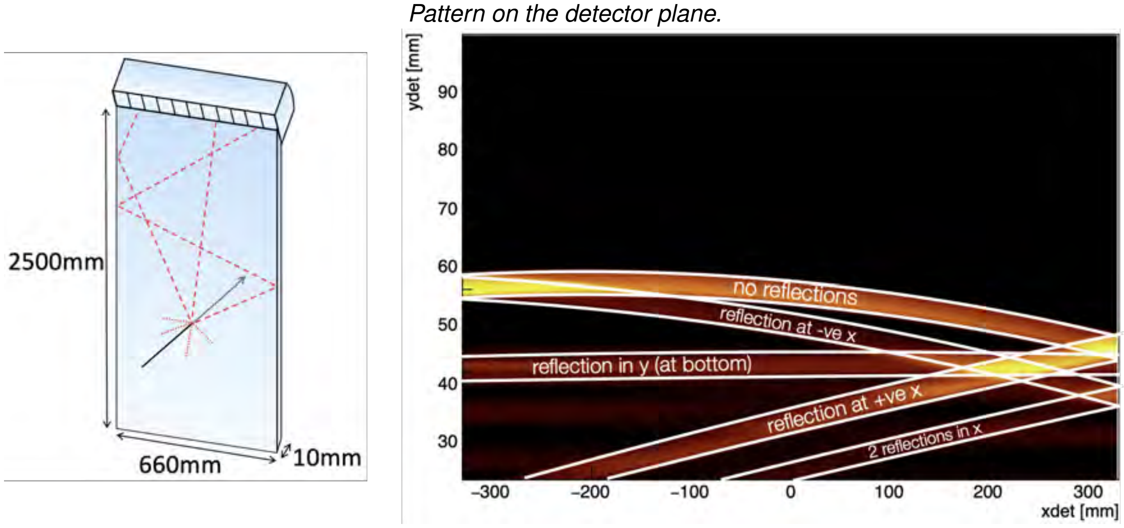
MSci
60/30

Description

TORCH is a novel time of flight detector technology that aims to measure the time a particle passes through it with a precision of 15ps - light travels less than 5mm in that time. This information is used to measure the speed of the particle (given that time and position of its origin are known). The detector uses Cherenkov light produced as the particle traverses a 10mm quartz pane. This gets internally reflected until it leaves the quartz pane at the top, where it passes through some optics onto a photo detector plane, where position and time of arrival are recorded. The pattern on the detector plane (and its interpretation in terms of reflections on the edges of the TORCH module) is illustrated in the figure. TORCH is intended for a future upgrade of the LHCb experiment, where protons collide 40 millions times per second, and each collisions produce many charged particles, each creating a pattern as illustrated in the figure. Reconstructing these patterns, and interpreting them in terms of particle speeds, is a formidable task. This project is about using cutting edge computing technologies (such as Intelligence Processor Units) and efficient algorithms (potentially involving machine learning) to speed up this event reconstruction.

This project is suitable for students with good programming skills in python and/or in C++. Experience with environments such as PyTORCH or TensorFlow would be an asset.

Left: TORCH module. The arrow represents a charged particle, the red dashed lines indicate photon paths. Right: Pattern on the detector plane.



Key References

1. "TORCH, a novel time of flight detector for LHCb upgrade II", PoS ICHEP2022 347
2. "Studying the Potential of Graphcore IPUs for Applications in Particle Physics", Comput.Softw.Big Sci. 5 (2021) 1, 8
3. Graphcore's website describing IPUs

Skills

- Programme fast pattern recognition algorithms on highly parallel computing architectures.
- Particle Physics detectors.

PP-M10 De-noising data

Supervisors: Prof. Jonas Rademacker (Bristol Particle Physics
Co-supervisor: Dr. Alex Marshall

MSci
60/30

Description

The computing requirements in high energy physics (HEP) are astronomical. The next phase of the LHCb experiment at CERN implements a revolutionary real-time analysis paradigm, where the full event reconstruction, calibration, selection will be done in all its detail on all data (without a pre-selection in a fast-but-primitive trigger). This means processing several Terabytes of data per second from the track reconstruction to the ultimate selection of signal decays. Potential speed-ups could be achieved using auto-encoders.

Architecture of a de-noising auto-encoder

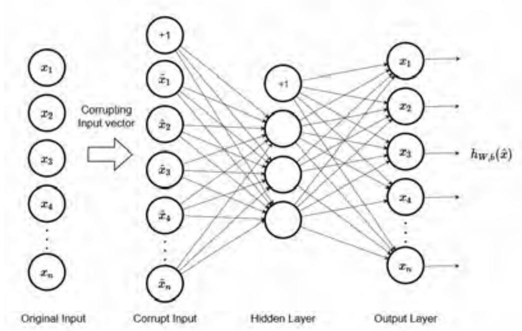


Image from Kumar et al, in IC3 proceedings 2014

- Auto-encoders can be used to de-noise data and thus speed up pattern recognition and remove backgrounds.
- The use of auto-encoders early in the data processing chain has the potential to significantly reduce the data volume that needs to be read out from the detector.

We will use the TORCH detector (see project PPM01) as an example system. TORCH is a novel time of flight detector technology that uses Cherenkov light to measure the time a particle passes through it with a precision of 15ps. It produces patterns in three dimensions (two position and one time dimension), which provides an additional challenge compared to the more common two dimensional patterns encountered in picture processing.
Depending on the interest of the student we might also consider other kinds of machine learning algorithms for pattern recognition in TORCH, such as Graph Neural Networks.

This project is suitable for students with good programming skills in python and/or C++. Experience with environments such as Keras, PyTORCH or TensorFlow would be an asset.

Key References

1. "TORCH, a novel time of flight detector for LHCb upgrade II", PoS ICHEP2022 347
2. A web search for "denoising auto encoders" will return plenty of useful results, such as https://paperswithcode.com/method/denoising-autoencoder

Skills

- Programming of fast pattern recognition algorithms on highly parallel computing architectures.
- Learn about modern particle physics detectors.

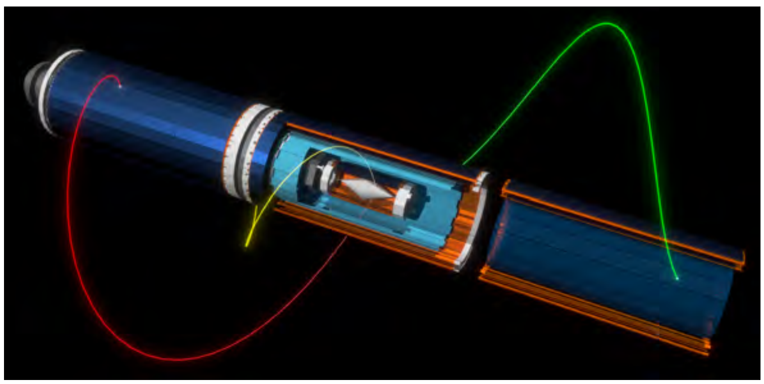
PP-M12 : New Physics with Mu3e

Supervisor: Prof. Joel Goldstein (Particle)
Co-supervisor: Dr. Kostas Petridis

MSci
60/30

Description

A number of low-energy but high-intensity experiments are starting to stretch the standard model of particle physics to breaking point. One such experiment is Mu3e, which will use the world's most intense continuous supply of muons. It will apply cutting-edge imaging and data processing technology to look for the one-in-a-trillion (or rarer) decay of a muon to three charged electrons/positrons with no neutrinos. If detected, such a decay would show that lepton flavour conservation does not hold, and that the standard model is wrong.
However, with the world's largest collection of muon decays and the latest improvements in detector technology, there are many other models of physics beyond the standard model to which Mu3e would be sensitive. Proposed new particles such as "familons" and "dark photons" may appear directly or as subtle deviations in the data, but have not yet been extensively studied.
In this project, you will conduct simulations of exotic new physics models and their interaction with the Mu3e detector. You will design data analysis strategies, establishing whether or not Mu3e will be sensitive to such models and how much data will be required.



Simulation of a $\mu^+ \to e^+e^-e^+$ decay in the Mu3e detector.

Key References

1. K. Arndt et al, Nucl. Instr. Meth. A 1014, 165679
   https://doi.org/10.1016/j.nima.2021.165679

2. J. Jaeckel, PLB 732, 1
   https://doi.org/10.1016%2Fj.physletb.2014.03.005

Skills

- Computational coding skills required
- Simulation
- Pythia/C++

PP-M13 : Mu3e Commissioning

Supervisor: Prof. Joel Goldstein (Particle)

MSci
60/30

Description

A number of low-energy but high-intensity experiments are starting to stretch the standard model of particle physics to breaking point. One such experiment is Mu3e, which will use the world's most intense continuous supply of muons. It will apply cutting-edge imaging and data processing technology to look for one-in-a-trillion (or rarer) muon decays that are not supposed to be observed in the standard model. If detected, such decays would show that lepton flavour conservation does not hold, and that the standard model is wrong.
The Mu3e experiment is currently under construction, and will start taking data in 2024. Bristol are developing the test equipment for the production of Mu3e's advanced silicon pixel detectors. In this project, depending on the exact timescale for the experiment, you will either be commissioning the test equipment and analysing the data from the pixel detectors in the lab, or working on the first data to come from detectors installed in the beamline.
This is an opportunity to be involved at a key stage in a new, ground-breaking experiment, and gain experience of some of the latest hardware and software technologies with applications far beyond the field of particle physics.

Figure shows a prototype Mu3e silicon pixel detector under test in Bristol

Key References

1. K. Arndt et al, Nucl. Instr. Meth. A 1014, 165679
   https://doi.org/10.1016/j.nima.2021.165679
2. H. Augustin et al, Nucl. Instr. Meth. A 936 681
   https://doi.org/10.1016/j.nima.2018.09.095

Skills

- Electronics
- Solid state detectors
- Fast digital data acquisition

PP-M14 : Flavour anomalies and charming loops

Supervisor: Dr. Konstantinos A. Petridis (Particle)	MSci 60/30

Description

Recent measurements by the LHCb experiment [1] at CERN's LHC involving decays of B-mesons (bound states of a bottom and up or down quark) such as $B^0 \to K^{*0}\mu^+\mu^-$ [2] are showing large deviations from the predictions of the Standard Model of particle physics [3] (flavour anomalies). These tensions could indicate the presence of a new fundamental interaction between quarks and leptons or could be due to a problem with calculations of the so called charm-loop contributions in the SM predictions. These predictions are fiendishly complex to compute and to categorically claim the existence of a new type of fundamental interaction the intractable aspects of the calculations need to be tested against the data.
The aim of this project is to develop techniques that are required to measure the dimuon mass spectrum in the decay $B_c \to \mu^+\mu^- e^+\nu_e$ using the LHCb detector. This measurement can provide important input to the theory calculations mentioned above.
You will employ novel reconstruction algorithms that help select these decays from the large amount of background. For instance, by exploiting the line of flight of the B_c meson you should be able to reconstruct the momentum of the neutrino and use that to discriminate against backgrounds [4].
You will use a mixture of simulation and LHCb data to develop and calibrate the performance of your reconstruction techniques and study the large number of background decays. You will also use machine learning methods in order to suppress the backgrounds while maintaining a large fraction of the signala decays.

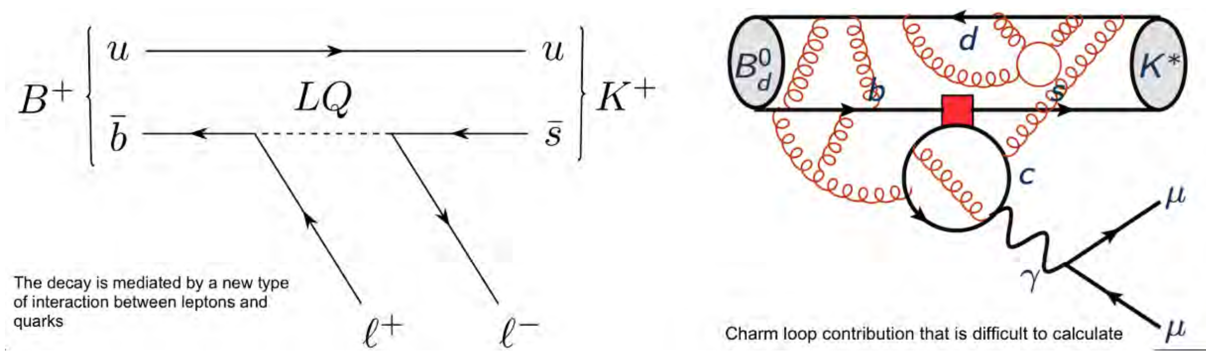


Figure illustrating a (left) a new interaction (right) a charm-loop contribution to $B \to K\mu^+\mu^-$ decays

Key References

1. LHCb Collaboration, *Int.J.Mod.Phys.A 30 (2015) 07, 1530022* https://arxiv.org/abs/1412.6352
2. LHCb Collaboration, Phys. Rev. Lett. 125, 011802 (2020) https://arxiv.org/abs/2003.04831
3. Gubernari et al, *JHEP 09 (2022) 133* https://arxiv.org/abs/2206.03797
4. LHCb Collaboration *Phys. Rev. Lett. 120, 121801 (2018)* https://arxiv.org/abs/1711.05623

Skills

- Programming in Python
- Advanced Machine Learning methods
- Experimental Particle Physics knowledge
- Monte-Carlo simulation

PP-M15 : Generative Neural Networks for fast but reliable simulations

Supervisor: Dr. Konstantinos A. Petridis (Particle)

MSci
60/30

Description

Generative networks are a class of machine learning algorithms designed to generate samples according to a multidimensional function, given a randomly distributed input sample. These algorithms were initially developed by the machine learning community for the purpose of image generation.
Particle physics simulations use computationally expensive algorithms to simulate the collisions and the subsequent particle interactions with the detector material. These simulated events are used for the design, optimisation and analysis of vast datasets. As such, huge simulation samples are imperative.
The computing demands of the simulation of high energy physics (and astrophysics) experiments are increasing exponentially. Recent algorithmic improvements that take advantage of high performance computing resources aim at reducing simulation time by one order of magnitude. However, this improvement is not sufficient to meet the simulation demands of future particle physics experiments, such as those at the High Luminosity LHC. Generative neural networks offer an alternative approach to simulation by modelling non-analytical functions in a computationally efficient way, capable of increasing computing speed by six orders of magnitude [1] with minimal loss in fidelity.
The aim of this project is to develop a new Generative Network to simulate the response of 100s of charged particles per collision, as they propagate through the Ring Imaging Cherenkov (RICH) detectors of the LHCb experiment at CERN's LHC. You will use a mixture of detailed simulated and real data events from LHCb to develop and train the Generative Network studying a multitude of architectures and benchmark their performance on both GPUs and IPUs [3].

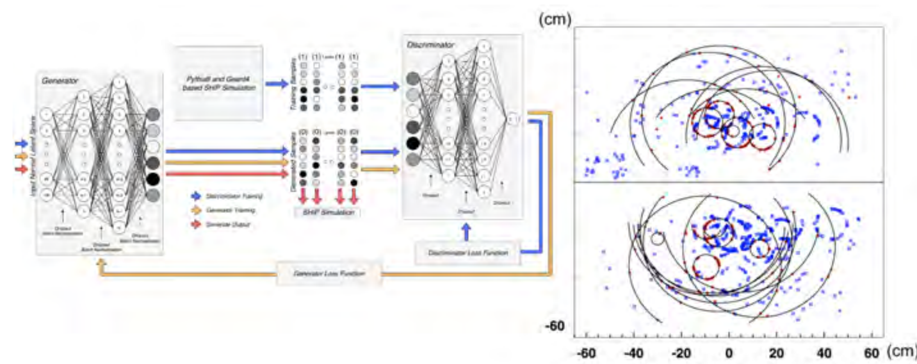


Figure illustrating (left) the architecture of a Generative Adversarial Neural network [1] (right) the Cherenkov photons detected by LHCb's RICH detector [2]

Key References

1. SHiP Collaboration, *JINST 14 (2019) P11028* https://arxiv.org/abs/1909.04451
2. LHCb Collaboration, Phys. Rev. Lett. 125, 011802 (2020) https://arxiv.org/abs/2205.13400
3. Graphcore, *Intelligence Processing Unit* https://www.graphcore.ai/products/ipu

Skills

- Programming in Python
- Advanced Machine Learning methods
- Experimental Particle Physics knowledge
- Monte-Carlo simulation

PP-M16 : Searches for New Physics with Machine Learning at the LHC

Supervisor: Prof. Henning Flaecher (Particle)

MSci
60/30

Description

The Large Hadron Collider (LHC) at CERN is the world's most powerful particle accelerator. Following an upgrade it resumed colliding protons at a centre of mass energy of 13.6 TeV in 2022. This offers a great opportunity develop new techniques for searches for new physics beyond the Standard Model (SM) of particle physics. We believe the SM is incomplete because of, e.g., the fine-tuning of the Higgs boson mass and the lack of a viable dark matter candidate. Supersymmetry and other theories that solve these problems predict production of new particles at the LHC. However, detecting a signal of the new particles will be very challenging because it will be buried under a large background of known SM processes. Furthermore, the new particles might not interact with detector material and only appear as ”missing energy”. The aim of this project is to develop new techniques for distinguishing a potential new physics signal from the SM background. You will investigate how machine learning can take advantage of subtle differences between a new physics signal and SM background and improve the sensitivity of the new physics searches. You will have access to simulated data of the CMS experiment and will be using modern data analysis and machine learning tools in Python.

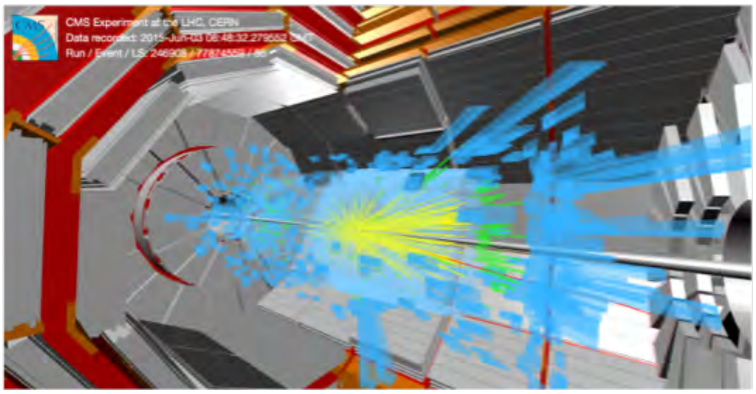


Figure shows a proton-proton collision at the LHC as recorded with the CMS detector.

Key References

1. Search for Higgs boson decays to invisible particles: https://cds.cern.ch/record/2827418/files/HIG-21-007-pas.pdf
2. Search for top squark production in fully-hadronic final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV: https://arxiv.org/abs/2103.01290
3. Applications of machine learning algorithms in high energy physics: http://inspirehep.net/record/1680302,https://arxiv.org/abs/1807.02876

Skills

- Computational coding skills, in particular programming in Python
- Data analysis and visualisation in Python, use of NumPy, Pandas, Jupyter Notebooks
- Machine learning with Keras, TensorFlow, Scikit-learn

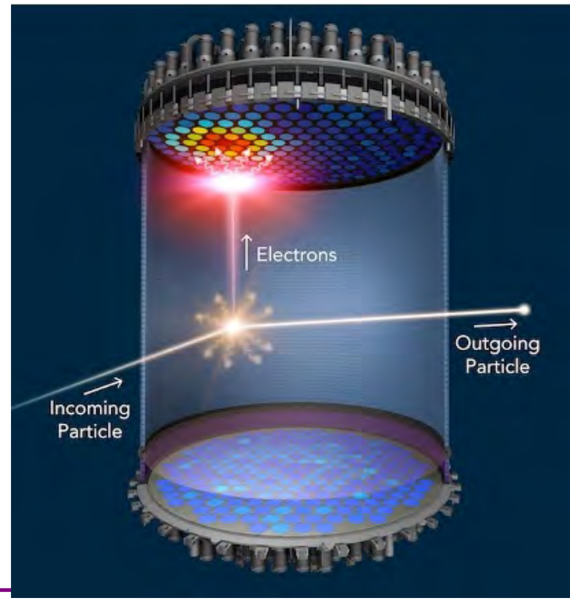
PP-M17: Event classification at the LUX-ZEPLIN experiment

Supervisor: Prof. Henning Flaecher (Particle)

MSci
60/30

Description

The nature of Dark Matter is one of the most intriguing open questions in particle physics and cosmology. One way to search for dark matter is to look for evidence of dark matter particles scattering off nuclei, resulting in ionization and scintillation light signals that can be detected with photo multiplier tubes. The LUX-ZEPLIN (LZ) experiment in the Homestake mine at SURF, South Dakota follows this approach. One of the main challenges for the experiment lies in distinguishing signals from dark matter collisions with the xenon nuclei from those of backgrounds, such as neutrons or gamma rays. Modern experiments have many thousand channels that register signals from an interaction. You will work with simulated data samples of a number of background processes and study the signals they leave in the detector. The goal of this project is to develop an algorithm that is able to distinguish signals from different types of background processes, and ideally compare results obtained from simulation with real data.



Key References

1. First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment: https://arxiv.org/abs/2207.03764

2. Background determination for the LUX-ZEPLIN (LZ) Dark Matter Experiment: https://arxiv.org/abs/2211.17120

3. Projected WIMP sensitivity of the LUX-ZEPLIN dark matter experiment: https://arxiv.org/abs/1802.06039

Skills

- Computational coding skills, in particular programming in Python
- Data analysis and visualisation in Python, use of NumPy, Pandas, Jupyter Notebooks
- Potential of using machine learning with Keras, TensorFlow, Scikit-learn

PP-M18: Preparing for HIKE

Supervisor: Prof. Helen Heath (Particle)

MSci
60/30

Description

HIKE is a proposed series of high intensity kaon experiments at the CERN Super Proton Synchrotron, building on a long history of investigating kaons with the current experiment being NA62. With kaons precision measurements can be made to explore new physics at masses larger than those that can be directly measured at the LHC.

There are many ongoing studies in preparation for the HIKE proposal – the formal document that will be presented to CERN. A flexible simulation has been developed by the HIKE collaboration to investigate potential experiments.

This project would look at the decays $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ to understand the sensitivity of HIKE Phase 2 to these decays, including acceptance and background estimates. So far there has been little investigation of this so it would be possible to make a useful contribution to this project on the timescale of a student project.

Key References

1. HIKE, High Intensity Kaon Experiments at the CERN SPS Letter of Intent https://arxiv.org/pdf/2211.16586.pdf

2. NA62 experiment https://na62.web.cern.ch/na62/Home/Home.html

Skills

- Computational coding skills, in particular programming in C++
- Developing computer based analysis as part of a large framework.
- Working as part of an international collaboration

QUANTUM ENGINEERING TECHNOLOGIES (QET)

The bizarre predictions of quantum mechanics are counter-intuitive to our everyday experiences and yet turn out to be fundamental to our understanding of the world around us. For example, quantum mechanics predicts that a particle can exist simultaneously in more than one place at the same time (superposition) or can exhibit wave- or particle-like behaviour, depending on how we observe it (wave-particle duality). Even more remarkably, we have now demonstrated that two or more quantum particles can share a connection through their combined quantum state even when they are separated by a distance, so that measurement of one of the particles influences the state of the other(s) (entanglement). Paradoxically, although quantum mechanics challenges our classical conceptions of how the world works, the existence of the classical observer in quantum mechanics still remains a fundamental tenet of the theory.

Quantum information science has emerged over the last two decades to investigate whether these weird behaviours can be usefully exploited. Work has been done to see how quantum bits (qubits) can be used to encode, transmit and process information with applications in secure communications, the simulation of complex molecules, high-precision measurement and computation. Photons make excellent qubits since they are well isolated from the environment and their quantum mechanical state can easily be manipulated. What began as an esoteric theory is now widely viewed as at the forefront of a new quantum technological revolution. With the UK government making over £500M investment in the field of quantum technologies, the race is on to turn these counter-intuitive ideas in fundamental physics into practical devices. Already, photons are being used to make more precise measurements, to transmit cryptographic keys with absolute security guaranteed by the laws of physics, to simulate the vibrational states of molecules, and eventually, an interlinked set of entangled photons will form a quantum computer, a machine capable of performing calculations that no classical computer will ever be able to do.

In the Quantum Engineering Technology Labs (QET Labs) a wide variety of research is undertaken into the underpinning theory, technology and practical applications of quantum information science. Our group also works within the related realms of quantum sensing, where quantum systems (like photons and atoms) are used to make precise measurements of inertial quantities, electromagnetic fields, and the concentration of chemicals in the environment. Additionally, researchers in QET Labs are working towards the quantum simulation of interesting physical systems with atoms and photons.

Within the group over 100 researchers and students work on developing the fundamental science of measurement, communication and computing technologies. As the world leader in quantum photonics, our work is routinely published in leading multidisciplinary science journals, including Science and Nature, and receives numerous national and international research awards. We are involved in three of the four National Quantum Technology Hubs, and our academics comprise 5 of 14 EPSRC Quantum Technology Fellows. Our work has also helped establish a growing quantum technology cluster in Bristol, with several spin-out companies emerging from our research group and the establishment of the £43M Quantum Technologies Innovation Centre, to collaborate with leading technologies companies in the process of taking quantum research from the lab and into the commercial world. However, photons is not all that we do: QET Labs has robust research groups exploring technologies based on quantum dots, atoms and molecules, and nitrogen-vacancy (NV) centres in diamond.

QET Labs remains at the forefront of quantum science and technology, and we are focussed on pushing the boundaries of scientific knowledge, whilst providing a route towards practical exploitation when the opportunity arises. Project students who join QET Labs will be involved in ambitious ongoing research projects, working closely with graduate students and post-docs, to get a real experience of working in a creative and world-class research environment.

WHO WE ARE

Prof. Anthony Liang (left): *photonic quantum technologies, quantum computing and simulation, quantum science and information*. **Prof. Jonathan Matthews** (right): *photonic quantum technologies, quantum sensing and measurement, quantum science and information*

Prof. Ruth Oulton: *Quantum Emitters, Quantum communications, Quantum simulation, Quantum Devices, Compound Semiconductor Nanophotonics*

Dr Jorge Barreto: *Quantum Devices, Quantum Systems Engineering, Single Photon Detectors, Photon Sources, Cryogenics, Scalability*

Dr Giacomo Ferranti: *Quantum optics, integrated quantum photonics*

Dr Jon Pugh: *Quantum Photonics, Classical Photonics, Integrated Photonics, Integrated Photon Sources & Detectors, Cleanroom Fabrication, Microfluidics*

Dr Carrie Weidner: *atomic physics, quantum sensing, simulation, and control*

QET-M1: Controlling atoms with light

Supervisor: Dr Carrie Weidner (QET)

MSci
60/30

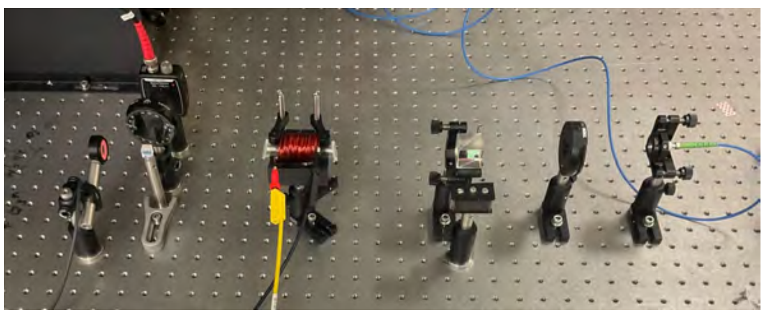
Description

Atoms make fantastic sensors of motion and electromagnetic fields, which makes them potentially very useful in a number of applications, from gravitational wave detection to environmental sensing. In addition, atoms are easily controlled by light fields, since any given atom will interact quite strongly with light of certain frequencies and polarizations.

In our research group, we are investigating hot rubidium-87 atoms (at temperatures of about 350 K) as precise sensors of magnetic fields. We do this by sending light of a very well-defined linear polarization through a glass cell filled with rubidium vapour and measuring an applied magnetic field via the Faraday effect, where the interactions of the atoms with an the applied magnetic field cause the polarization of the incident light to rotate. The precision of this measurement can also be improved by *squeezing* the light's polarization so that its precision appears to be below the limit imposed by Heisenberg's uncertainty principle. (The trick here is that the precision in the other polarization axis is made much larger, so the uncertainty principle is never violated.)

Your project will be to take the simple Faraday setup shown in the figure below and make it even better. This will involve building laser setups and precisely controlling their wavelength through electronic servoing, generating squeezed light, and/or designing and building an optical cavity around the vapour cell so that light interacts more strongly with the applied magnetic field.

This project involves the use of lasers, optics, and electronics.



This figure shows a very basic setup for measuring magnetic fields via the Faraday effect. Light from a fibre (blue, right) passes through some polarization optics, then into a glass cell filled with rubidium vapour, surrounded by wire used to generate a magnetic field. The light then passes through some more polarization optics and into a detector. Your job will be to make this simple setup better!

Key References

1. E.E. Mikhailov et al., J. Modern Opt. **56**, 18 (2008)
   https://doi.org/10.1080/09500340903159503
2. D. Budker and M. Romalis, Nature Physics **3**, 227 (2007)
   https://doi.org/10.1038/nphys566

Skills

- Experimental methods in atomic physics
- Precision measurement
- Optical system design and construction

QET-M2 : Quantum dot spins for quantum information

Supervisor: Prof. Ruth Oulton (QET)

MSci 60

Description

Semiconductor quantum dots (QDs - known as artificial atoms) are a good platform to perform quantum information processing and communications due to their unique properties. Firstly, semiconductor QDs as emitters can provide deterministic and bright single photons with high efficiency and high indistinguishability. Secondly, semiconductor QD spins are promising candidates to construct qubits for storing and processing quantum states due to the long electron spin coherence time (micro s) and spin relaxation time (ms). Moreover, self-assembled QDs can be embedded in various high-finesse optical microcavities or nanocavities, so cavity-QED can be exploited to engineer QD emissions. The most attractive feature is its compatibility with standard semiconductor processing techniques. Therefore, the QD-cavity system holds great promise for compact and scalable solid-state quantum networks and quantum computers.
Recently we have proposed a series of deterministic photon-spin entangling gates using a quantum dot spin in optical microcavties. These gates are universal and could be used in all aspects of quantum information science and technology, not only for large-scale quantum communication networks, but also for scalable quantum computing [1]. We have performed initial experiments towards the realization of these quantum gates [2]. In this experimental project you will be involved in a key area of our research in the optics lab. You will be involved in advanced experimental techniques to measure QDs at low temperatures, likely developing a part of the set-up yourself. You will also be involved in data analysis of the measurement results. To ensure that the work you will be doing is up-to-date with the latest research we do not prescribe the exact tasks until the start of the project itself.

Literature Work You will need to familiarize yourself the fundamental physics behind the experiments, including:
• Basic equations of quantum theory of light-matter interactions
• Basics of cavity electrodynamics
• Photon statistics and correlation: quantum optics concepts such as “single photon sources” “indistinguishability”, “superposition” and “entanglement”

A.M. Fox “Quantum Optics” Oxford University Press. Contains useful background reading on basics of quantum optics and quantum cavity QED.
Walls and Milburn “Quantum Optics” Springer 2008 ISBN 978-3-540-28574-8
M.A. Nielsen and I.L. Chuang, “Quantum Computation and Quantum Information” , Cambridge University Press, 2000.

Key References

1. Gines et al, Phys Rev Lett **129**, 033601 (2022)
   https://DOI:10.1103/PhysRevLett.129.033601
2. P. Androvitsaneas et al, ACS Photonics 20196,429 (2019)
   https://pubs.acs.org/doi/full/10.1021/acsphotonics.8b01380

Skills

- practical optics skills
- lab based software eg Labview
- data analysis skills

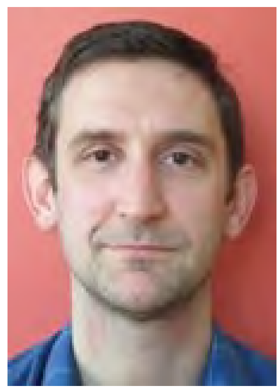
Quantum and Soft Matter (QSM)

Our aim is to find and understand new phenomena of quantum and classical matter. We study solid matter ranging from superconductors to insulators as well as soft materials like liquids, molecules and proteins. We offer projects spanning the range from experiment to computations and from fundamental behaviour of electrons in metals to applications in biophysics. We use the quantum theory of electrons as well as the laws of statistical mechanics to understand a wide range of materials. 9 academics and two research fellows work in the Quantum and Soft Matter group at the School of Physics and we collaborate with many colleagues in Bristol, the UK, and abroad. We are particularly renowned for our research on high-temperature superconductors, magnetic materials, and proteins. Many of our final year projects are directly linked to this cutting-edge research. Below is a brief description of some of these areas.

High-Temperature Superconductivity

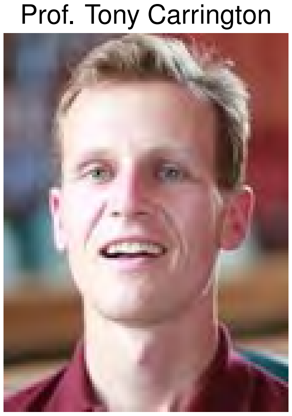
Prof. Tony Carrington

Prof. Stephen Hayden



Dr. Chris Bell

Prof. Stephen Dugdale



Dr. Sven Friedemann

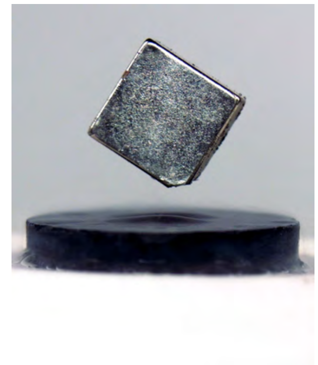
Prof. Nigel Hussey

Dr Jake Ayres

Our fundamental research aims to understand the microscopic mechanism of high-temperature superconductivity. This understanding, at a microscopic level, with help us to find new superconductors that can be exploited for important applications such as in renewable energy generation, transport, and medicine. Our work includes studies of materials which have only recently been discovered to superconduct at temperature approaching room temperature. These materials require very high pressures which we achieve using diamond-anvil pressure cells.

We have pioneered methods for electrical measurements at such high pressures and work on novel spectroscopic measurements that will help to identify how such a high transition temperature can be realised at low and ambient pressure.

A focus of our research is on unconventional superconductors, where the microscopic mechanism for superconductivity is generally unknown or differs markedly from the conventional BCS theory. We study magnetic, thermodynamic, spectroscopic, and electrical properties of these materials to provide experimental constraints on the various models proposed for the mechanism of superconductivity. We also study the normal state when superconductivity is suppressed, e.g., in large magnetic fields. This is important for the understanding of electrons prior to formation of Cooper pairs,



Neutron and X-Ray Scattering

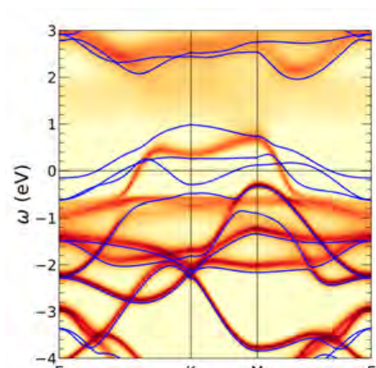
Prof. Stephen Hayden, Prof. Stephen Dugdale, Dr. Adrian Barnes

We use neutron and X-ray scattering as powerful probes of the structure and excitations of condensed matter. Neutrons scatter with matter through their nuclear and magnetic interactions, x-rays scatter through the interaction with charges. This enables both structure and magnetic properties to be probed with high resolution. We study superconductors, magnetic systems, liquids, glasses, and thin films with scattering experiments. Experiments are performed at DIAMOND and ISIS, near Oxford, and at various neutron sources abroad including ILL and ESRF in Grenoble. Research is this area is focused on novel magnetic systems and superconductors.

Electronic structure calculations

Prof. Stephen Dugdale, Prof. Tony Carrington, Dr. Sven Friedemann.

We use high-performance (super) computers to calculate, from first principles, the behaviour of electrons in metals, using density-functional-theory (DFT) and Dynamic Mean Field Theory (DMFT). These calculations aim to reproduce the electronic structure underlying the physical properties of these materials. We use these calculations to interpret our experiments and they provide a basis for an in-depth understanding of many electronic properties ranging from superconductivity to electronic



Calculated band-structure of $PdCrO_2$

devices. The DMFT is a relatively new area which aims to understand electron-electron correlations which are missing in standard DFT.

Solid-liquid interfaces


Prof. Walther Schwarzacher


Dr. Adrian Barnes


Dr. James Drewitt

Many interesting physical phenomena take place at solid liquid-interfaces. We are offering projects on two of these: electrodeposition and ice nucleation. Metal electrodeposition plays an essential role in a huge variety of applications. For these applications, the microstructure and surface morphology of the electrodeposited film are key, but there are still many outstanding questions concerning the atomic-scale processes involved. We investigate these using scanning probe microscopy and other advanced characterization techniques. Ice nucleation is vitally important in contexts as varied as cryobiology, materials chemistry, and environmental science. We aim to understand and control ice nucleation using model ice nucleating agents engineered to have a pre-determined size, surface chemistry and topographic features. Currently we are concentrating on ice nucleation by bio-nanoparticles such as quasi-spherical cage-like proteins.

Protein Assembly


Dr. Jennifer McManus

We are interested in how and why proteins, peptides and other macromolecules assemble into condensed phases such as crystals, amorphous aggregates, gels and fibres. We use protein phase diagrams to understand how protein-protein interactions lead to different assembled states. This helps us to understand the pathogenesis of disease and how best to formulate protein-based drugs to keep them stable and efficacious during storage. We are also interested in the rational design of protein-based materials, in the mechanical properties of protein gels and tissues and in the formulation and stability of proteins. Current projects within the research group include, liquid-liquid phase separation of proteins, membrane protein crystallization, peptide assembly and protein formulation and stability.

QSM-M1 : Ice magnetism

Supervisor: Prof. Walther Schwarzacher (QSM) | MSci 60/30

Description

Our aim in this project, which is a collaboration with the British Antarctic Survey (BAS), is to determine how best to analyze snow and ice samples for their magnetic dust content. Magnetic dust, mainly consisting of iron minerals, can enter the atmosphere through human activity, soil erosion, volcanism and even derive from meteors. The magnetic dust content of snow then depends on atmospheric circulation and how efficiently snow removes the dust from the atmosphere. Similarly, the magnetic dust content of ice from Arctic or Antarctic ice cores, for example, provides a unique historic record that can be used to test our understanding of key atmospheric processes.

In this project, we shall test different methods to separate ultrafine magnetic and non-magnetic dust particles from samples of melted snow and ice. We shall model the dust using nanoparticles with well-defined diameters, and apply separation techniques such as centrifugation and membrane filtration. We shall use an ultrasensitive SQUID magnetometer to make magnetic measurements and atomic force microscopy (AFM) to image the nanoparticles. Towards the end of the project, we shall test our newly-developed analysis methods using samples supplied by our collaborators at BAS.

Key References

1. L. Lanci et al. J. Geophys. Res. 113, D14207 (2008)
   https://doi.org/10.1029/2007JD009678
2. P. Southern et al. J. Phys. Condens. Matter 19, 45624 (2007)
   https://doi.org/10.1088/0953-8984/19/45/456204

Skills

- Physical chemistry techniques such as ultrafiltration
- Magnetometry
- Atomic Force Microscopy
- Statistical analysis

QSM-M2 : Ice nucleating agents control freezing

Supervisor: Prof. Walther Schwarzacher (QSM)

MSci
60/30

Description

Whether clouds consist of water droplets or ice particles affects their reflectivity as a function of wavelength, and therefore how they contribute to global warming. Unfortunately for climate modellers, predicting whether water is present as ice or liquid water isn't always straightforward. Water droplets may remain liquid down to temperatures as low as -40 centigrade, but can freeze at much higher temperatures when heterogeneous nucleating agents (HNAs) are present. In the atmosphere, particles including volcanic ash, mineral dust and biological matter could all act as HNAs.

The aim of this project is to study the effectiveness of candidate HNAs experimentally by adding them to samples of pure water and using one of the automated systems developed in our lab to determine their freezing temperatures. Although it is known that HNAs act by lowering the energy barrier to forming the first region of solid ice (the ice nucleus), many details remain unclear. Hence the need for experimental data. In addition to measurements, there will be scope to carry out related computer simulations using commercial finite element software.

Key References

1. G. C. Sosso et al. Chem. Rev. 116, 7078 (2016).
   https://doi.org/10.1021/acs.chemrev.5b00744
2. J. D. Atkinson et al. Nature 498, 356 (2013).
   https://doi.org/10.1038/nature12278

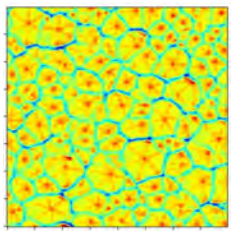
Skills

- Physical chemistry techniques
- Instrument control
- Statistical analysis
- Finite element analysis

QSM-M3 : Copper hexagons

Supervisor: Prof. Walther Schwarzacher (QSM) | MSci 60/30

Description



Metal electroplating is a process with a long history and numerous applications ranging from traditional (e.g. decorative coatings) to high-tech (e.g. integrated circuits and high energy density batteries). Furthermore, the patterns that the electroplated metal forms under different deposition conditions can be of fundamental physics interest. This project focuses on one such pattern: hexagonal pyramids. These form when copper (Cu) is prepared at very high electrode potentials by pulsed electrodeposition, which is when intervals of metal deposition alternate with intervals in which no deposition takes place.

The figure shows atomic force microscope (AFM) data for an electrodeposited Cu film following some simple image processing with Python. The presence of hexagonal features is obvious. During the project, you will prepare similar films, measure them by AFM and analyze the results quantitatively to find how the number, size and surface slope of any hexagons present depends on the amount of Cu deposited and the electrode potential during the deposition pulses. The results should deliver insight into the mechanisms by which the hexagons form. There will also be scope to innovate as far as the data analysis is concerned, for example by applying some of the machine learning tools in Python to the problem of identifying the hexagons.

Key References

1. X. Zhan et al., Electrochim. Acta 365, 137391 (2021).
   https://doi.org/10.1016/j.electacta.2020.137391
2. C. Liu et al., Sci. Rep. 4, 6123 (2014).
   https://doi.org/10.1038/srep06123

Skills

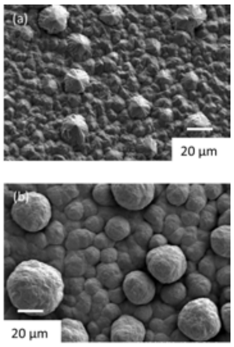
- Sample preparation (applying electrochemical methods)
- Atomic Force Microscopy
- Python coding

QSM-M4 : Probing the microstructure of metal films to understand their growth

Supervisor: Prof. Walther Schwarzacher (QSM)
Co-supervisor: Dr. Tomas Martin

MSci
60/30

Description



This is a project is for those with an interest in materials physics who are keen to learn to use and apply state-of-the-art experimental tools. Its aim is to gain a deeper understanding of copper electrodeposition, a low-cost and versatile process that is used widely in industry to prepare thermally and electrically conductive metal coatings. By simply changing the potential applied during deposition it is possible to prepare quite different surface finishes from the same starting chemicals (electrolyte), such as the rough grains and round nodules shown in Figures 1 (a) and (b). However, the physical processes underlying the formation of these diverse structures are still poorly understood.

To remedy this, your project will use transmission electron microscopy (TEM) to understand how the observed surface texture is related to the microstructure (the underlying crystal grain structure). You will electrodeposit Cu films under different conditions, image them using a scanning electron microscope, then prepare cross-section samples using focused ion beam for study by TEM. With the help of the TEM images, you should gain insight into the mechanisms by which the remarkably diverse textures observed for electrodeposited Cu form.

Key References

1. M. C. Lafouresse et al. Electrochem. Solid-State Lett. 14, D77 (2011).
   https://doi.org/10.1149/1.3578016
2. C. V. Thompson, Annu. Rev. Mater. Sci. 30, 159 (2000).
   https://doi.org/10.1146/annurev.matsci.30.1.159
3. A. Bastos et al., Acta Materialia 54, 2451 (2006).
   https://doi.org/10.1016/j.actamat.2006.01.033

Skills

- Electrochemistry (which is very relevant to 'net zero' as it underpins battery technology)
- Scanning electron microscopy, transmission electron microscopy and focused ion beam milling

QSM-M5 : Cavitation Rheology of Biological Fluids

Supervisor: Dr. Jennifer McManus (QSM)

MSci
60/30

Description

The elasticity or squishiness of biological structures defines their behaviour. For example, cancerous cells display different mechanical properties to those of healthy cells. Measuring the mechanical properties of biological materials in-situ remains a challenge. Cavitation rheology (CR) involves inducing a single cavity, at the tip of syringe needle, within a soft material and quantifying the critical pressure of mechanical instability, or cavitation. For elastic gels, the pressurization of a defect will either cause network chains to deform rapidly to accommodate an elastic instability, commonly called cavitation, or to rupture in unstable fracture. The transition between elastic cavitation (i.e. reversible and non-damaging) and fracture (i.e. irreversible and damaging) has been investigated and shown to depend directly on the size of the defect, or syringe needle radius, and the material length scale set by the balance of fracture toughness and elastic modulus. In this project, we will measure the non-linear mechanical properties of biological polymers and assess if the viscoelastic properties of the materials can be measured by CR.

Objectives of the project:

• To measure the mechanical properties of biological polymers at different length-scales using cavitation rheology.

• To further develop the technique of CR to allow viscoelastic properties of materials to be assessed using this technique.

Key References

1. Blumlein, N. Williams, J.J. McManus, Mechanical properties of individual cell spheroids, Sci. Rep. **7** (1): 7346 - 7356 (2017).
   https://doi.org/10.1038/s41598-017-07813-5
2. J. S. Zimberlin, J.J. McManus, A.J. Crosby, Cavitation Rheology of the Vitreous: Mechanical Properties of Biological Tissue, Soft Matter **6**: 3632-3635 (2010).
   https://doi.org/10.1039/b925407b
3. A.J. Crosby, J. J. McManus, Blowing bubbles to study living material, Physics Today,**64** (2), 62-63 (2011).
   https://doi.org/10.1039/clsm05340j

Skills

- Biopolymer handing
- Interdisciplinary training
- Physico-chemical techniques

QSM-M6 : Biomolecular condensation of proteins

Supervisor: Dr. Jennifer McManus (QSM)

MSci
60/30

Description

Biological cells are rich in structural and functional complexity and contain several microcompartments, which may themselves be heterogeneous, containing gradients, macromolecular assemblies and/or liquid droplets [1,2]. There are suggestions that self-assembly of macromolecules from dilute prebiotic pools into functional structures may have been facilitated by their concentration inside self-assembled vesicles or droplets and facilitated the origin of life. Intracellular liquid droplets (non-membrane bound organelles) have been increasingly described and are thought to be important in cellular functions such as RNA splicing, cell division, translational repression and mRNA degradation [3]. Liquid-liquid phase separation (LLPS) of proteins has been observed for proteins since the 1950s and was described in the eye lens over 30 years ago [4], but an increasing number of biological processes and neurodegenerative diseases have been associated with this process. Non-membrane bound organelles are found both in nuclear and cytoplasmic regions of mammalian cells. Of particular interest are RNA assemblies, such as GW or mammalian P-bodies, found in the cytoplasm and involved in eurkaryotic gene expression. In this project, we will use the phase separation boundary of proteins, to probe the influence of poly-anions (e.g. ATP, RNA) on the temperature at which LLPS occurs. The LLPS boundary is sensitive to changes in both the protein surface and on the solution conditions, hence allowing improved understanding of the role of polyelectrolytes on the phase separation of proteins in solution and greater insights into the formation and regulation of non-membrane bound organelles inside cells.

Key References

1. McManus JJ, Charbonneau P, Zaccarelli E, Asherie N, Curr. Opin. Coll. Int. Sci. **22**: 73 (2016).
   https://doi.org/10.1016/j.cocis.2016.02.011
2. Jakymiw A, Pauley KM, Li S, Ikeda et. al. J. Cell. Sci., **120** (8), 1317 (2007).
   https://doi.org/10.1242/jcs.03429
3. Eulalio A, Behm-Ansmant I, Schweizer D, Izaurralde E, Mol. Cell. Biol., **27** (11), 3970 (2007).
   https://doi.org/10.1128/MCB.00128-07
4. Asherie, N. Methods, **34**, 266 (2004).
   https://doi.org/10.1016/j.ymeth.2004.03.028
5. Bye, J. et al., Biomedicines, **9** (11), 1646 (2021).
   https://doi.org/10.3390/biomedicines9111646

Skills

- Protein Handling
- Physico-chemical lab techniques
- Interdisciplinary training

QSM-M7 : High-Temperature Superconductivity at high pressures

Supervisors: Dr. Sven Friedemann (QSM)
Co-supervisor: Prof. Antony Carrington

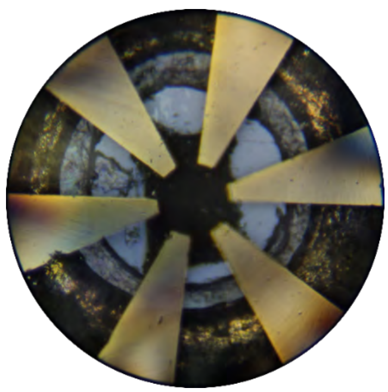
MSci 60

Description

Superconductivity offers the prospect for a wide variety of future applications. For instance, the quantum nature of superconductivity is exploited in quantum computers whilst the zero-resistance state is exploited for high magnetic fields in MRI scanners and fusion reactors. Many low-temperature superconductors are well described by BCS theory. However, cuprate superconductors with the highest transition temperatures at ambient pressure still lack a full understanding. It is important to identify the mechanism of superconductivity in these materials in order to enable the search for better superconductors. High-pressure studies of have the prospect to distinguish between different theoretical models

In this project, you will study how the transition temperature of high-temperature cuprate superconductors like YBa2Cu3O6+x (YBCO) and Tl2Ba2CuO6+x (Tl2201) can be tuned with pressure. You will use diamond-anvil pressure cells to apply pressures up to 10 GPa. You will trace the transition temperature with the help of magnetic measurements in a user-friendly magnetometer and/or study the evolution of electronic properties with pressure. The results will help to understand the mechanism of superconductivity and to find new superconductors with higher transition temperature.

This experiment involves use of liquid helium and strong magnetic fields.



Sample (rectangle at centre) inside a diamond-anvil pressure cell with electrodes (gold) for electrical studies.

Key References

1. A. C. Mark et al, High Pressure Research **42**, 137 (2022)
   https://doi.org/10.1080/08957959.2022.2059366

2. W. Buckel and R. Kleiner, Superconductivity: Fundamentals and Applications (2004)
   https://doi.org/10.1002/9783527618507

Skills

- Data aquisition
- Data analysis
- Experimental methods of low temperature physics
- High-pressure methods

QSM-M8 : High-Pressure Stability of Hydrogen-Storage Compound Ammonia Borane

Supervisors: Dr. Sven Friedemann (QSM)
Co-supervisor: Dr. Jonathan Buhot

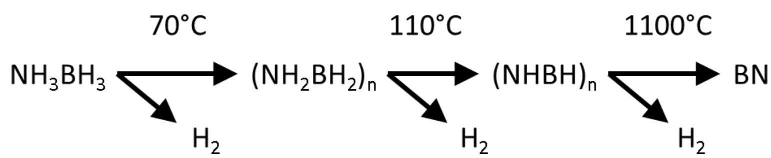
MSci 60

Description

Compounds that can release a large amount of hydrogen are in demand for hydrogen-powered applications. Ammonia borane (NH_3BH_3) is being investigate as one such material. It can release hydrogne on gentle warming above 70 C. Ammonia borane is also used as a hydrogen source in high-pressure experiments for the synthesis of high-temperature superconductors. Both these avenues render ammonia borane important for research towards sustainability.

In this project, we will explore how the release of hydrogen is affected by high pressure. Hydrogen is released step-wise in dissociation reactions. Generally, these dissociations are shifting to higher pressures. We will explore how much these shift at pressures up to 100 GPa significantly extending the range of previous studies. You will use diamond-anvil pressure cells to reach such high pressures. The work will require steady hands for handling small samples in the diamond anvil cell.

Raman spectroscopy will be used to detect the released H_2 and the dissociation of ammonia borane. Raman spectroscopy relies on shining a well defined wavelength of light (laser) and detecting the light scattered by the sample that has absorbed some energy from exciting molecular or lattice vibrations. The energies of these vibrations are a fingerprint of chemical compounds. For instance, the H_2 molecule has a H-H vibration with a very characteristic and high energy.



Thermal decomposition of ammonia borane at ambient pressure.

Key References

1. J. Nylén et al, J. Chem. Phys. **131**, 14506 (2009) https://doi.org/10.1063/1.3230973
2. Solid-state physics, H Ibach and H Luth, (2009) https://bris.on.worldcat.org/oclc/317753230

Skills

- Data acquisition
- Data analysis
- Optical methods
- laser safety
- High-pressure methods

QSM-M9 : Revealing the electronic structure of 2D materials with photoemission

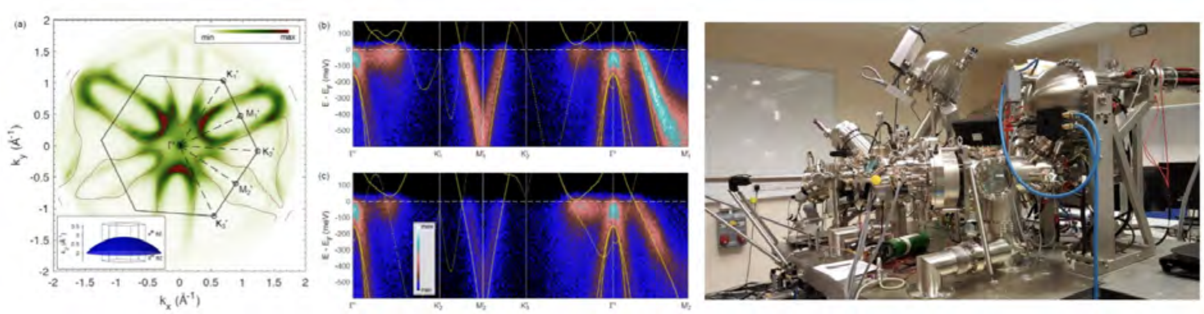
Supervisor: Prof. Stephen Dugdale (QSM)
Co-supervisor: Dr. Jude Laverock

MSci
60/30

Description

As exemplified by graphene, when the dimensions of a material are reduced from 3D to 2D, its properties can be dramatically altered. This can lead to new and exciting mechanical, magnetic or electronic behaviour. 2D materials now include a wide range of “beyond-graphene” atomic layer crystals (e.g. transition metal dichalcogenides, TMDs), which can be artificially stacked together to create new combinations with “designer” properties. This exciting area of research promises a range of future advanced materials for new technologies.

In this project, you will use a variety of sample preparation methods to achieve ultrathin layers and flakes and subsequently evaluate and optimise the surface preparation procedures. You will investigate the electronic structure of 2D materials of various thicknesses (from the bulk to just a few atomic layers) viewing the nanostructure of the material in real space with photoelectron emission microscopy (PEEM) and the electronic band structure (in reciprocal space) with angle-resolved photoemission (ARPES) with the NanoESCA. There will also be the opportunity to make calculations of the electronic structure. **We would hope that the work would lead to a publication.**



Example of Fermi surface and electronic band structure of a 2D material (1T-VSe_2) (left) measured using ARPES on the NanoESCA instrument (right).

Key References

1. M. Cattelan and N.A Fox, Nanomaterials **8**, 284 (2018) URL

Skills

- Photoemission spectroscopy
- Surface science and UHV techniques
- Analysis of large datasets
- Computer modelling of electronic structure

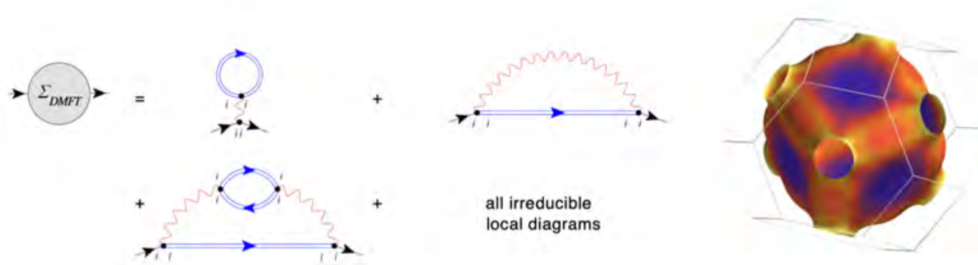
QSM-M10 : Fermi Surfaces and Momentum Densities of Strongly Correlated Oxides

Supervisor: Prof. Stephen Dugdale (QSM)

MSci
60/30

Description

X-ray Compton scattering of the electrons in metals gives access to the Fermi surface [1] as well as uniquely probing the (many-body) ground-state electron wavefunction. While the properties of many materials can be understood in a so-called "one electron" framework in which the non-interacting electrons are described using Bloch waves, there are also many materials where this breaks down *completely*. This unique insight into the many-body wavefunction from Compton scattering is ideal for strongly correlated oxides which show a range of exotic phenomena such as superconductivity, heavy-fermion behaviour, non-Fermi liquid behaviour, and so on. These properties, as well as their response to a variety of external stimuli (magnetic, electrical, thermal, or even mechanical), is highly desirable for advancing modern technologies. Understanding these materials at a fundamental, quantum level is at the forefront of modern-day research. In this project, you will use cutting-edge electronic structure methods which go beyond the standard density functional theory approach. This project will use dynamical mean field theory [2,3], which is required to model strongly correlated oxides such as Li_2VO_4 and NiO. **Your work will to help to interpret unpublished experimental data, meaning you have the chance to make an important contribution which would then be recognised, like previous students, by being an author of a future paper.** In this project you will make use of high-performance computing (HPC).



Left : Some Feynman diagrams for the DMFT self-energy. Right : Fermi surface of a NiFeCoCr high-entropy alloy measured by Compton scattering.

Key References

1. S. B. Dugdale, Physica Scripta **91**, 053009 (2016).URL
2. G. Kotliar and D. Vollhardt, Physics Today **57**, 3 53 (2004)URL
3. A. D. N. James *et al.*, Phys. Rev. B **103**, 035106 (2021)URL

Skills

- Analysis of synchrotron Compton scattering data
- Dynamical mean-field theory
- Computer modelling of electronic structure using HPC

QSM-M11 : Acoustic Schlieren Imaging

Supervisor: Dr. Adrian Barnes (QSM)
Co-supervisor: Dr. James Drewitt

MSci
60/30

Description

Schlieren imaging has been used for many years as a method for 'seeing' small changes in the refractive index of air.

In our laboratory, for several years, we have been developing acoustic levitation devices for trapping and heating samples for materials preparation. These devices are quite capable and able to levitate, for example, 2mm diameter lead spheres in the acoustic field produced. However, one of the difficulties of using acoustic levitation when heating is that the acoustic field is modified as the air heats and this can give rise to instabilities and possible loss of levitation. We have also found that the strength of levitation is critically affected by the quality in construction and tuning the device (currently we rely on 3D printing).

Schlieren image of acoustic levitator taken in the previous project

In a project last year students have built a schlieren apparatus, that can be used to experimentally visualize the acoustic field in our levitator (see figure) and have used it to compare the measured field with predictions from simulations. The results show that the field produced by currently constructed devices does not match the predictions well and suggests greater care in construction and control is need to optimise the acoustic levitator for our high temperature experiments.

In this project you will develop a more carefully constructed levitator (see reference [1] for example) that can be carefully optimised while the field is observed using the schlieren imaging system. This will improve the levitation force produced and improve stability. An important part of the project is you will incorporate the schlieren apparatus into our current interlocked enclosure that can be used to safely heat levitated samples with Class 3B lasers (upto 500 mW).

Key References

1. Contreras and Marzo Rev. Sci. Inst. (2021), 92, 015107, doi.org/10.1063/5.0013347
2. Schlieren imaging - Wikipedia (and references within)

Skills

- Safe use of high power laser systems
- Optics and Interference - Aligning optical systems
- Image processing and visualization

QSM-M12 : Development of an aero-acoustic levitator for containerless processing

Supervisor: Dr Adrian Barnes (QSM)
Co-supervisor: Dr James Drewitt

MSci
60/30

Description

Containerless processing is an advantageous technique for the fabrication and analysis of novel materials at high-temperature, where the absence of a container helps to prevent chemical contamination and control solidification processes.

Aerodynamic levitation with laser heating is a well established containerless technique that is widely employed in materials physics and planetary science applications, but it has limitations. It is not uncommon for the sample to touch the levitation nozzle, resulting in instant solidification and/or contamination, and there is limited access to the sample for *in situ* analysis. We have developed acoustic levitation devices using opposed arrays of ultrasonic transducers capable of stable mid-air confinement of dense liquid and solid materials. However, at high-temperatures the stability of the acoustic trap deteriorates and the sample is ejected.

Aero-acoustic levitation of a laser heated sample

In this project you will design and construct an *aero-acoustic* device in which a sample is levitated on a gas jet stream and stabilised using an acoustic field. The aim is to overcome the limitations of the two techniques by combining their strengths and enable mid-air levitation with unimpeded access to the sample for laser heating and contact-free measurements (e.g., spectroscopy, diffraction). By using arrays of multiple off-the-shelf ultrasonic emitters this system will be substantially more compact and low-cost compared to previous aero-acoustic systems (figure 1). You will investigate incorporating heating methods using radiant bulbs for levitation at moderate temperatures ($< 1000°$C) and potentially at higher temperatures using laser-heating.

As the project progresses there is potential to develop contact-free analysis techniques for studying the formation of novel glass materials and ceramic catalysts for industry, advanced molten nuclear reactor coolants, and volcanic liquids.

Key References

1. A. Marzo, A.C. Barnes, and B.W. Drinkwater (2017) Rev. Sci. Instr. **88**, 085105
   https://doi.org/10.1063/1.4989995
2. P.C. Nordine *et al.* (2012) Rev. Sci. Instr. **83**, 125107
   http://dx.doi.org/10.1063/1.4770125

Skills

- Acoustic field simulation
- Computer aided design and 3D printing
- Use of standard electronic lab apparatus (oscilloscopes, signal generators etc.)
- Learn how to use microprocessor (Arduino, Raspberry Pi) control systems

QSM-M13 : Searching for quantum criticality

Supervisor: Prof. Nigel Hussey (QSM)
Co-supervisor: Dr. Jake Ayres

MSci
60/30

Description

The iron chalcogenide FeSe is unique among the family of iron-based superconductors in that it undergoes a transition into so-called electron nematic order (like a liquid crystal but with electrons moving along a preferred direction) without developing magnetic order. At low temperatures, FeSe also becomes superconducting. By replacing some of the Se atoms with sulphur, the transition temperature into the nematic state is suppressed, eventually vanishing at a S content of around 16%. Typically, when the transition temperature for a second-order phase transition is suppressed to absolute zero, quantum critical fluctuations associated with that phase give rise to electrical transport properties that are markedly different from those found in conventional metals. In this project, the resistance of several single crystals of FeSe$_{1-x}$S$_x$ with S content close to the critical concentration will be measured as a function of temperature and magnetic field in order to study in detail how signatures of anomalous charge transport arise. This project will be combined with measurements of the specific heat of the same single crystals carried out by a PhD student. This experiment involves use of liquid helium and strong magnetic fields.

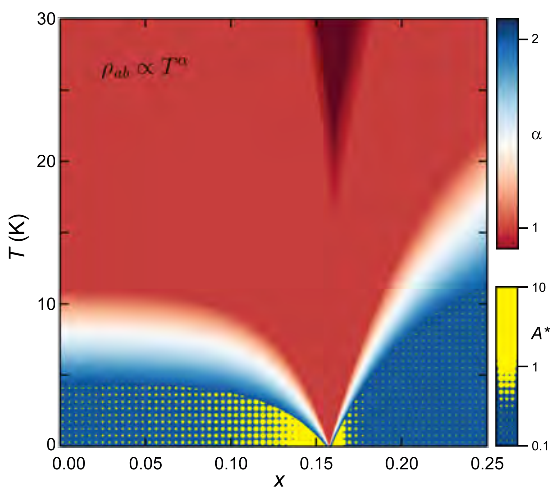


Figure: *Exponent of the power-law T-dependence of the electrical resistivity in FeSe$_{1-x}$S$_x$ around its putative quantum critical point. Yellow bars indicate the magnitude of resistivity.*

Key References

1. S. Licciardello *et al.*, Nature **567**, 213 (2019)
   https://doi.org/10.1038/s41586-019-0923-y
2. A. E Böhmer and A. Kreisel, J. Phys.: Condens. Matter **30**, 023001 (2018)
   https://doi.org/10.1088/1361-648X/aa9caa

Skills

- Experimental methods of low temperature physics and computer modelling

QSM-M14 : On the edge between zero and infinite resistance

Supervisor: Prof. Nigel Hussey (QSM)
Co-supervisor: Dr. Jake Ayres

MSci 60

Description

The material $Li_{0.9}Mo_6O_{17}$ (LMO) – also known as purple bronze due to its iridescent purple sheen – has been a subject of intense research for several decades due to its one-dimensional electronic structure and unusual electrical transport properties, most notably its resistivity is insulating-like below 30 K but superconducting below 2 K. The origin of superconductivity in LMO is not known, nor whether its electronic ground state (i.e. in the absence of superconductivity) is metallic or insulating. The emergence of superconductivity from an insulating ground state is a very rare phenomenon and may indicate a novel superconducting pairing mechanism.
In this project, the resistance of several single crystals of purple bronze will be measured as a function of temperature (down to 0.5 K) and magnetic field (up to 14 T) in order to analyse this remarkable transition from insulator to superconductor in more detail. In superconducting samples, the magnetic field will also be used to suppress the superconductivity and to test whether the underlying electronic ground state is indeed metallic or insulating. The Hall effect will also be studied to gain further insights into this unusual and fascinating compound. This experiment involves use of liquid helium and strong magnetic fields.

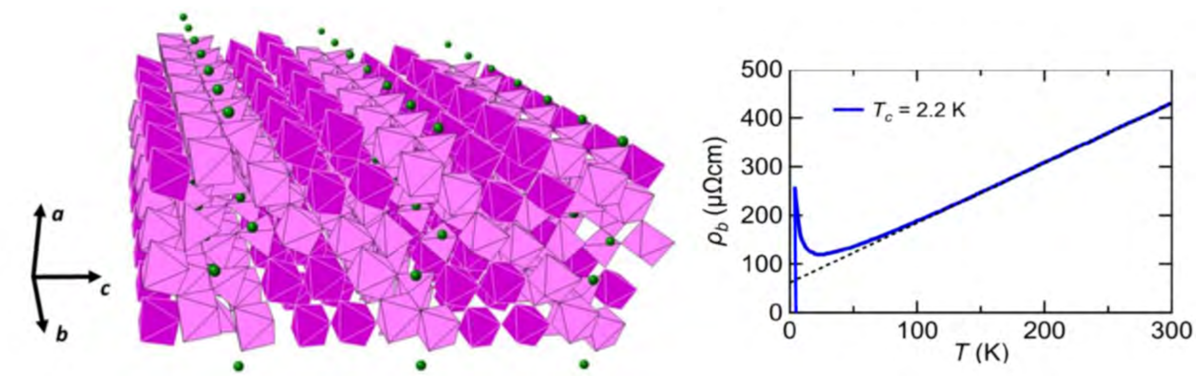


Figure: *Left panel: crystalline structure of LMO showing the conducting zig-zag chains. Right panel: T-dependence of the electrical resistivity in LMO showing its metallic, insulating and superconducting regions.*

Key References

1. X. F. Xu *et al.*, Physical Review Letters **102**, 206602 (2009)
https://doi.org/10.1103/PhysRevLett.102.206602

2. J. Lu *et al.*, Science Advances **5**, eaar8027 (2019)
https://doi.org/10.1126/sciadv.aar8027

Skills

- Experimental methods of low temperature physics
- Computer modelling

QSM-M15 : Can we conceive of an alternative to the electric car?

Supervisor: Prof. Nigel Hussey (QSM)
Co-supervisor: Mr. Kourosh Shirkoohi

MSci
60/30

Description

If one were to conceive of a transport system, from scratch, fit for the 21st Century, would one really opt for the electric car, with its resource-intensive battery, moving around a gridlocked infrastructure? Well, if given the chance, one might seek to combine the efficiency of public transportation with the flexibility, and privacy, of the automobile. The solution, as envisaged by NIfTI (short for National Individual *floating* Transport Infrastucture), is a levitated pod, without engine or tyres, propelled by pulses of electromagnets embedded in the existing road network and controlled by state-of-the-art IT, escorting passengers of all ages and disability smoothly, swiftly and safely to their specified destination, without congestion.

This project will follow up on initial calculations from previous project students on the feasibility of NIfTI (now submitted for publication in an Engineering journal) in order to create a more sophisticated design concept for the electromagnetic coil system that would include the insertion of small permanent magnets inside the coils. The student will use a combination of Python-based programming and MatLab to produce simulations of the magnetic field profiles for various coil and magnet combinations and calculate the resulting forces, both levitating and propulsive, and the energy costs involved in propelling the pod along a stretch of road. The aim of the project is to go beyond simple conceptual ideas and develop a sophisticated framework for the subsequent development of a large-scale prototype that is currently being carried out by students at the HAN Automotive Institute in Arnhem, the Netherlands. The student will work closely with Prof. Hussey and will meet initially on a biweekly basis. Visits to the Netherlands may be arranged as and when beneficial to the project.

Figure: *Artist impression of a NIfTI pod*

Key References

1. *Magnetic Levitation: Maglev Technology and Applications*, Yung-Suk Han and Kim Dong-Sung, Springer (2016)

Skills

- Computer modelling

QSM-M16 : Flowing heat and charge in exotic thin films

Supervisor: Dr. Chris Bell (QSM)
Co-supervisor: Dr. Ross Springell (Mat.Dev.)

MSci
60/30

Description

How materials conduct electricity and heat is intimately connected to the nature of their electronic band structures: for example metals, with a Fermi surface, can carrier heat via mobile carriers as well as lattice vibrations (phonons). The phonons do not carry charge, but the electrons do, and therefore give rise to electrical conductivity in parallel. When we look at metals, a good electrical conductor is therefore typically a good thermal conductor. For a semiconductor, on the other hand, the number of mobile carriers is much smaller, so the phonon contribution to the thermal conductivity is much more important. This project seeks to study the electronic and thermal conductivity of exotic thin films of actinide materials (such as UO_2, UN and Th-based compounds). The University of Bristol hosts a dedicated actinide deposition system, unique in the UK, and our group has extensive experience in synthesising these types of exotic U- and Th-based films as polycrystal or single crystal phases. The project will focus in particular on the cross-over from semiconductors to 'bad metals' (which are high resistivity metals). These materials are important for applications, but also a challenge to disentangle the different contributions to heat flow. We will use Time-Domain ThermoReflectance (TDTR) to understand the thermal properties, and electrical transport (longitudinal resistivity and Hall effect) to determine the electrical behaviour.

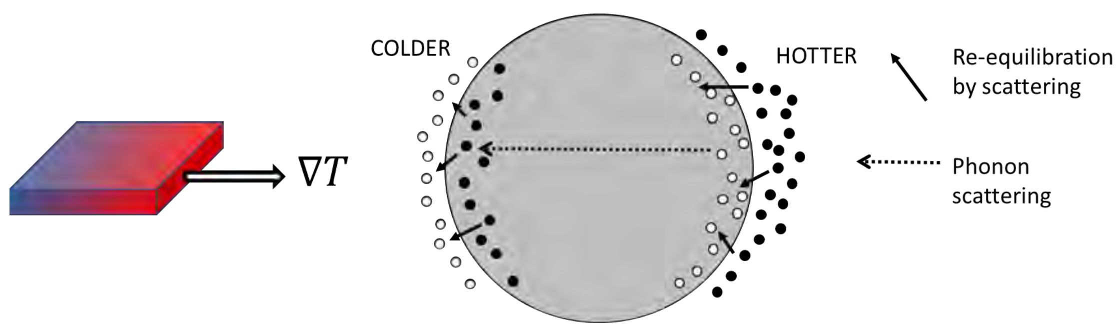


Figure shows real space temperature gradient applied to a sample (left), and the equivalent picture in momentum space for a metal with a Fermi surface (right).

Key References

1. General review: G.H. Lander, E.S. Fisher & S.D. Bader, Advances in Physics, **43** 1-111 (1994),J. Bartlett et al, Cryogenics **50**, 582 (2010)
2. P. Jiang *et al.* J. Appl. Phys. **124**, 161103 (2018)

Skills

- Literature survey
- Experimental methods of time-domain thermoreflectance measurements and low noise magnetoresistance measurements
- Thin film x-ray characterisation

QSM-M17 : Creating new superconductors with heavy elements

Supervisor: Dr. Chris Bell (QSM)

MSci
60/30

Description

When a conventional superconductor is made as a thin film together with a ferromagnetic material (e.g. Nb/Ni), the superconductivity is suppressed since one of the electrons in the superconducting Cooper pairs anti-parallel to the aligned spins in the ferromagnetic layer, and is spin-flipped, strongly weakening the superconductivity. However, in the presence of heavy elements such as U, Th, Pt etc, we can generate a novel type of spin-triplet superconductivity in which the Cooper pair spins are both aligned parallel (1). In this limit ferromagnetism and superconductivity can combine peacefully. This project will investigate creating these types of superconductivity in thin film structures, using a combination of conventional superconductors, ferromagnets, and heavy element materials. The eventual aim is to realise novel “superconducting spintronic” (2) devices - which combines the best of both worlds of low resistance superconducting electronics, and the non-volatile memory of magnetism.

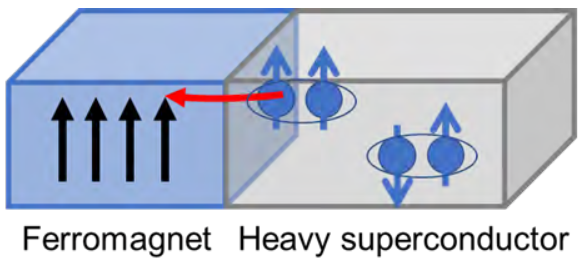


Figure shows the generation of unconventional triplet superconducting pairs of electrons using heavy elements, which can are not destroyed by nearby ferromagnetism.

Key References

1. J. R. Eskilt, M. Amundsen, N. Banerjee, and J. Linder, Phys. Rev. B, **100**, 224519 (2019).
2. J. Linder & J. W. A. Robinson, Nature Phys. **11**, 307 (2015)

Skills

- Literature survey
- Thin film growth / x-ray characterisation
- Magnetic and/or low temperatures transport measurements

QSM-M18 : Electron Nematic Behaviour in Superconductors

Supervisor: Prof. Stephen Hayden (QSM) | MSci 60

Description

Superconductivity is a collective property of the conduction electrons of certain metals. Electrons form Cooper pairs and condense into a macroscopic quantum state. In recent years many new superconducting materials have been discovered and the highest transition temperatures have been pushed up to 150K. Superconductors already have many practical applications for example producing high magnetic fields in MRI scanners and generating power in the compact generators in wind turbines. This project concerns the fundamental properties of the correlated electrons in materials such as superconductors. In some materials [Nature Physics 8, 871-876 (2012)] the conduction electrons order to form “charge stripes” or “spin stripes”. This means that the transport and magnetic properties of the conduction electrons are highly anisotropic. In this project you will use a strain cell with piezo-electric crystals or springs to manipulate the structure of a cuprate superconductor and see whether the resulting changes effect of the transport properties (resistivity).

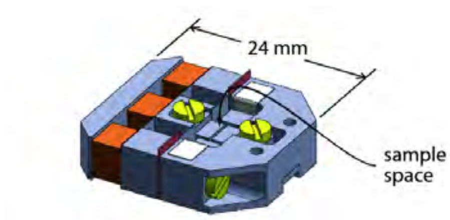


Figure shows a piezo-electric to be used in the experiment

Key References

1. Hicks et al., Sci. Instrum. 85, 065003 (2014).
   https://doi.org/10.1063/1.4881611.
2. Chang el al., Nature Physics 8, 871-876 (2012).
   https://doi.org/10.1038/nphys2456
3. J. Choi et al. Phys. Rev. Lett. 128, 207002 (2022.)
   https://doi.org/10.1103/PhysRevLett.128.207002

Skills

- Data acquisition with MATLAB or python
- Low temperature measurements.

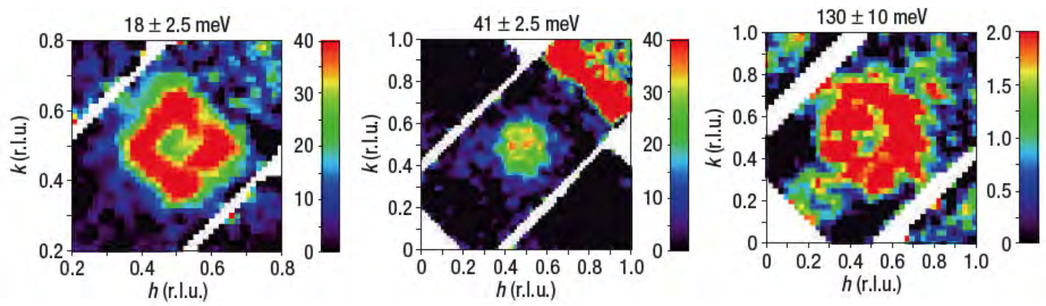
QSM-M19 : Spin Fluctuations in Superconductors

Supervisor: Prof. Stephen Hayden (QSM)

MSci 60

Description

Superconductivity is a key quantum technology available to mankind. Superconductors are already widely used to make high field magnets for magnetic resonance imaging (MRI). They also have applications in power generation and transmission, transportation, and quantum computing. The most promising higher temperature superconductors are based on materials comprised of copper oxide planes such as $YBa_2Cu_3O_7$. It is widely accepted that superconductivity in the cuprates is magnetically mediated, that is spin-fluctuations cause an effective interaction between conduction electrons that results in them forming Cooper pairs. Collective spin fluctuations can be observed by inelastic neutron scattering. In this project you will analyze neutron scattering data collected at the ISIS spallation source on cuprate superconductors. The aim to develop analysis methods to extract the very highest energy excitations and model these excitations with theory. The project will use data analysis tools and involve writing new code to compute the excitations.



Spin Fluctuations in $La_{2-x}Sr_xCuO_4$ measured with neutron scattering

Key References

1. B. Vignolle, et al., Nature Physics 3, 163 (2007).
   https://doi.org/10.1038/nphys546
2. M. Zhu, et al., Nature Physics 19, 99 (2023).
   https://doi.org/10.1038/s41567-022-01825-3

Skills

- Neutron scattering
- MATLAB (python) programming
- Multi-dimensional data analysis

QSM-M20 : Cooling to Zero

Supervisor: Prof. Antony Carrington (QSM)

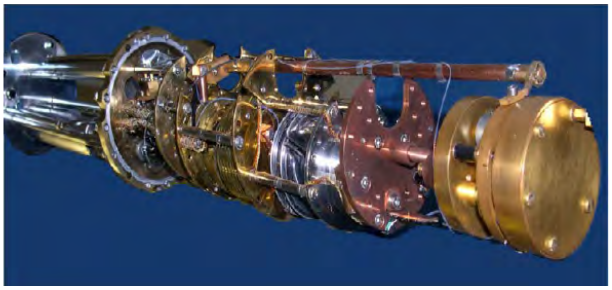
MSci 60

Description

The technology to cool experiments to low temperature is at the heart of many different fields of science ranging from condensed matter physics to space science or quantum computing. Cooling to temperatures of around 2 K can be achieved simply by immersing the experiment in liquid helium and reducing its vapour pressure. Cooling below 2 K is more challenging. The usual way to do this is to use adiabatic demagnetisation of a paramagnetic salt. Compared to other methods the adiabatic demagnetisation refrigerator (ADR) has the advantage of being simple, cheap and reliable. This is the preferred technology for use on space satellites for example.

In this project you will build an ADR with the aim of cooling to temperatures below 0.1 K and developing an accurate model of its performance. The performance of the device will depend on the choice of materials for each of the components, such as the paramagnetic salt, the thermal link and the experimental stage. A key part will be to develop an efficient switchable heat link, so that the pill can be cooled effectively during the magnetisation stage, but then effectively isolated during the adiabatic demagnetsation stage. This is a practical project so will suit students who enjoy constructing experiments from the basic components.

This experiment involves use of liquid helium and strong magnetic fields. The strong magnetic fields may mean this project is unsuitable for some students with certain health conditions.



A dilution refrigerator which can cool experiments to 0.01 K

Key References

1. Primer on adiabatic demagnetisation referigators from the Goddard Space Flight Center URL
2. M.J. Hills PhD. Thesis, University College London (2015) URL
3. J. Franco et al. Physics Procedia **67**, 1117 (2015). URL

Skills

- Low temperature physics experimental techniques.
- Computer modelling.
- Cryogenic design and construction skills.

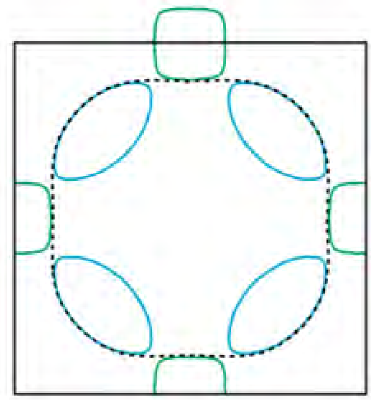
QSM-M21 : Magnetic Quantum Oscillations: breakdown and tunnelling

Supervisor: Prof. Antony Carrington (QSM)

MSci 60

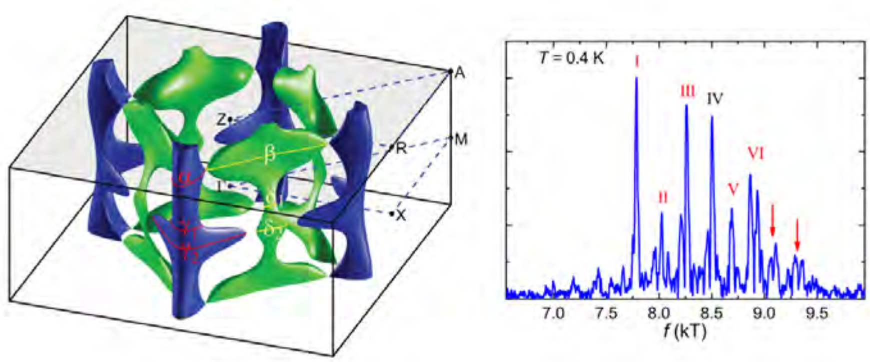
Description

This theoretical project aims to model experimental data on ‘hot topic’ materials, such as high-temperature superconductors and topologial nodal-line metals. In a magnetic field, electrons are subject to a Lorentz force which causes them to move on orbits on the Fermi surface. An interesting effect occurs when two parts of the Fermi surface are in close proximity (in k-space). Then as the magnetic field is increased the electrons can tunnel across the gap and complete a different type of orbit. This is illustrated to the left for a 2D section of a Fermi-surface, where at low field there are two possible Fermi surface orbits (blue and green) and then at high field a new orbit (black dashed line) is possible. This gives rise to change in the quantum oscillation frequencies which are observable experimentally and is known as magnetic-breakdown (MB). Modelling how the electrons tunnel through these gaps is essential to interpret the experimental data, and hence experimental determine the nature of the Fermi surface. In turn, this builds our microscopic theoretical understanding of the materials which allows us to design better materials for future advanced electronic applications.



Fermi surface of a cuprate superconductor showing the possible quantum oscillations orbits with-/without magnetic breakdown

In this project, you will use exact diagonalisation to explore magnetic-breakdown in different materials. You will perform Density Function Theory calculations to obtain the band-structure, fit this to tight-binding models and then calculate the MB properties and compare to experimental data. If the project is successful it is likely the results will lead to a published paper.



Fermi-surface of ZrSiS and quantum oscillation spectrum up to B=31 T

Key References

1. C.S.A. Müller et al., Phys. Rev. Research **2**, 023217 (2020). URL
2. J-M Carter et al., Phys. Rev. **B81**, 064519 (2010). URL

Skills

- Building computer models using Matlab
- Density functional Theory

QSM-M22 : Modelling Meissner Screening in Superconductors

Supervisor: Prof. Antony Carrington (QSM)

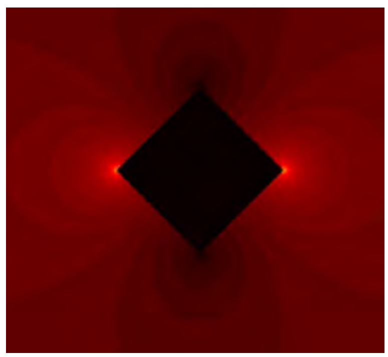
MSci
60/30

Description

A defining characteristic of a superconductor is its ability to screen the applied magnetic field, this is known as the Meissner effect and is modelled by solving the London equation;

$$\nabla^2 B = B/\lambda^2.$$

This describes the superconducting screening currents which flow close to the surface of the superconductor and are reduced exponentially towards the centre with a characteristic decay length scale λ, which is known as the London penetration depth.
This equation is trivial to solve for the one-dimensional example of the superconductor / vacuum interface, however, for when we wish to apply this to real experiments the equations become intractable by analytical means. However, it is possible to use finite element techniques to solve these for real systems. In this project, you will use a finite-element package to solve the electromagnetic equations for various important geometries, and use the results to find approximate analytic expressions. The results have direct application to the interpretation of experimental data and if successful will likely be published.



Magnetic flux density for a superconducting material in an external magnetic field

Key References

1. R. Prozorov et al. Phys. Rev. B **62**, 115 (2000) URL
2. R. Prozorov Phys. Rev. Applied **16**, 024014(2021). URL

Skills

- Electromagnetism of superconductors.
- Finite element modelling using packages such as Comsol or Elmer.

MATERIALS and DEVICES (MD)

Academics in the Materials and Devices Theme undertake research on all aspects of materials design, fabrication, and characterisation across the length scales. We cover a broad portfolio of topics, from fundamental materials physics, to materials currently being used in industrial applications. We are inherently interdisciplinary and have strong links to research groups in chemistry, medical and life sciences, engineering, as well as numerous industrial partners. Academics within the theme are internationally renowned and actively engaged in research. Within the theme, we have seven key areas of expertise detailed below. If you have any questions regarding a particular topic please feel free to get in touch with the individuals of that area or please drop an email to the Theme Lead (Dr. Dong Lilly Liu at dong.liu@bristol.ac.uk).

Centre for Device Thermography and Reliability

Prof. Martin Kuball

Dr. Andrei Sarua

Dr. James Pomeroy

Dr. Matthew Smith

Centre for Device Thermography and Reliability (CDTR) led by Prof. Kuball currently has 20 PhD/PDRA researchers. The broad aim of the is to understand the structure-property relationship of materials and, thus, how materials and devices with new or improved properties can be fabricated. CDTR's interests range from fundamental physics to solving industrial problems. Topics include Semiconductors, Synthetic Diamond, Gallium Nitride (GaN), Gallium Oxide and other wide and ultra-wide bandgap semiconductors are being studied for potential applications in advanced electronic devices, for example new monolithic microwave integrated circuits for information transmission in mobile communication systems, as well as next generation power electronics device for reducing UK carbon footprint. Heterogenous materials integration and the ultimate fabrication of devices, including their design, characterization and modelling are important components of the research activities. CDTR is one of the world-leading groups in the research field and has strong collaboration with numerous key semiconductor industries in the UK and worldwide. CDTR research is supported by large amount funding via numerous research grants from the UK, EU, USA including EPSRC Programme and Platform Grants.

Nanophotonics and Nanophysics

The Nanophotonics and Nanophysics Group is a research group focusing on development, application and exploitation of novel imaging and characterization techniques at the nanoscale for biology and medicine. It is internationally renowned for strengths in scanning probe microscopy, nanophotonics, and x-ray and neutron scattering and has state-of-the-art equipment to pursue experimental work, including custom built equipment to undertake research into optical forces, scanning probe microscopy, nanophotonics and singular optics. This unique experimental platform based on technologies pioneered in Bristol puts the group in a strong position in collaborative links to Lifesciences, Biochemistry, Medical Science, Chemistry, Engineering as well as with industrial partners. Our work allows us to answer questions in areas such as healthy aging, food security and antibiotic resistance, leading to a broad spectrum of ongoing collaborative and interdisciplinary projects in which undergraduate projects play an important role to explore new avenues or demonstrate a proof-of-concept.

Surface Physics


Dr. Natasa Vasiljevic

In the Surface Physics Group, we study physical processes taking place at the interface between a solid, usually a metal, and a liquid or a gas, looking at length scales from a few micrometers down to atomic dimensions, using techniques such as atomic force microscopy, scanning tunnelling microscopy and light scattering. These processes are of fundamental interest as well as being relevant to applications ranging from magnetic recording to renewable energy. Our current interests include: (i) electrodeposition, where we aim to employ knowledge of atomic scale processes in the 'smart' design of novel nanomaterials; (ii) molecular spintronics (using organic molecules to construct nanoscale electronic devices that exploit the spin as well as the charge of the electron); (iii) nucleation and growth phenomena in materials ranging from metals to water ice.

Sensors and Functional Materials


Dr. Andrei Sarua

Wide band gap semiconductors, such as GaN or ZnO offer great potential for a wide range of sensing applications: from gas sensors suitable for operation in harsh environmental conditions to a variety of biocompatible chemical/bio-sensors for medical and security applications. Research in this area combines different fields of material science: device physics, engineering and applied chemistry. We employ novel methods to engineer device structures on the micro- and nano-scale, to modify and functionalise their surfaces, as well as non-invasive optical techniques to study functionality of fabricated structures.

Experimental Mechanics of Advanced Materials

Dr. Dong (Lilly) Liu

Experimental Mechanics of Advanced Materials EMAM Group led by Dr. Liu currently has around ten master/PhD/PDRA researchers specialised in nuclear fission/fusion and aerospace materials collaborating with numerous industrial partners in the UK, EU, USA, Australia, Japan and Korea. Composite materials with improved properties to survive harsh environments such as neutron/proton irradiation and elevated temperatures are the key for current and future nuclear fission/fusion reactors and aero engines. The materials of interest to EMAM include carbon/graphite, SiC/SiC, Oxide/Oxide, TRISO fuel particles/compacts, novel nuclear fuel cladding materials and MAX phases. Unique and cutting-edge techniques are developed to study these materials over multiple length-scales to correlate the materials processing, nano-/micro-structure to the macro-scale damage and fracture in service conditions. EMAM has built up strong collaboration with key national and international players in nuclear and aerospace fields with the aim to use scientific approaches to acquire mechanistic understanding of the failure modes in these materials to underpin their industrial applications.

Materials for Energy

Prof. Neil Fox

Synthetic, isotopically pure diamond is being researched for applications in radiation monitoring, fusion power generation, concentrated solar power and nuclear batteries for terrestrial and space applications. The research is supported by diamond growth facilities in the School of Chemistry where seven research reactors are used to produce single crystal and polycrystalline diamond coatings and free-standing membranes for device evaluations. To support materials for energy surface analysis the group operates the university's NanoESCA facility which is based in the ultra-quiet laboratories located in the NSQI building. This state-of-the-art instrument platform is unique in the UK giving researchers the ability to analyse the top three atom layers of a crystalline material to reveal chemical and electronic information in real space and electronic band structure in momentum space. In addition to diamond, many materials for energy are evaluated including 2D materials, magnetic materials, photovoltaic materials, nuclear reactor materials, topological insulators, and single crystal metals. Material samples are routinely pre-analysed by NanoESCA and transported by vacuum suitcase to the national synchrotron facility (Diamond Light Source) on the Harwell Campus for analysis on by researchers on the Diamond Light Source beam line endstations.

The Interface Analysis Centre

Prof. Tom Scott

Dr. Ross Springell

Dr. Tomas Martin

Dr. Peter Martin

Dr. John Day

The Interface Analysis Centre is a cutting-edge multidisciplinary research hub within the School of Physics and works on a range of materials science based issues focused on real-world problem-driven applications. It is fortunate to host a wide array of analytical equipment that is attractive to both academia and industry, leading to a large number of external collaborators. Our staff and postgraduate students are driven to solve real-world problems and make fundamental discoveries related to developing and understanding new and existing materials. At the IAC, our time is split between a broad portfolio of fundamental research (funded by UK Research Councils, NHS, EU charitable organisations, etc), industrial research and short-term contract analysis. The Centre maintains laboratories which house a complementary array of microscopes and spectrometers for conducting surface and materials analysis. These includes specially-equipped laboratories to safely handle radioactive materials, which form a major part of our research. Current research interests include studies into: Fundamental actinide physics; Metallurgy on a range of metals and alloys; Nuclear forensics - ore mineralogy and fallout characterisation; High-speed atomic force microscopy; Nuclear reactor graphite; Power plant lifetime extension; Raman spectroscopy; Safe and long-term storage of nuclear wastes; Low altitude unmanned aerial vehicles for radioactive contamination monitoring; Nanoparticles and environmental remediation; Deep-sea sulphide ore deposits; Accident-tolerant nuclear fuels and fuel performance; Development of new radiation detectors for high-dose environments - diamond-based systems.

MD-M1 : Development of simulation tool for rapid analysis semiconductor devices

Supervisor: Dr. Matthew Smith (Mat.Dev.)
Co-supervisor: Dr. Simon Hanna

MSci
60/30

Description

Semiconductor devices are the backbone of electronics, and understanding their operation is critical for taking full advantage of their ability to control the flow of energy in modern circuits and systems. This is typically achieved using finite-element TCAD simulation software [1], in which the laws of physics are applied to a user-defined 2- or 3-dimensional device structure to predict electrical characteristics, which are then compared with experimental measurements. However, the complex calculations necessary for effective TCAD simulation of full devices are computationally intensive, taking up large amounts of memory and time and requiring costly licenses. Simplified 1-dimensional simulation tools (Fig. 1) have emerged as open-source alternatives to TCAD, offering rapid analysis of key elements of device operation, such as the band structure of metal-oxide-semiconductor (MOS) junctions [2] and wide bandgap heterostructures [3]. In this project students will develop a 1-dimensional simulation tool for rapid visualization of band diagrams in semiconductor devices. The tool will build on existing solutions [2, 3], improving functionality to enable exploration of polarized materials, MOS junctions and trapping effects. Band diagrams will be calculated using establish material properties and consideration of the Fermi level at each point in the structure [4], with results used to predict capacitance-voltage profiles which can be compared to experimental measurements on real state-of-the-art devices from ongoing projects in the School of Physics.

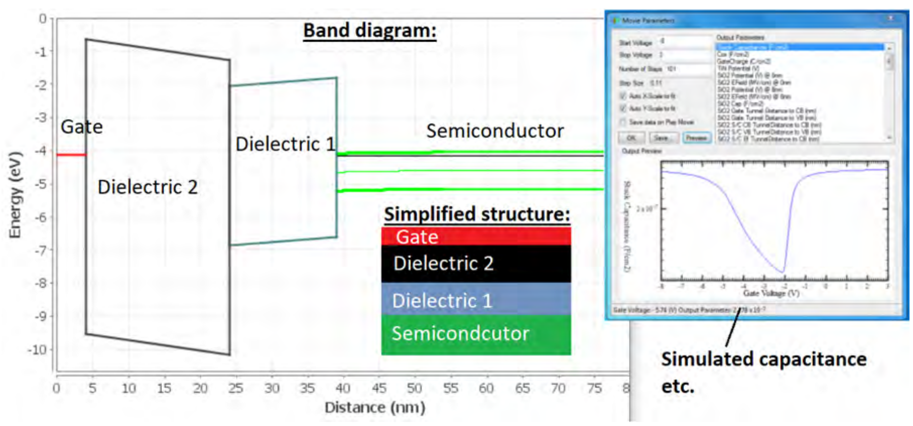


Figure shows user interface of similar existing tools

Key References

1. Silvaco website
   https://silvaco.com/tcad/
2. Multi-dielectric energy band diagram program URL
3. BandEng program URL
4. Cendula et al., J. Phys. Chem. C 118, 51, 29599 (2014) URL

Skills

- Students will gain an in-depth scientific understanding of semiconductor physics, as well has how to combine theory and experimental data to implement practical, user-friendly modelling software in an environment of their choice. Students will also develop skills to effectively review literature and manage a scientific project.

MD-M2 : Power electronic device simulation of Ga2O3 high power transistors

Supervisor: Dr. Matthew Smith (Mat.Dev.)
Co-supervisor: Prof. Martin Kuball

MSci
60/30

Description

Gallium(III) oxide (Ga2O3) is an exciting material with potential to replace Si in power electronic applications including electric vehicles, renewable energy generation and heavy industry, with material figures of merit surpassing even advanced materials like GaN and SiC [1]. It is THE material which will enable NET ZERO and our carbon footprint to be dramatically reduced. The ultra-wide electronic band gap of offers the boost in the efficiency of electrical power handling at high voltage desperately needed in the quest for improved device performance. However, this brings additional challenges in realizing functional, high performance devices such as transistors, as it is difficult to effectively modulate conductivity at the material level and to form 3 dimensional structures at the device level. Thus, while Ga2O3 has been around for over 70 years it is only recently that it has become a serious candidate for next generation power electronics, and the race is on to innovate new device structures, material combinations and integration techniques that take full advantage of the outstanding material properties of Ga2O3 toward revolutionizing efficiency in high power systems.
This project will use commercial device simulation software [2] (widely used in academia as well as industry) to explore novel Ga2O3 transistor device architectures. An established baseline simulation [3] will be used to generate novel device structures, with appropriate simulation meshing, and apply physical models such as those governing electron transport to extract electrical characteristics, which can be calibrated to experiment. Ga2O3 device structures that meet the performance requirements of next generation power transistors (to be determined by a review of the scientific literature) will then be simulated. Innovative new device features will be realized by controlling the effects of doping, device geometry and current path direction (i.e. horizontal or vertical), or by integrating Ga2O3 devices with alternative substrate materials to account for the relatively low thermal conductivity. The results will ultimately contribute to the inevitable proliferation of ultra-wide band gap semiconductor devices and streamline routes to wide-scale use, helping to combat climate change by reducing wasted heat in power electronics.

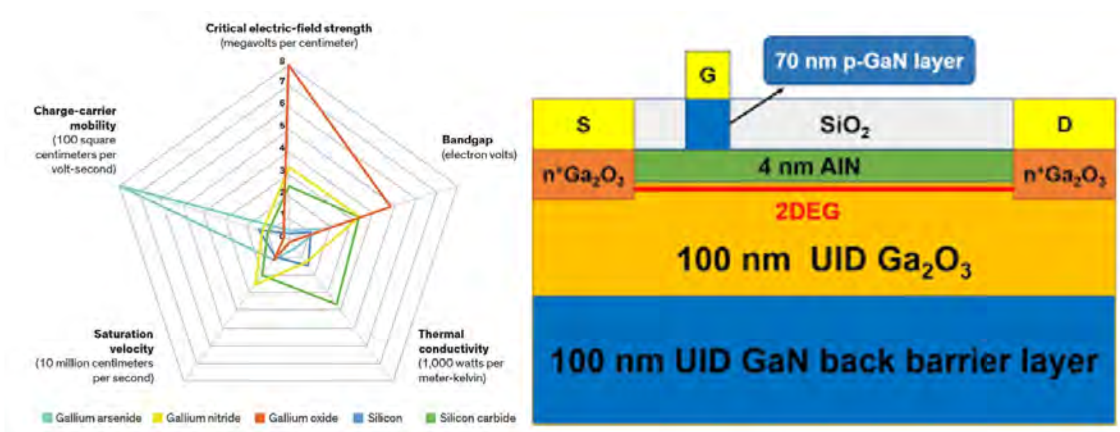


Figure shows Ga2O3 figure of merit (left) and example device structure (right)

Key References

1. Silvaco website URL
2. Higashiwaki et al., Appl. Phys. Lett. 112, 060401 (2018)URL
3. Silvaco example standard Ga2O3 power transistor URL

Skills

Students will gain the ability to:

- Use commercial simulation software widely used in the semiconductor device industry
- Undertake a focused literature review and identify future trends for high impact
- Understand semiconductor device physics and optimize device design to improve performance

MD-M3 : Developing the atomic force microscope of the future with full automation

Supervisor: Dr. Massimo Antognozzi (Mat.Dev.)

MSci
60/30

Description

The nanophysics group in Bristol has produced some crucial developments of the atomic force microscope (AFM), especially related to high-speed microscopy and extreme force resolution applications. We now can break new ground by developing the blueprints for a fully automated AFM that could image at high speed and measure sub-picoNewton forces. The project builds on the results obtained in the previous iteration, where we introduced critical improvements in the AFM. In particular, a new micro-cantilever holder was introduced that can facilitate tip-exchange automation. During the project, you will have the opportunity to interact with members of the Engineering Systems and Design Research Group to design a completely integrated solution for sample and probe exchange. We will also consider future requirements, such as sample preparation and probe functionalisation, to ensure our design is compatible with these standard procedures in atomic force microscopy. To keep the project within the time available, after the initial assessment of the design solution space, you will start working on one particular area of the problem (i.e. tip exchange or sample exchange). Depending on the type of automation implemented, the last part of the project will focus on one key application to demonstrate the advantages of this approach. Specifically, we could use the improved system to obtain better precision on our spin optical momentum measurements or significantly improve the statistics when imaging biomolecules using AFM.

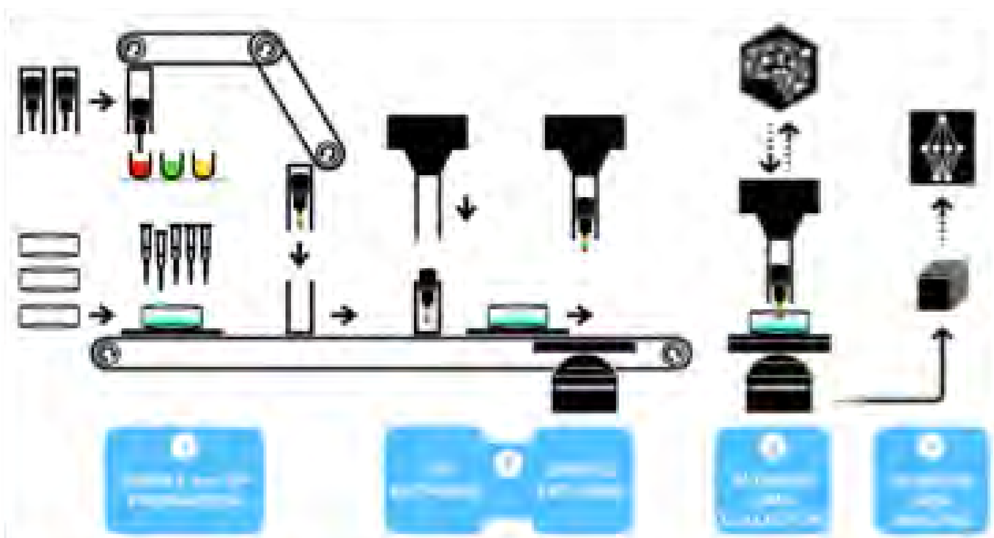


Figure: How the new design can unlock the four automation levels required for full AFM automation. A conventional automated micropipetting combined with a conveyor system can directly prepare and deliver samples to the microscope (level 1 and 2). Similarly, the micro-cantilever holder can be used for probe functionalisation, while the same conveyor belt design can deliver the probe to the microscope head. AI can control the fully motorised microscope for data acquisition (3) and perform data analysis (4). Adapted from [1].

Key References

1. Szeremeta, W. K., et al, Towards a Fully Automated Scanning Probe Microscope for Biomedical Applications. Sensors, 21(9), 3027 (2021).
2. L M Picco et al, Breaking the speed limit with atomic force microscopy, Nanotechnology, 18, 044030 (2007).
3. Antognozzi, et al, Direct measurements of the extraordinary optical momentum and transverse spin-dependent force using a nano-cantilever. Nature Phys 12, 731–735 (2016).

Skills

- The project will develop skills in applied instrumentation and control, such as using dedicated finite element analysis software and acquiring basic principles for implementing automation in measuring devices.
- The project will also introduce the students to data science for control systems.

MD-M4 : Investigation of bouncing oil droplets as a macro-scale analogue of Quantum Physics effects.

Supervisor: Dr. Massimo Antognozzi (Mat.Dev.)
Co-supervisor: Dr. Karim Thebault (Philosophy Department)

MSci
60/30

Description

The wave-particle duality is one of the most puzzling aspects of quantum Physics, and it is generally considered an atomic-scale phenomenon. In 2006, Yves Couder and his group showed that a vertically oscillating oil bath could sustain the bouncing of sub-millimetre size oil droplets. Furthermore, Couder observed that the interaction between the droplets and the bath produced standing waves on the surface of the oil that became linked to the particle. Surprisingly, when these droplets moved through apertures created just below the oil surface, they selected well-defined paths reminiscent of the interference effects produced by photons through a slit. As suggested by Bush and co-authors, these walking droplets resemble, at the macro-scale, the pilot wave theory developed by Louis de Broglie in 1926. This year project is the continuation of a very successful project run in a previous year, where we built and tested the apparatus to generate, sustain and record the droplets. This new project investigates how far the bouncing oil droplets can be used as a macro-scale analogue of the quantum realm. We will also use the most recent developments in the field to upgrade our system and the experimental protocol. In addition, the project will benefit from the collaboration with Dr Karim Thebault in the Department of Philosophy. With Dr Thebault, we will investigate the potential implications of this experiment for the interpretation of Quantum Physics and, more generally, the power of analogues in Physics.

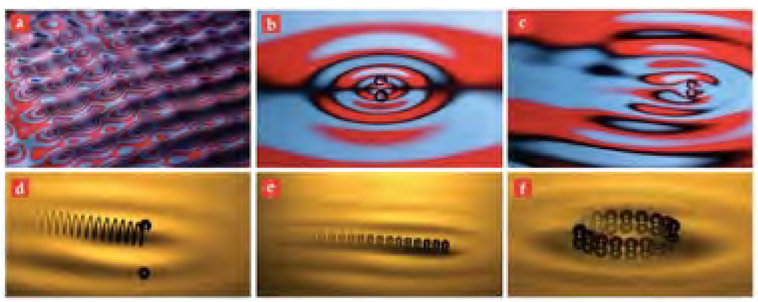


Figure: examples of stable oil droplets bouncing on an oil surface. see Bush, Physics Today (2015)

Key References

1. Brun, P. T., et al,Shedding light on pilot-wave phenomena. Phys. Rev. Fluids 1, 050510 (2016).
2. Harris, D. M., et al, Visualization of hydrodynamic pilot-wave phenomena. Journal of Visualization 20, 13–15 (2017).
3. Fort, E., et al, Path-memory induced quantization of classical orbits. Proc. Natl. Acad. Sci. USA 107, 17515–17520 (2010).
4. Couder, Y. , Fort, E. Single-particle diffraction and interference at a macroscopic scale. Phys. Rev. Lett. (2006).
5. Evans, P.W., Thébault, K.P.Y. What can bouncing oil droplets tell us about quantum mechanics?. Euro Jnl Phil Sci 10, 39 (2020).
6. Bush, J.W.M. Pilot-Wave Hydrodynamics. Annual Review of Fluid Mechanics, 47 (1), 269–292 (2015).

Skills

- The project will develop experimental skills to reproduce Couder's and Bush's results.
- In addition, analytical skills will be required to understand how far this macroscopic analogue of quantum systems can be extended before losing its predictive power.
- A deeper understanding of the value of analogues in Physics will also be developed through collaboration with Dr Karim Thebault in the Department of Philosophy.

MD-M5: Smart Windows

Supervisor: Dr. Natasa Vasiljevic (Mat.Dev.)

MSci
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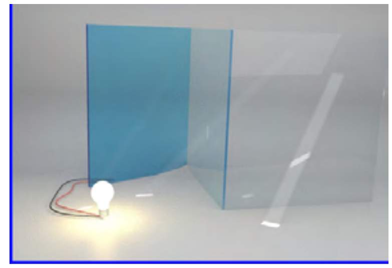
Description



Electrochromic materials dynamically change colour under applied voltage, and they are exploited in 'smart windows'. An ideal smart window material should independently control the transmittance of visible sunlight and solar heat into a building. Desirable properties will depend on the (nano)structure, thickness and composition of the material.
The most studied smart window material is WO_3 (tungsten trioxide). The colour change in WO_3 involves the insertion and removal of charged ions (such as H^+, Li^+, or Na^+), also known as the intercalation process.
Some of the most exciting directions of current research to improve WO_3 performance and range of applications include: design of nanostructured films for portable and bio-sensing platforms; design of composites to obtain a range of different colours; doping of WO_3 to improve performance and use as energy storage; extending stability and durability upon repeated cycling between coloured (blue) and transparent states.
The project will be focused on making WO_3 films and studying their electrochromic properties. The key investigations during the project will include the following:

- Design of nanostructured WO_3 layers using the electrodeposition method.
- Characterisation of their structural (crustal structure and morphology) and optical properties (transmittance, absorbance and reflectance);
- Measurements of smart windows properties, such as such as colouration efficiency and switching response time between the coloured and non-coloured (bleached) states dependent on the film thickness and nanostructure of the films.

Key References

1. C.G. Granqvist, Thin Solid Films **564**, 1 (2014) https://doi.org/10.1016/j.tsf.2014.02.002
2. R. J. Mortimer, Annual Review of Materials Research **41**, 241 (2011); https://doi.org/10.1146/annurev-matsci-062910-100344
3. G. Cai, J. Wang, and P.S Lee, Accounts of Chemical Research **49**, 1469 (2016) https://doi.org/10.1021/acs.accounts.6b00183

Skills

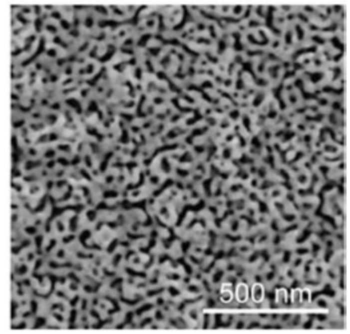
- Electrochromism and optical characterisation of the materials
- Introduction to electrochemistry and electrochemical methods
- Thin film growth
- Surface characterisation using AFM, and SEM techniques.

MD-M6: Nanoporous gold - material for sensing catalysis and energy storage

Supervisor: Dr. Natasa Vasiljevic (Mat.Dev.)
Co-supervisor: Dr. Andrei Sarua

MSci
60/30

Description



In this project, you will design and explore the properties of nanoporous gold (NPG) for potential use as active substrates in molecular detection (sensors), catalysis (environmental remediation) and energy (generation and storage). Nanoporous gold is a highly porous material composed of an interconnected three-dimensional network of pores and Au ligaments. The pores can range from a few nanometres to hundreds of nanometres. NPG is known for its unique physical, mechanical and chemical properties, high surface area, and excellent biocompatibility. The NPG also has a desirable nanostructure that can be exploited in strong coupling with light in plasmonic applications. These properties make it an attractive material for sensors, catalysis, energy storage, and biomedical devices. NPG is produced from Au-containing alloys, such as AuAg, by selective dissolution of a less noble metal component (such as Ag). This process is a corrosion process, also known as dealloying, and it can be done via chemical or electrochemical metal dissolution routes. The pores and ligament sizes can be tailored by a 'parent' alloy composition, the method and temperature of selective dissolution, and the post-thermal treatment.
We will use a commercially available 12-carat white-gold decorative leaf (AuAg alloy with 50wt% of Au) in the form of a very thin foil of 0.1-0.5 μm thickness. The foil will be dealloyed to form a free-standing, large-area, nanoporous gold that will be transferred to a solid support and characterised by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The project will include the following: a) design of a set-up that will enable the handling and transferring of gold leaves and derived NPG structures; b) development of NPG surfaces with different porosity and active areas, either by controlling the dissolution or thermal post-treatment; c) explore developed NPGs in one of the potential applications, such as biosensing (in glucose or DNA sensing), photocatalytic removal of toxic dyes from water, energy storage (as supercapacitor) or as active electrodes for surface-enhanced Raman scattering (SERS).

Key References

1. Y. Ding et al., Advanced Materials **16**, 1897 (2004) https://doi.org/10.1002/adma.200400792
2. S. H. Kim, Current Applied Physics **18**, 810 (2018); https://doi.org/10.1016/j.cap.2018.03.021
3. A. N. Koya, ACS Nano **15**, 6038 (2021);https://doi.org/10.1021/acsnano.0c10945

Skills

- Dealloying and metal corrosion basics
- Surface characterisation of materials using SEM and TEM.
- Processes and interactions of molecules on metal surfaces

MD-M7: PROVE Cubesat thermal imager

Supervisor: Dr Andrei Sarua (Mat.Dev.)
Co-supervisor: Prof. Lucy Berthoud (AS Eng)

MSci
60/30

Description

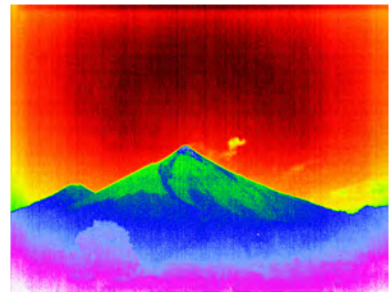


Figure shows a Fuego volcano in IR

This project is a part of University of Bristol PROVE Cubesat development[1] and aims is to exploit progress in uncooled bolometer array thermal imaging technology.[2] Combining this technology with a flexible low-cost CubeSat platform has the potential to provide frequent and accessible thermal images of ground targets, such as volcanic eruptions from low earth orbit. To discriminate ash plumes from clouds method based on two spectroscopic channels at 11.2µm and 12.6µm is required,[3,4] which can be captured by such detector. While the performance of a uncooled bolometer array is limited, it is possible to develop an effective instrument and measurement protocols which could be useful for determination of signal differences down to 1K level over the range 220 to 300K with a ground resolution of 50m. This would be sufficient to achieve the Bristol Cubesat mission goals. In this project, the team will: • Explore design and performance of uncooled thermal imagers and methods of instrument calibration on the ground and in space. • Characterise the performance of a prototype miniature thermal imaging camera (in terms of brightness temperature accuracy and split window relative performance). • Propose, built and test a prototype CubeSat camera design for imaging volcanic eruptions based on the above results and developed calibrations.
You will be a part of a larger Bristol Cubesat team of undergraduates working on different aspects of the satellite.

Key References

1. http://www.uobsat.uk/
2. http://www.flir.co.uk/home/
3. A.J. Prata, C. Bernardo, Retrieval of volcanic ash particle size, mass and optical depth from a ground-based thermal infrared camera, Journal of Volcanology and Geothermal Research, 186 (1–2), 91-107 (2009). https://doi.org/10.1016/j.jvolgeores.2009.02.007
4. Prata, A., Dezitter, F., Davies, I. et al. Artificial cloud test confirms volcanic ash detection using infrared spectral imaging. Sci Rep 6, 25620 (2016). https://doi.org/10.1038/srep25620
5. D.P. Osterman, S. Collins, J. Ferguson, W. Good, T. Kampe, R. Rohrschneider and R. Warden (2016) "CIRiS: Compact Infrared Radiometer in Space", Proc SPIE Vol. 9978 99780E-1.

Skills

- Scientific instrument design and testing for space.
- Thermal physics and computer thermal modelling
- Electronics

MD-M8 : The phase chemistry and microstructure of pattern welded steel

Supervisor: Dr. Tomas Martin (Mat.Dev.)

MSci
60/30

Description

Damascus steel, or pattern-welded steel, is a technique that expert blacksmiths have used since ancient times to create blades and tools with a balance between a sharp edge and strength. The technique, in which two types of metal with different carbon concentrations are twisted or folded together and then hammered and folded further at temperature, results in a beautiful two-phase structure visible by eye. This method was used regularly by the Celts and Romans to add strength and decoration in their blades and is perhaps most famous in Viking weapons. Damascus steel from India was credited to the superior steel encountered by Christian warriors during the Crusades, and the pattern welding technique is still used today in high-end kitchen knives, samurai swords and historical replicas.

Pattern-welded steel is an example of a hypereutectoid steel. Because the two phases are so different in structure and carbon concentration, the material offers an interesting subject for the study of metallurgy and phase chemistry. For example, computational modelling predicts that the composition should become homogenous at the temperatures experienced in a forge, but clearly from the pictures of pattern-welded material this doesn't entirely occur and differences in composition are 'trapped' during the process.

In this project, students will analyse the structure pattern-welded steel made traditionally by a blacksmith, with pieces having been cut from the blade at different stages of the process. Students will compare the microstructure of these pieces using electron microscopy to determine the phase fractions and compositions. They will then expose the pattern-welded steel to a series of different annealing temperatures to observe the way the structure changes under heating. Using a combination of microstructural characterisation and phase modelling of the Fe-C phase diagram, the students will match the microstructure observed to the phases expected thermodynamically, to understand why this type of metal has the structure it does, and why it had such a historical reputation for excellence.

Key References

1. J.D. Verhoeven, Materials Technology: Steels Research **73**, 356-365 (2002)
   https://doi.org/10.1002/srin.200200221

2. S.A. Fedesov, Metallurgist **51**, 681-695 (2007)
   https://doi.org/10.1007/s11015-007-0123-0

3. P. Kürnsteiner, et al. Nature **582**, 515–519 (2020)
   https://doi.org/10.1038/s41586-020-2409-3

Skills

- Scanning electron microscopy
- Computational modelling of phase diagrams
- Understanding the microstructure of steel

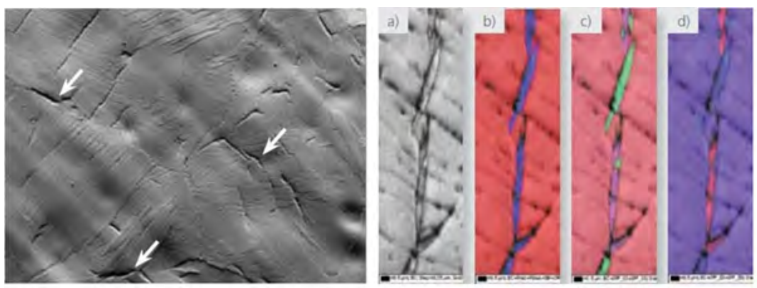
MD-M9 : Electron backscatter diffraction studies of hydrogen embrittlement in fuel cladding

Supervisor: Dr. Tomas Martin (Mat.Dev.)
Co-supervisor: Dr. Mariia Zimina

MSci
60/30

Description

Zirconium alloys are used in nuclear reactor cores as a fuel cladding under high-temperature water environments. During service, hydrogen is generated by corrosion processes, and is readily absorbed by these materials. When hydrogen concentration exceeds the terminal solid solubility, excess hydrogen precipitates as zirconium hydride (ZrH2) platelets or needles. Zirconium alloys are susceptible to a mechanism for crack initiation and propagation termed delayed hydride cracking (DHC). The presence of brittle hydrides results in a severe loss in ductility and toughness when platelet normal is oriented parallel to the applied stress. When a platelet reaches a critical length it ruptures. If the tensile stress is sufficiently great, crack initiation starts at some of these hydrides. Crack propagation occurs by repeating the same process at the crack tip. Delayed hydride cracking can degrade the structural integrity of zirconium alloys during reactor service. This project focus on a microscopic study of preloaded hydrided Zr1Nb alloy with varying amount of hydrogen content. Electron backscatter diffraction (EBSD) will be used to study the local stresses and orientation of ZrH2 hydrides in the specimens to understand the fracture mechanics and aspects of the effect of load conditions on hydride behaviour in the material.



Hydrides distribution in zirconium alloy (white arrows) a) pattern quality, b) phase composition (red=Zr and blue=ZrH2), c) IPF X and d) IPF Z EBSD images.

Key References

1. R.M. Lobo, A.H. Andrade and M. Castagnet, 2011 International Nuclear Atlantic Conference, (2011) https://inis.iaea.org/collection/NCLCollectionStore/_Public/43/063/43063110.pdf

2. C.M. Silva, F. Ibrahim, E.G. Lindquist, J.W. McMurray and C.D. Bryan, Materials Science and Engineering: A **767**, 138396 (2019)
https://doi.org/10.1016/j.msea.2019.138396

3. Oxford Instruments NanoAnalysis, EBSD Characterization of Hydrides in Zirconium Alloys (2023) https://www.azom.com/article.aspx?ArticleID=10700

Skills

- Specimen metallographic preparation
- Scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD)
- Focused ion beam microscopy (FIB)

MD-M10: Tuneable Plasmonics for biosensing

Supervisor: Dr Andrei Sarua (Mat.Dev.)
Co-supervisor: Dr Natasa Vasiljevic

MSci
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Description

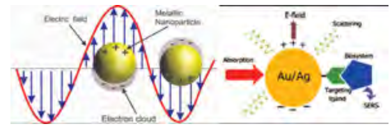


Figure shows localised surface plasmon and gold nanoparticle plasmonic antenna

The project aims to create large area nanostructured templates, consisting of metal plasmonic antennas. These templates have remarkable optical properties, allowing manipulation of light and ability to greatly enhance light-matter interaction, changing the absorption and emission patterns of surfaces and create localised surface plasmon resonances (LSPR) on the surfaces of the nanostructures. Hence there has been continual drive to design plasmonic nano-materials for numerous applications in molecular sensing and analysis, photo-catalysis, magnetic recording and light trapping.[1] Plasmonics is related to the localization, and directing of light through strong interaction of light with the free electrons in metal nanostructures. Concentrating light leads to an electric field enhancement owing to surface plasmons that can be used to manipulate light–matter interactions. One of the main drivers for the development of plasmonic materials has been the gigantic signal enhancement that can be achieved in surface-enhanced Raman spectroscopy (SERS) on metallic structures much smaller than the wavelength of light. SERS is a powerful analytical tool with the potential to provide structural information of singe molecules as well the surface and interfacial processes in variety of applications such as biophysics, catalysis, medical diagnostics, security and environmental monitoring.[2] More recent interests include efficient plasmon-enhanced photovoltaics and composite photocatalysts where the surface plasmon induced light concentration generally occurs at the interface between the metallic nanostructure and dielectric layer.[3] In this project you will explore fabrication of the plasmonic structures and optical and surface characterisation. This work also will be complimented by numerical modelling using FDTD code on Bluecrystal.

Key References

1. W.L. Barnes, A. Dereux, T.W. Ebbsen, Surface plasmon subwavelength optics, Nature, 424 (2003) 824.
2. M. Stockman, Nanoplasmonics: The physics behind the applications, Physics Today, 64, (2011) 39.
3. N. Shiming, S.R. Emory, Probing Single Molecules and Single Nanoparticles by Surface-Enhanced Raman Scattering, Science, 275 (1997) 1102.
4. P. K. Jain, X. Huang, I. H. El-Sayed, M. A. El-Sayed, Noble Metals on the Nanoscale: Optical and Photothermal Properties and Some Applications in Imaging, Sensing, Biology, and Medicine, Accounts of Chemical Research 41, (2008), 1578.
5. X. Li, C. Jia, B. Ma, W. Wang, Z. Fang, G. Zhang, X. Guo, Substrate-induced interfacial plasmonics for photovoltaic conversion, Scientific Reports 5, (2015), 14497.

Skills

- Fundamentals of nanoscale properties of materials and light interactions
- Metal electrodeposition and lithography
- Optical spectroscopy, AFM, SEM, EDX, TEM characterisation
- Finite-element optics modelling

MD-M11 : High-speed atomic force microscopy of aerospace materials

Supervisor: Dr. Tomas Martin (Mat.Dev.)
Co-supervisor: Dr. Stacy Moore

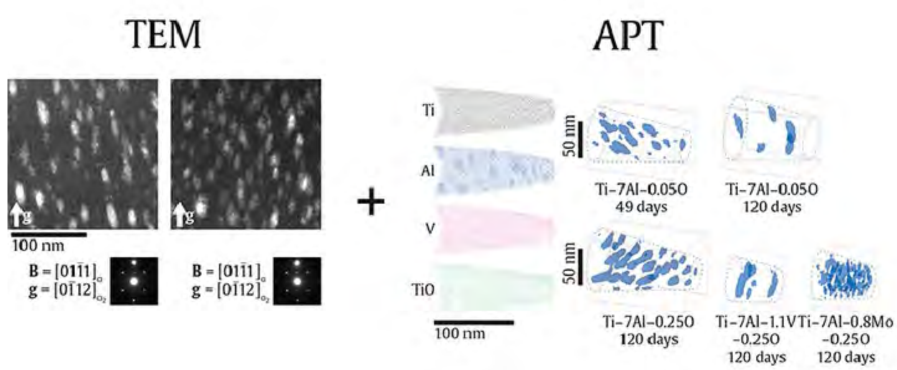
MSci
60/30

Description

The high temperatures, stresses and challenging environments of aerospace components require the use of advanced materials such as titanium and nickel alloys and composites. Understanding how these materials evolve during operation is essential to improve performance and prevent undesirable degradation that could result in premature failure. Many of these degradation mechanisms involve the formation of features at the nano-scale that are challenging to observe.

This project will use the nano-scale mapping capability of high-speed atomic force microscopy (HS-AFM) to map the surfaces of polished specimens of well-known aerospace alloys such as titanium-64 and Inconel 718 used in aircraft undercarriage and turbine engines. Short range ordered alpha 2 precipitates in titanium alloys and gamma double-prime in Inconel718 have formerly been identified by transmission electron microscopy (TEM) and atom probe tomography (APT). These are time consuming techniques, and HS-AFM's high spatial resolution and fast acquisition time may prove a valid alternative.

This project will look to understand how HS-AFM can be used for rapid recognition and characterisation of material phases in thermally aged and pre-over-temperatured specimens, and to understand size and morphology change against overtemperature – to assist with in-service component temperature exposure understanding. This project is of interest to Rolls-Royce plc (Bristol), and will include some supplementary industrial supervision from there.



TEM and atom probe tomography of precipitates in aerospace alloys.

Key References

1. A. Radecka et al, Acta Materialia, **112**, 141-149 (2016) https://doi.org/10.1016/j.actamat.2016.03.080
2. F.F. Dear et al, Acta Materialia **212**, 116811 (2021) https://doi.org/10.1016/j.actamat.2021.116811
3. O.D. Payton, L. Picco and T.B. Scott, International Materials Reviews, **6608**, (2016) https://doi.org/10.1080/09506608.2016.1156301

Skills

- High-speed atomic force microscopy
- Scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD)
- Focused ion beam microscopy (FIB)

MD-M13 : Harvesting phonons with graphene and diamond

Supervisor: Prof. Neil Fox (Mat.Dev.)
Co-supervisor: Dr. Jude Laverock

MSci
60/30

Description

In conventional voltaic devices a significant amount of energy is lost ultimately as heat. Some of this lost energy manifests itself briefly as optical phonons (lattice vibrations) and these can be recovered in the same way as exitons if a material is present with a band gap small enough to capture these quanta. In synthetic diamond optical phonons can have energies that are five or six times kT (kT 25meV), so a conceptual phonovoltaic device operating at room temperature would be feasible. The addition of a phonovoltaic structure to a diamond betavoltaic battery could significantly enhance its ability to convert nuclear beta decay energy into useful electrical output. In this project you will construct a phonovoltaic structure using semiconducting diamond and graphene and use it to study phonon generation and harvesting using the photoemission tools installed on the Bristol NanoESCA in the Nano Science and Quantum Information Building. This experiment involves training and the use of ultra high vacccum techniques including X-ray photoemssion spectroscopy and ultra violet photoelectron spectroscopy and data reduction/analysis.

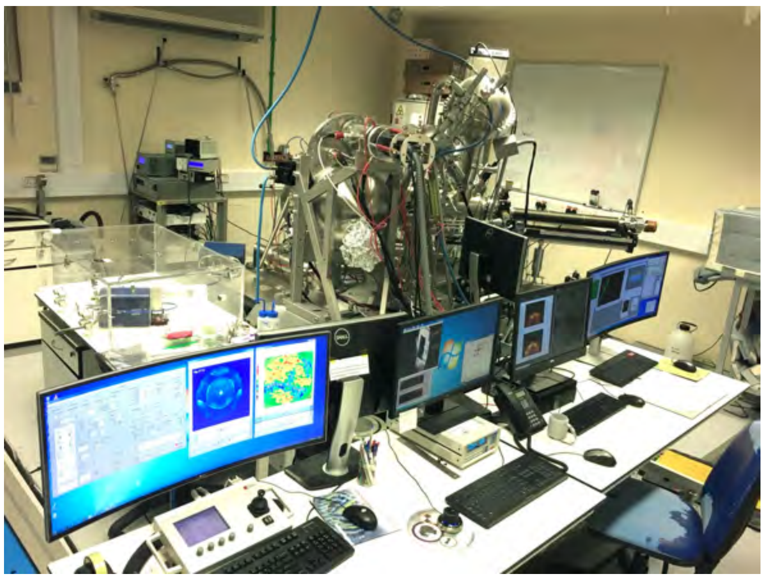


Figure shows the NanoESCA facility in the ultra quiet labs in NSQI K

Key References

1. K O'Donnell et al., J. Phys.: Condens. Matter **26 (2014) 395008**
2. C.Melnick,M Kaviany, Appl. Phys. Rev. **. 6, 021305 (2019); https://doi.org/10.1063/1.5031425**

Skills

- Material Synthesis of structure on single crystal diamond.
- Material characaterisation using NanoESCA facility.

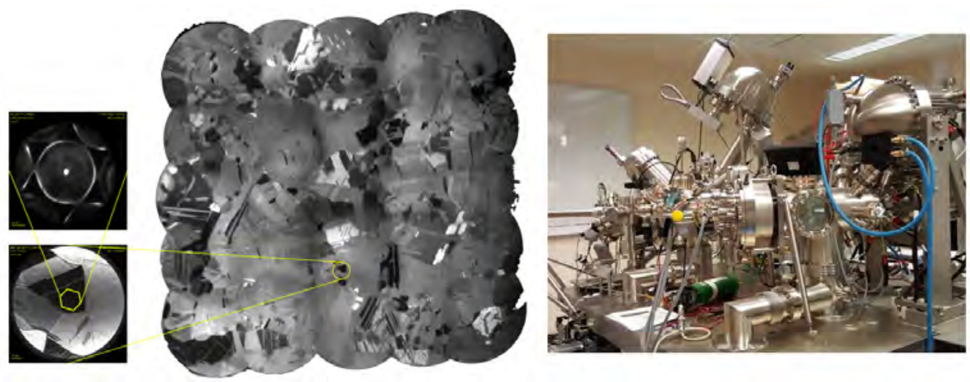
MD-M14 : Photoemission microscopy of 2D materials

Supervisor: Prof. Neil Fox (MD)
Co-supervisor: Dr. Jude Laverock

MSci
60/30

Description

The photoelectric effect was instrumental in the early development of quantum mechanics, and describes the emission of electrons due to illumination by light. Analysing these so-called photoelectrons – specifically their energy and momentum – is now commonplace, and provides a wide range of detailed information on the underlying electronic properties of a material. The NanoESCA instrument in Bristol combines such photoelectron spectroscopy with microscopic information in *where* the photoelectrons originated from in a technique called PhotoElectron Emission Microscopy (PEEM).
In this project, you will learn how to use the NanoESCA PEEM instrument to acquire three-dimensional spectro-microscopic data from the surface of 2D materials. These materials are of particular interest for future low-power, high-efficiency electronic devices. You will compare data using different light sources, including some new light sources that have recently been installed on the instrument. The goal of the project is to combine data from the different light sources to reveal new information on the electronic structure and micro-structure of the material.



(Left) PEEM image of the surface of silver; (Right) the NanoESCA instrument.

Key References

1. M. Cattelan and N.A Fox, Nanomaterials **8**, 284 (2018)
   https://doi.org/10.3390/nano8050284
2. G. Wan *et al.*, Adv. Funct. Mater. **3**1, 2007319 (2021)
   http://doi.org/10.1002/adfm.202007319

Skills

- Surface science and ultra-high vacuum techniques
- Analysis of large datasets
- Photoemission microscopy and spectroscopy

MD-M15 : The effect of high temperature thermally treatment to the microstructure and local properties of SiC/SiC composite cladding material

Supervisor: Dr.Dong Liu (Mat.Dev.)

MSci
60/30

Description

Due to its low neutron absorption and good corrosion resistance, Zirconium-based alloys (Zircaloy) are widely used as fuel cladding materials in water-cooled nuclear reactors. However, during design-basis accident (DBA) and loss of-coolant accident (LOCA) conditions, Zircaloy can rapidly oxidize in high-temperature steam and release combustible hydrogen gas. As such, it is planned to apply a Cr coating to the Zircaloy cladding to increase it's accident tolerance. There are two common methods for applying Cr coating on the Zircaloy: cold spray (CS) and physical vapor deposition (PVD). For CS process, the Cr particles are accelerated to a high speed by the carrier gas, which is forced through a spray nozzle; upon impact, Cr particles deform plastically and bond mechanically to the substrate and finally form the coating. In comparison, for PVD method, Cr materials are firstly vaporized in vacuum and then deposited on the substrate surface to form the coating. These two coating processes result in varied crystal sizes and structures which subsequently affect the coating local properties and mechanical performances. For these materials, you will first use a high temperature furnace for thermally treatment in various temperatures and times. You will then use nano-identation to quantify the local properties of coating and substrate and scanning electron microscopy for microstructural characterization of these thermally treated materials. Also, electron backscatter diffraction will be helpful to detect the of grain sizes and orientations of Cr grain inside coatings. Your results will be feed back to the processing to better the materials design and will have the opportunity to participate in journal paper writing.

Key References

1. Yang et al, Review on chromium coated zirconium alloy accident tolerant fuel cladding, Journal of Alloys and Compounds, 2022, URL

2. Jiang et al, Comparative study on the tensile cracking behavior of CrN and Cr coatings for accident-tolerant fuel claddings, Surface and Coating Technology, 2021, URL

3. de Menibus et al, Thermomechanical loading applied on the cladding tube during the pellet cladding mechanical interaction phase of a rapid reactivity initiated accident, Journal of Nuclear Materials, 2014, URL

Skills

- Image analysis software training
- Imaging and diffraction experimental skills
- Mechanical properties of materials
- Accident tolerant fuel designs

MD-M16 : Investigating local microstructure and residual stresses in TRISO particle layers

Supervisor: Dr.Dong Liu (Mat.Dev.)

MSci
60/30

Description

Moving forward with GEN IV reactor designs, fuels with increased accident tolerance and improved capabilities are on the rise. TRISO fuel particles are an evolution of coated fuel particles which first originated in the Dragon reactor of the 1960s. Current applications of TRISO particles include embedding them in a graphite or a SiC matrix, where they can then be compressed into fuel compacts for block type high temperature gas reactors or spherical fuel elements for pebble type high temperature gas reactors. To ensure the performance of these fuel particles at extreme conditions, investigations into their local microstructure and any residual stresses is key to correctly predicting their behaviours and lifetime within a working reactor.
While the materials used in TRISO particles, pyrolytic carbon (PyC) and silicon carbide (SiC), are well known and well investigated, any changes in associated material characteristic constants have not been investigated once these materials have been manufactured into TRISO particles.
This project will mainly be focussing on the application of Raman spectroscopy to investigate how pressure/stresses affect Raman peak shifts, paired with Diamond Anvil Cell (DAC) measurements in the Earth Sciences department to calibrate pressure upshift conversion factors for the materials of the TRISO particle layers. Calibration of this conversion factor will allow for more accurate calculations of residual stresses and pressures within TRISO particle layers. Since this work will be an entirely novel application, the possibility of co-authorship on a paper is possible at the end of the project.

Key References

1. Demkowicz et al, Coated particle fuel: Historical perspectives and current progress, Journal of Nuclear Materials, 2019, URL
2. Hosemann et al, Mechanical characteristics of SiC coating layer in TRISO fuel particles, URL
3. Krajewska et al, Raman Spectroscopy Studies of TRISO-Particle Fuel, Journal of Physics, 2021, URL

Skills

- Raman Spectroscopy technique
- Diamond Anvil Cell theory
- Materials sample preparation training
- Presentation and paper writing skills (if results are good)

MD-M17 : Improving advanced technology nuclear fuels

Supervisor: Dr. Ross Springell (Mat.Dev.)
Co-supervisor: Dr. Chris Bell PDRA support: Dr. Lottie Harding

MSci
60/30

Description

Uranium dioxide has been the principal component of nuclear fuel in the majority of nuclear reactors worldwide for over 50 years. The commercial nuclear industry is now in a position at the initial construction phase of a new generation of reactors, where it can investigate potential candidate materials that might replace UO_2. The replacement is mainly driven by attributes, such as efficiency; UO_2 is not a good thermal conductor, and safety; at end of lifetime, in storage, uranium dioxide can form readily soluble higher oxides where it might dissolve, allowing highly radioactive fission products into the local environment.

Uranium nitride (UN) is a potential replacement, but fundamentally, its behaviour in the extreme environments that UO_2 is exposed to, are not well-understood. One of the major pitfalls of using this fuel is the poor corrosion behaviour when exposed to water or steam at high temperature. We plan to investigate the addition of thorium in this system. Using an actinide-dedicated thin film deposition system (https://nnuf-farms.bristol.ac.uk/) we will grow a series of uranium nitride thin films, both polycrystalline and single crystal with varying Th compositions. Their underlying thermal and corrosion properties will be investigated, using experiments designed by the student/supervisor team.

This project will involve working closely with the nuclear fuels team in the School of Physics; it will include creative experimental design, hands-on experience of working with radioactive materials, sample synthesis and sophisticated diffraction methods.

Figure (LHS) shows typical fuel pellets used around the world in thermal fission reactors and (RHS) the UoB actinide deposition facility with the sputtering plasma in action.

Key References

1. E. Lawrence Bright et al., Thin Solid Films **661**, 71 (2018)
   https://doi.org/10.1016/j.tsf.2018.07.018

2. Yun et al., Materials Reports:Energy **1**, 100007 (2021)
   https://doi.org/10.1016/j.matre.2021.01.002

Skills

- Thin film deposition
- X-ray reflectivity and diffraction

MD-M18 : Modelling the uranium-tritium reaction for fusion fuel storage

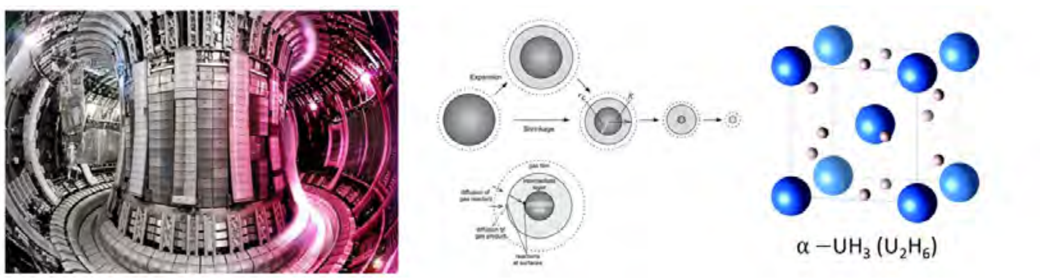
Supervisor: Dr. Ross Springell (Mat.Dev.) | MSci 60/30

Description

The fuel of choice for commercial fusion power is a mixture of tritium and deuterium, because the D-T reaction has a high cross-section at low enough temperatures and a high energy output. This is relatively well-known, however, what is not such common knowledge is that the storage of this material is very specialised, not simply high pressure cylinders! The lightes elements are stored in one of the heaviest, uranium.

For the JET programme, and planned for ITER, tritium is currently stored on beds of uranium metal, as uranium hydride. In a powdered, high surface area form, the uranium metal is able to react with the hydrogen (same for deuterium and tritium) in a passively safe way and it is then possible to retrieve the gas by gently heating to just 300°C. We have investigated this process experimentally at UoB for over a decade, but in the past year we have been developing a computational model for this process in order to better understand and predict possible scenarios in this intriguing system.

This project will focus on modelling the hydriding reaction in a particulate system and then further, investigate the isotopic dependence of this process with the aim of making a predictive tool for determining composition and decomposition rates in a UH_3 storage system (there may also be the opportunity to carry out benchmarking experiments in our radioactive materials laboratory). This could be extremely useful for the UoB fusion research group, but also have further applications with our partners at CCFE.



RHS shows fusion Tokamak, middle panel shows the shrinking core model proposed to simulate the particulate hydride reaction and RHS is the crystal structure of UH_3

Key References

1. A. Banos et al., Corrosion Science **136**, 120 (2018)
   https://doi.org/10.1016/j.corsci.2018.03.002
2. S. Imoto et al., International Journal of Hydrogen Energy **7**, 597 (1982)

Skills

- Metal-hydride reaction kinetics
- Computational modelling

MD-M19 : Machine learning for efficient analysis of multi-layer electronics device material thermal conductivities

Supervisor: Prof. Martin Kuball (QSM)
Co-supervisor: Dr. James Pomeroy

MSci
60/30

Description

Electronic devices such as used in power electronics for green energy saving technologies or for RF applications in mobile/satellite communication, have a stack of different materials (e.g. GaN, GaAs, SiC, Ga2O3), from active layers through to the substrate and packaging. For example, high power devices such as GaN RF amplifiers, used in mobile phone base stations or communication satellites, are thermally limited, means waste heat generated in the devices cannot extracted efficiently at present. Improving heat extraction is therefore a key challenge for improving this technology; corresponding challenges/limitations apply for high voltage electronics used in our national grid to feed in wind turbine or solar plant generated energy. High thermal conductivity heat spreading layers can be integrated, including diamond or composites, in the devices. However, the thermal boundary between different materials and the thermal conductivities of the materials themselves can have high uncertainties, making it difficult to predict/improve device thermal resistance. We have recently developed a frequency domain thermorelfectance (FDTR) technique for measuring the thermal properties of multi-layer electronic devices, which is also being applied to other fields, including nuclear and aerospace materials. There will be an opportunity to use finite element simulation (FE) to investigate how the thermal conductivity of each layer influences the overall thermal resistance.
FDTR uses a modulated heating (pump) laser, and another continuous laser reflected to monitor the surface temperature, which is phase shifted relative to the pump. Phase shift is plotted as a function of modulation frequency and an analytical heat diffusion model is fitted to obtain unknown material properties, e.g., the thermal conductivity of the nth layer. Least squares fitting and error estimation works well for 1 or 2 fitting parameters, but is less reliable for multiple fitting parameters, which is often the case.
The aim of this project is to investigate the most efficient and robust uncertainty estimation method for FDTR analysis. FDTR data sets will be provided, as well as the opportunity to do measurements. Existing Python code for least squares fitting and error estimation will be provided (including heat diffusion model for generating frequency vs phase plots). You will then apply the Monte Carlo method to the code above (running the code mentioned above repeatedly using randomised input parameters). Monte Carlo will give benchmark uncertainty estimates to test the robustness of the least squares method as the number of fitting parameters increases. Neural network machine learning is a novel data processing method which is fast and accurate. The possibility of applying machine learning based techniques will then be investigated, e.g., how to train a neural network (Pytorch) for FDTR data analysis.

Key References

1. N. Poopakdee et al., In situ Thermoreflectance Characterization of Thermal Resistance in Multilayer Electronics Packaging, ACS Appl. Electron Mater. 26, 1558 (2022).

2. J. Yan et al., Uncertainty analysis of thermoreflectance measurements, Review of Sci. Instruments 87, 014901 (2015).

3. Y. Pang et al., Machine learning-based data processing technique for time-domain thermoreflectance (TDTR) measurements, Journal of Appl. Phys 130, 094901 (2021).

Skills Training

- Frequency Domain Thermoreflectance measurement
- Finite element thermal analysis (ANSYS)
- Python

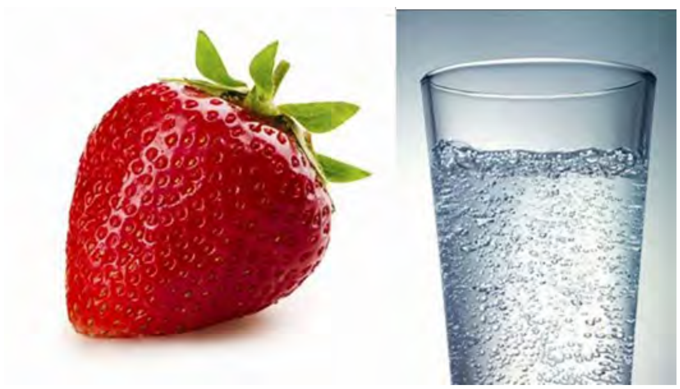
MD-M20 Fizzy Drinks

Supervisor: Prof. Annela Seddon (Mat.Dev.)
Co-supervisor: Prof. Peter Barham

MSci
60/30

Description

Fizzy drinks are usually made by injecting carbon dioxide at high pressure into the carbonated liquid. However, it is also possible often easier to make fizzy drinks of all kinds simply by adding a couple of dry ice pellets to the liquid to be carbonated. Carbon dioxide (CO_2) is much more soluble in water at low temperatures, than it is at high temperatures– so if you add solid carbon dioxide to cold water then as it sublimes much of the resulting gaseous CO_2simply dissolves in the water. Now if the liquid with dissolved carbon dioxide is warmed up – e.g. by putting in a glass, or in the mouth during drinking – as the temperature rises, so the solubility of CO_2 decreases and gaseous CO_2 is released in the form of bubbles thus making it appear fizzy. If a couple of pellets of dry ice are dropped into any drink it will become fizzy once all the solid CO_2 has sublimed. The maximum solubility of CO_2 in water at 0° C is 3.4g CO_2 per litre of water so a typical dry ice pellet weighing around 2g is sufficient to make glass of a fizzy drink. the purpose of this project to investigate at the use of cryo-carbonation sas well as carbonation under pressure to make fizzy solids, for example carbonated fruits such as oranges, grapes or peaches, or 'model' foods such as moulded jellies. You will design an experiment to measure the uptake of CO_2 into a range of edible gels with different shapes and degrees of cross-linking, and compare these with the literature. You will then test these methods with real fruit and propose why deviations from the model system may occur.



Key References

1. I Dalmolin et al. Fluid Phase Equilibria **245**, 193 (2006)
   https://doi.org/10.1016/j.fluid.2006.04.017
2. A.E. Illera et al. The Journal of Supercritical Fluids **143**, 120, (2019)
   https://doi.org/10.1016/j.supflu.2018.07.009

Skills

- Experimental design and building of apparatus to carbonate model systems
- Data fitting

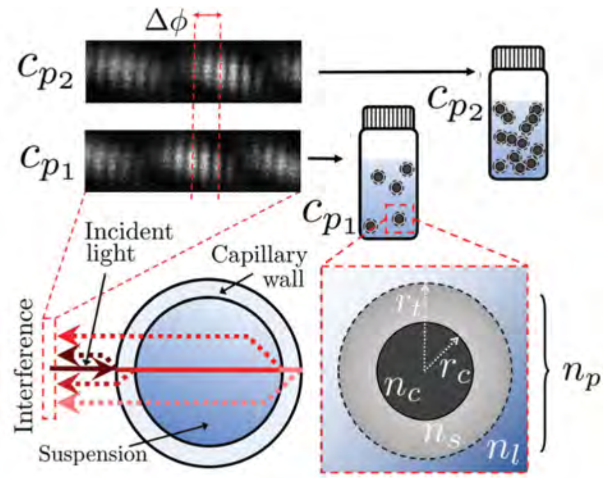
MD-M21 : Identifying contaminants in Semiconductor Fabrication by Atomic Force Microscopy

Supervisor: Dr. Ian Lindsay (Mat.Dev.)
Co-supervisor: Prof Andrew Humphris (Infinitesima Ltd / University of Bristol)

MSci
60CP

Description

Atomic force microscopy (AFM) is a powerful surface analysis technique capable of capturing 3D images of individual atoms and which ignited the nanotechnology revolution. Nanophysics research at Bristol, originally led by Prof Mervyn Miles, is known internationally for its development of a high-speed version of AFM - capable of imaging 100,000 faster than a normal AFM and has spun out a number of companies, including Infinitesima Ltd, founded by CTO Prof Andrew Humphris, which specialises in equipment for metrology and inspection in integrated process control, particularly in the semiconductor industry. One of the major current challenges in semiconductor manufacturing is that nanoparticle contamination as small as 15nm entering the fabrication process can cause devices to fail and wafer yields to fall. Determining the source of such contamination is extremely challenging without detailed knowledge of the composition of the nanoparticle in question. AFM technology, as used by Infinitesima, can easily resolve such particles even at wafer-scale. However, the AFM technique primarily measures sample topography and is generally unable to determine the material or chemical composition of contaminants.



Elastic modulus measurement on a 4x4μm area of a polystyrene-polycaprolactone blend taken using an Asylum MFP-3D Infinity AFM similar to that used in the research labs [1].

This project aims to explore whether local force measurement can assist with the compositional identification of nanoparticle contaminants. AFM has spawned a large number of techniques capable of measuring mechanical properties of samples at the nanometre scale such as Young's modulus, viscosity, surface adhesion and hardness [1]. However, quantitative interpretation of this data can be challenging which has, for example, led to the exploration of machine learning approaches as an adjunct to direct analytical interpretation [2]. Students working on this project will have access to research-grade AFM instruments capable of a range of imaging and force measurement modes and will explore the extent to which these can be used for nanoscale materials identification.

Key References

1. "The NanomechPro Toolkit: Nanomechanical AFM Techniques for Diverse Materials" and references therein. (Oxford Instruments application note).
2. Chandrashekar et al., Nanoscale Advances **4**, 9, 2134 (2022). https://doi.org/10.1039/D2NA00011C

Skills

- AFM imaging and force measurement techniques using a research-grade instrument.

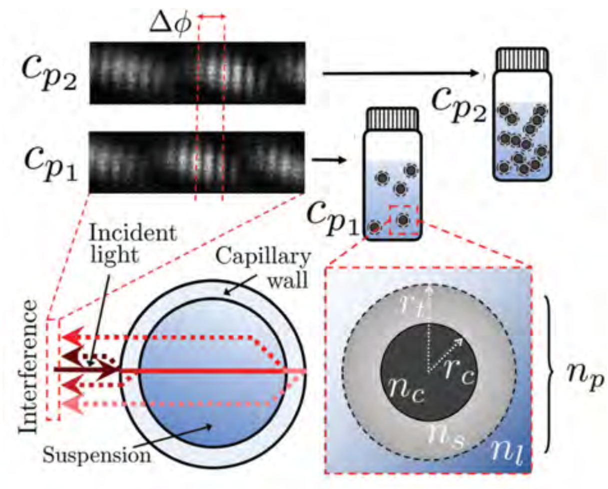
MD-M22 : Simplifying interferometric refractive index measurement of liquids

Supervisor: Dr. Ian Lindsay (Mat.Dev.)
Co-supervisor: Dr. Henkjan Gersen (iLoF / University of Bristol)

MSci
60CP

Description

We recently demonstrated the use of ”backscatter interferometry” (BSI) to measure the refractive index of nanometre sized particles[1]. BSI routinely enables refractive index measurements with a sensitivity 1 part in 10^6 and, with care, as high as 1 part in 10^8 allowing sensitive detection of changes in the concentration of dissolved components [2]. Such measurements have important applications in, for example, detecting binding between biomolecules or trace level pollutants in water supplies. An attractive aspect of BSI is its apparent simplicity: a capillary containing the analyte is illuminated by a laser and interference occurs between reflections from various glass-air and glass-liquid interfaces, encoding refractive index changes in the analyte as phase shifts in the resulting fringe pattern. However, while glass capillaries are commonplace in analytical labs, their cylindrical geometry yields multiple interference paths and overlapping fringe patterns only some of which encode refractive index, significantly complicating analysis [3].



Pictoral representation of BSI: Changes in surface functionalisation of suspended nanoparticles change the bulk refractive index of the liquid in the capillary causing a detectable shift in the interference pattern (reproduced from [1]).

One of the most basic optical interference effects achievable is that due to the wedge-shaped gap between two glass plates at a slight angle: an even simpler instance of the ”fringes of equal thickness” seen in a Newton’s rings experiment. This geometry would be expected to produce fringes at a single spatial frequency, whose phase depends on the refractive index of the material within the ”wedge”. Thus, at the expense of more complex fabrication, it should yield a BSI system with much simpler analysis than the commonly used capillary. This project will investigate BSI in wedge-shaped cells, establish the benefits of this geometry compared to the capillary and test the limits of sensitivity to refractive index changes (and therefore concentration of dissolved components) achievable.

Key References

1. Mulkerns et al. Nanoscale **14**, 22, 8145 (2022). https://doi.org/10.1039/d2nr00120a
2. Kussrow et al. Anal. Chem. **84**, 2, 779 (2012). https://doi.org/10.1021/ac202812h
3. Mulkerns, et al., Sensors, **22**, 2157 (2022). https://doi.org/10.3390/s22062157

Skills

- Design, construction and testing of optical and opto-electronic systems
- Computerised data acquisition and analysis

Theoretical Physics (TP)

Bristol has an outstanding record of world-class research in theoretical physics, with highlights including the discoveries of the Aharonov-Bohm effect and the Berry phase. Currently the group's research encompasses a wide range of phenomena in many-body and statistical physics, both in the quantum regime applied to condensed matter and cold-atom systems, and the classical regime applied to complex liquids and soft-matter systems. Theory at Bristol also has a long and distinguished tradition of research into the geometrical aspects of waves and physical asymptotics as well as quantum information theory and non-locality. Theoretical Physics at Bristol comprises nine academic staff who actively work on a broad range of problems divided into three strands: (i) **Quantum Information and Foundations** working to understand the unique and fundamental peculiarities of quantum mechanics; (ii) **Many-Body Physics of Quantum Matter** focused on unravelling the collective behaviour of interacting electrons in novel materials; and (iii) **Soft and Active Matter** studying the properties of complex liquids and ensembles of self-propelled particles. All of the projects across the Theoretical Physics theme will involve challenging analytical work, and some will require the use of sophisticated numerical/programming methods.

Quantum Information and Foundations

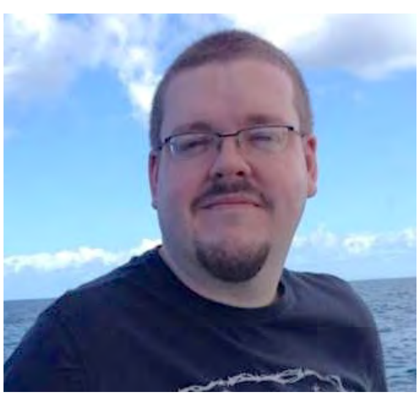
Dr. Paul Skrzypczyk

Dr. Tony Short

Prof. Sandu Popescu

Quantum mechanics, the theory that describes the behaviour of microscopic particles (atoms, molecules, subatomic particles) is our best theory of nature - it explains every experimental result with unprecedented accuracy. Yet, although its basic laws have been known for almost nine decades there is an almost universal consensus that we still do not have a deep understanding of its nature. Unexpected and almost paradoxical new results are discovered with disconcerting frequency – they are paradoxical only because we do not yet have the conceptual tools to explain them. Quantum information theory seeks to deepen our understanding of quantum theory so that we might harness its strange properties for information processing. Ideas from this field have shed new light on foundational problems. For example, part of the reason quantum mechanics is so counter-intuitive is that it is nonlocal. Quantum systems which interacted in the past and then moved away from each other, remain, in a certain sense, connected with one another. Nonlocality has played a central role in the study of quantum foundations and has subsequently stimulate new approaches to thermodynamics and statistical mechanics.

Many-Body Physics of Quantum Matter



Dr. Stephen Clark

Dr. Martin Gradhand

Prof. James Annett

The physical properties of solids depend crucially effects arising from systems composed of many electrons that not only behave quantum mechanically, but also interact strongly with one another. This enables delicate quantum effects to manifest collectively at a many-body level, giving rise to a tantalizing variety of novel phenomena like superconductivity. Recent spectacular experimental advances have further demonstrated that even richer physics emerges when quantum matter is driven out of equilibrium. Understanding all these behaviours remains one of the most challenging problems in modern physics. This theoretical research strand uses large scale supercomputer calculations to investigation of simplified model Hamiltonians exploiting numerical methods, including some inspired from machine learning and quantum information, as well as tools from quantum field theory and statistical mechanics. Systems of interest include unconventional superconductors, including high temperature superconductors as well as those with p-wave spin triplet pairing and topological properties, ferromagnet-superconductor nanostructures, and materials where interactions between spins, charges and orbitals give rise to novel magnetism, charge density waves or orbital ordering.

Soft and Active Matter


Dr. Thomas Machon


Dr. Simon Hanna


Prof. Nigel Wilding


Dr. Francesco Turci

Powerful techniques from statistical physics, geometry and topology are being combined and developed for applications to fluids, liquid crystals at interfaces and ensembles of self-propelled particles. For example inhomogeneities in density or magnetisation, which arise from the breaking of translational invariance, give rise to novel 'surface' phase transitions and critical phenomena which have no direct counterpart in bulk. Meanwhile the structure and bulk phase equilibria of simple models of polymers, colloidal suspensions and liquid crystals are being investigated using the methods of density functional theory, Monte Carlo simulations and via theories of topological defect dynamics. Beyond this new physics is also being explored in active matter where a "fluid" is built from objects that propel themselves with applications to systems of synthetic nano particles as well as bacteria and swarms of insects or birds.

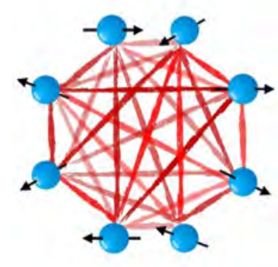
TP-M1 : Interacting quantum system on highly-connected graphs

Supervisor: Dr. Stephen Clark (Theory)

MSci
60/30

Description

A set of spins which are interacting according to a fully connected graph



The study of many-body quantum systems comprising of microscopic degrees of freedom (qubits/spins) interacting with each other is central to condensed matter physics and quantum technologies. Typically, for good reasons, research focuses on spins interacting locally with each other according to some regular graph, say like a simple cubic lattice. However, it is becoming an increasingly relevant question to ask what physics emerges in many-body systems where interactions between constituents is not limited to such geometries [1]. One reason is that quantum simulators, such as Rydberg atoms, ion-traps and superconducting circuits, can now implement interactions over long-ranges allowing novel patterns of interaction to be experimentally realised. Another reason is that the physics of highly connected graphs with randomness, such as the so-called Sachdev-Ye-Kiteav (SYK) model [2], have been shown to display very rich physics. Specifically, the SYK model has exotic non-Fermi liquid states without quasiparticle excitations, similar to the strange metal phase in optimally doped high-temperature superconductors, as well as a holographic duality analogous to Black-hole physics and quantum chaotic properties. The SYK model has also been implemented in a nuclear-spin quantum simulator [3].

This project will use tensor network methods to compute the ground state properties of interacting spin models in complex graphs similar to the SYK model. These sophisticated calculations will be performed using the ITensor package [4] based on the `Julia` programming language (no prior familiarity required). `Julia` code is similar to `Python` and can be conveniently executed inside a `Jupyter` notebook as well as on the BlueCrystal 4 high performance computing facility. The central scientific question to be explored is the interplay between connectivity of interactions and the randomness of their strength on the complexity of the ground state as quantified by it entanglement entropy scaling.

Key References

1. J. Tindall et al, Quantum physics in connected worlds, Nature Comm. **13**, 7445 (2022) URL
2. D. Chowdhury, Rev. Mod. Phys. **94**, 035004 (2022)URL
3. Z. Luo et al, npj Quantum Information **5**, 53 (2019).URL
4. ITensor documentation available at `https://itensor.github.io/ITensors.jl/stable/` and the paper `https://www.scipost.org/SciPostPhysCodeb.4`.

Skills

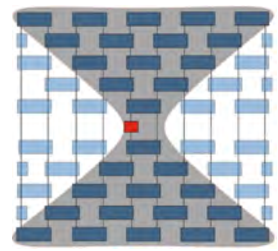
- Develops a deeper understanding of many-body quantum physics.
- Builds coding and analysis skills.
- Provides experience of using high-performance computing.

TP-M2 : Scrambling in quantum systems

Supervisor: Dr. Stephen Clark (Theory)

MSci
60/30

Description



Scrambling is the process by which quantum information spreads across a complex many-body quantum system making it inaccessible to local probes [1]. It commonly occurs in systems displaying chaotic behaviour. Like in the classic butterfly effect thought experiment, chaotic quantum evolution is characterised by an extreme sensitivity to initial conditions and a tendency for simple initial conditions to quickly develop into enormously complicated configurations with time. Chaotic behaviour occurs in system ranging from simple spin chains and quantum circuits to excitations in metals and even to black holes where scrambling relates to the information paradox. In short, scrambling is an important concept lying at the interface between quantum information, quantum matter and quantum gravity.
A concrete setting for scrambling considers the Heisenberg time-evolution of a local operator, say like a Pauli spin operator. This is depicted in the figure as the red-box conjugated by a quantum circuit. Generically we expect the local operator to evolve into a complicated mixture of operators spread over all the spins inside the light-cone. This complexity is quantified by so-called out-of-time-ordered correlators (OTOCs) [2]. This project will use tensor network methods to compute the OTOC for simple paradigmatic spin-chain models as well as for dual unitary quantum circuits [3]. These sophisticated calculations will be performed using the ITensor package [4] based on the `Julia` programming language (no prior familiarity required). `Julia` code is similar to `Python` and can be conveniently executed inside a `Jupyter` notebook as well as on the BlueCrystal 4 high performance computing facility. The central aim of the project is to test a conjectured universal form [2] for the OTOC wave-front propagation in a variety of novel settings.
Figure shows the emergent light-cone evolution of a local operator due to a generic brickwork quantum circuit of two-qubit gates from Ref. [2]

Key References

1. S. Xu and B. Swingle, Scrambling Dynamics and Out-of-Time Ordered Correlators in Quantum Many-Body Systems: a Tutorial, preprint URL
2. S. Xu and B. Swingle, Nature Phys. **16**, 199 (2020). URL
3. L. Piroli et al, Phys. Rev. B **101**, 094304 (2020). URL
4. ITensor documentation available at `https://itensor.github.io/ITensors.jl/stable/` and the paper `https://www.scipost.org/SciPostPhysCodeb.4`.

Skills

- Develops a deeper understanding of many-body quantum physics.
- Builds coding and analysis skills.
- Provides experience of using high-performance computing.

TP-M3: Simulating the resistive state in superconducting nanostructures

Supervisor: Dr Jonathan Fellows (Theory)

MSci 60

Description

The wikipedia article for Superconductivity begins: "Superconductivity is a set of physical properties observed in certain materials where electrical resistance vanishes and magnetic flux fields are expelled from the material."
This is wrong.
Or at least, the truth is more subtle, more intricate, and more interesting.
The wikipedia article goes on to qualify that in type 2 superconductors it is possible for a magnetic field to penetrate the material, but only by passing through isolated points known as vortices.
Vortices are an example of a topological defect, a concept which is fundamental to all kinds of theoretical physics ranging from condensed matter theory to cosmology.
Less well known, and very counterintuitive, is that sufficiently thin superconducting wires do proffer a finite resistance. The culprit in this case is another kind of topological defect, a so-called phase-slip centre. Both vortices and phase-slip centres can be seen to arise naturally from the governing equations of the superconducting state, the Time Dependent Ginzburg Landau (TDGL) equations. These equations are highly non-linear and exact solutions can only be found in highly contrived situations in special geometries. The goal of this project will be to develop a python code which uses modern finite-elements techniques to be able to solve the TDLG equations with different boundary conditions on arbitrary geometries. This code will then be used to explore how phase-slips and vortices emerge and evolve in complex superconducting nanostructures.
This project is well-suited to students with a strong mathematics and computer programming background who wish to develop skills in numerical analysis that are applicable in a wide range of contexts in science and engineering.

Key References

1. Ivlev, B. I., & Kopnin, N. B. (1984). Electric currents and resistive states in thin superconductors. Advances of Physics, 33(1), 47-114.
2. Halperin, B. I., Refael, G., & Demler, E. (2011). Resistance in superconductors. Bcs: 50 Years, 185-226.
3. Langtangen, H. P., & Mardal, K. A. (2019). Introduction to numerical methods for variational problems (Vol. 21). Springer Nature.

Skills

- Review literature on the resistive state in superconductors.
- Learn how to express a PDE in its variational form.
- Learn how to implement a finite-elements solver in the FEniCSx computing platform.
- Obtain and set up a computer account on the University supercomputer. Learn to submit jobs to supercomputer
- Scope to demonstrate strong computational and coding skills

TP-M4: Computationally Colliding Cold Condensates. . . Cool!

Supervisor: Dr Jonathan Fellows (Theory) MSci 60

Description

Bose-Einstein Condensation is the phenomenon in which a rarefied gas of bosonic atoms, chilled to a temperature close to absolute zero, can enter an exotic state of matter in which every atom occupies the same quantum state. In such a Bose-Einstein Condensate (BEC), quantum mechanical phenomena such as the diffraction and interference of matter itself can be observed on a macroscopic scale.
A celebrated experimental realisation of the quantum properties of the BEC involves taking two BECs trapped in potential wells, releasing the trap and allowing the BECs to collide. An interference pattern can then be seen in the expanding cloud of particles, demonstrating a quantum interference effect. Since its first demonstration [1], this experiment has been performed by groups across the world.
The goal of this project is to directly simulate the dynamics of a BEC, which are governed by the Gross-Pitaevskii equation, using the XMDS2 [2] PDE solver and to write custom analysis code with a view to reproducing the results of the colliding condensate experiment and then to investigate new experimental setups *in silico*.
This project is well-suited to students with a strong mathematics and computer programming background who wish to develop skills in numerical analysis that are applicable in a wide range of contexts in science and engineering.

Key References

1. Andrews, M. R., Townsend, C. G., Miesner, H. J., Durfee, D. S., Kurn, D. M., & Ketterle, W. (1997). Observation of interference between two Bose condensates. Science, 275(5300), 637-641. https://www.rle.mit.edu/cua_pub/ketterle_group/Projects_1997/Pubs_97/andr97-Science_int.pdf

2. Dennis, G. R., Hope, J. J., & Johnsson, M. T. (2013). XMDS2: Fast, scalable simulation of coupled stochastic partial differential equations. Computer Physics Communications, 184(1), 201-208. https://www.sciencedirect.com/science/article/pii/S0010465512002822?casa_token=oIImhPH_fIkAAAAA:0fdy3cB6Wi9lA8EPRcZSHaIcuem9WeRfwmRC4LWOwMPauwVklGOBQik_a9VHf9gWsv3mouHOfQ

Skills

- Review literature on Bose-Einstein condensation.
- Learn how to implement a fast PDE solver using XMDS.
- Obtain and set up a computer account on the University supercomputer. Learn to submit jobs to supercomputer.
- Scope to demonstrate strong computational and coding skills

TP-M5 : Particles in discrete space-time

Supervisor: Dr Tony Short (Theory)

MSci 60/30

Description

Could space and time really be discrete at some tiny scale (such as the Planck scale)? If so, how can we explain the apparently continuous evolution laws of the world around us?

In this project, we will investigate the dynamics of quantum particles in discrete space-time, using quantum walks from quantum information theory. We will be particularly interested in discrete models with a good continuum limit, where quantum states which are spread smoothly over many spatial sites change only slightly over some finite time interval. For example, there exists a simple model for a spin ½ particle moving on a body-centred-cubic lattice, which reproduces the relativistic Weyl equation ($H = \sigma.pc$) in the continuum limit. This model can also be extended to yield the Dirac equation. Note that despite the asymmetries of the discrete space-time lattice, the particle recovers full rotational and relativistic symmetry in the continuum limit.

The project will investigate other natural quantum walks and their continuum limit, including those with increased symmetry at the level of the discrete dynamics. We will also investigate how concepts like the Dirac sea can be transferred to this picture.

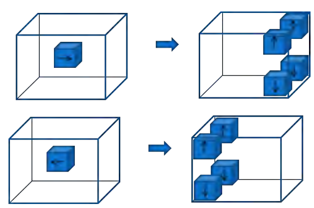


Illustration of a quantum walk generating the Weyl Hamiltonian

Key References

1. Weyl, Dirac, and Maxwell equations on a lattice as unitary cellular automata, I. Bialynicki-Birula. Phys. Rev. D, **49**:6920 (1994). https://doi.org/10.1103/PhysRevD.49.6920
2. Discrete Spacetime and Relativistic Quantum Particles, T.C.Farrelly and A.J.Short, Phys. Rev. A **89**, 062109 (2014). https://doi.org/10.1103/PhysRevA.89.062109
3. A review of Quantum Cellular Automata, T. Farrelly, Quantum **4**, 368 (2020). https://doi.org/10.22331/q-2020-11-30-368

Skills

- Mathematical analysis
- Deeper understanding of quantum theory and particle physics
- Computational skills to analyse and simulate quantum walks

TP-M6 : Probability in many worlds

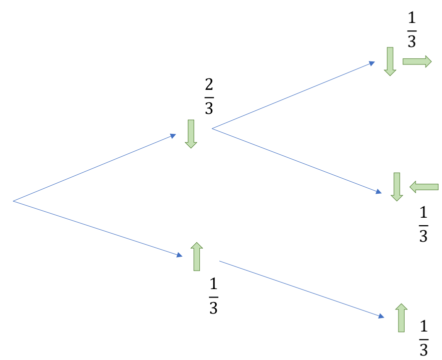
Supervisor: Dr Tony Short (Theory)

MSci
60/30

Description

In the many worlds interpretation of quantum theory, states evolve unitarily via the Schrödinger equation at all times. Instead of introducing separate probabilistic collapse laws, measurements are understood as a unitary branching of the quantum state into a superposition of different worlds, in each of which a different result is obtained. A key challenge is to understand how to recover the probabilistic predictions of quantum theory within this approach.

This project will investigate different approaches to this problem in the literature, and will seek to extend the recent results obtained in [1], in which the quantum probability distribution was recovered from a small set of natural assumptions. Possible extensions include replacing the fixed basis of worlds used with a more course-grained and flexible definition, exploring connections with the consistent histories approach, and attempting to construct other many worlds theories besides quantum theory.



A quantum state branching due to sequential spin measurements (an $\hat{S}_z$ measurement, followed by an $\hat{S}_x$ measurement if the first result was spin down), showing their associated probabilities.

Key References

1. Probabilities in many worlds, A.J.Short, https://arxiv.org/abs/2106.16145, accepted in Quantum (2022).
2. Derivations of the Born rule, L. Vaidman. In: Hemmo, M., Shenker, O. (eds) Quantum, Probability, Logic. Jerusalem Studies in Philosophy and History of Science. Springer, Cham. https://doi.org/10.1007/978-3-030-34316-3_26 (2020). http://philsci-archive.pitt.edu/15943/
3. The Quantum Measurement Problem: State of Play, D.Wallace, https://arxiv.org/abs/0712.0149. Ashgate Companion to the New Philosophy of Physics (2008)

Skills

- Understanding of quantum theory and its foundations
- Mathematical analysis and creativity

TP-M7 : Recycling quantum nonlocality

Supervisor: Dr. Paul Skrzypczyk (Theory)
Co-supervisor: Dr. Chung-Yun Hsieh

MSci
60/30

Description

Entanglement is one of the most important quantum properties of two or more particles. Entangled particles are inextricably linked in a manner which has no classical analogue. This leads to fascinating quantum effects all surrounding nonlocality, such as teleportation, Einstein-Podolsky-Rosen steering and Bell's theorem.

While standard demonstrations of quantum nonlocality based upon Bell's theorem consist of two parties who measure a pair of quantum particles, an interesting question was raised in [1]: whether it is possible to *recycle* (or share) the nonlocality of an entangled pair, and use them to generate nonlocal correlations between multiple parties, by considering the state of the pair of particles after the initial measurement, which is then passed on to further parties in a type of chain. Remarkably this was indeed shown to be possible in some situations.

The original demonstrations of nonlocality recycling were based upon the use of *weak* or *uninvasive* measurements, which did not appreciably reduce the entanglement of the pair of particles. A recent interesting paper [2] showed that – somewhat surprisingly – nonlocality recycling can be achieved using standard quantum measurements, as long as *classical randomness* is also used. This result raises many interesting questions, which will form the basis of this project.

In particular, possible directions this project could take include generalising the results of [2] in several ways, including to situations involving more recycling (more parties), considering higher-dimensional quantum systems, or recycling by both parties instead of just one. Alternatively, it could focus on studying the analogous type of nonlocality recycling, either for quantum teleportation or Einstein-Podolsky-Rosen steering.

Key References

1. R. Silva, N. Gisin, Y. Guryanova, and S. Popescu, *Multiple observers can share the nonlocality of half of an entangled pair by using optimal weak measurements*, Phys. Rev. Lett. **114**, 250401 (2015).
https://doi.org/10.1103/PhysRevLett.114.250401

2. A. Steffinlongo and A. Tavakoli, *Projective Measurements Are Sufficient for Recycling Nonlocality*, Phys. Rev. Lett. **129** (2022)
https://doi.org/10.1103/PhysRevLett.129.230402

Skills

- Analytical calculations in quantum nonlocality
- Scope for numerical investigation, in particular in numerical optimisation

TP-M8 : Indefinite quantum causal order

Supervisor: Dr. Paul Skrzypczyk (Theory)
Co-supervisor: Dr. Giulia Rubino

MSci
60/30

Description

The notion of causality is an innate concept, defining the link between physical phenomena that follow one another temporally, with one phenomenon being the cause of the other. In all established physical theories, for any two "causally related" events A and B, either A signals to B, or B signals to A. However, it has recently been realised that quantum mechanics may allow for the existence of causally-related processes that are neither causally ordered, nor a probabilistic mixture of causally ordered processes. For these processes, it is truly undefined whether A signals to B or B signals to A, and so they are called processes with an indefinite causal structure.

A particular model for the study of quantum causal relations is the 'process matrix framework' [1], where one considers parties performing operations that locally obey the laws of quantum theory, but globally are not embedded in any a priori causal structure. This framework allows for situations where the causal order between the parties is genuinely indefinite [2]. In particular, so-called *causal inequalities* have been derived, which play a role similar to Bell inequalities in the study of quantum nonlocality. These inequalities are satisfied whenever a process has a definite causal order, but can be violated by processes with indefinite causal order.

Very recently progress in this direction has been made, by combining the notion of indefinite causality with the notion of nonlocality [4]. In particular, it was shown that in the presence of a locality constraint on a spacelike-separated observer, it is possible to certify processes as being genuinely indefinite, that previously could not be shown to be. This result highlights the need for an extension of the framework of causal inequalities that incorporates locality constraints.

The aim of this project is to build upon [4] to further investigate the connection between nonlocality and indefinite causality. There are multiple directions that could be considered, including higher dimensional processes, or those involving more parties with additional locality constraints.

Key References

1. O. Oreshkov, F. Costa, and Č. Brukner, *Quantum correlations with no causal order*, Nat. Commun. **3**, 1092 (2012) https://doi.org/10.1038/ncomms2076
2. C. Branciard, M. Araújo, A. Feix, F. Costa, and Č. Brukner, *The simplest causal inequalities and their violation*, New J. Phys. **18**, 013008 (2016) https://doi.org/10.1088/1367-2630/18/1/013008
3. T. van der Lugt, J. Barrett and G. Chiribella, *Device-independent certification of indefinite causal order in the quantum switch*, arXiv:2208.00719 [quant-ph] https://doi.org/10.48550/arXiv.2208.00719

Skills

- Analytical calculations in quantum information theory and foundations
- Scope for some numerical investigation, in particular in numerical optimisation

TP-M9 : Hunting Majorana Fermions

Supervisor: Dr. Martin Gradhand (Theory)
Co-supervisor: Prof. James Annett

MSci
60/30

Description

Majorana-Fermions, quasiparticlss originally predicted by Ettore Majorana in 1937 have recently attracted new attention as they might have been realized in various superconductors. (1-4) As topological states of matter, protected by symmetry and the superconducting energy gap, they are considered as one possible building block for quantum computers. In this project we are using state of the art computational methods, developed in Bristol (5, 6) to investigate distinct superconductor-impurity combinations in order to establish trends for the ideal configuration in which Majorana-Fermions might be observed in real materials.

Key References

1. M. Ruby,et al., Physical Review Letters **115**, 197204 (2015)
2. C. Beenakker, Annual Review of Condensed Matter Physics **4**, 113 (2013)
3. J. Alicea, Reports on Progress in Physics **75**, 076501 (2012)
4. S. R. Elliott and M. Franz, Reviews of Modern Physics **87**, 137 (2015)
5. T. G. Saunderson et al., Physical Review B **101**, 064510 (2020)
6. T. G. Saunderson et al., Physical Review B **102**, 245106 (2020)

Skills

- Understanding of the theoretical description of the superconducting state
- Understanding of the concept of Majorana Fermions
- Using of state of the art electronic structure codes
- Working with the supercomputer facility BlueCrystal
- Basic understanding of the theoretical framework (density functional theory, Greens functions, Bogoliubov-deGennes equation)

TP-M10 : The Marching Cube Algorithm for efficient visualization of Fermi surfaces

Supervisor: Dr. Martin Gradhand (Theory)
Co-supervisor: Prof. James Annett

MSci
60/30

Description

The aim is to implement a marching cube algorithm within an existing Density Functional theory (DFT) code for the efficient visualization of Fermi surfaces with multiple sheets and small pockets. The existing code quickly runs into difficulties when the curvature of the considered Fermi surface changes too quickly and restricts not only effective visualization but although the integration of various properties over the Fermi surface. A previous student programmed the principle algorithm outside the DFT code and successfully tested it on simple band structures. The aim of this project would be to transfer this code package to the full DFT package to make it available for Fermi surface visualisation as well as integration. Especially the integration is a crucial part in any electronic transport calculation based on this DFT method. The ultimate aim will be to apply the implemented method to the description of spin-dependent transport in real materials within the Boltzmann transport theory as well as Berry curvatures of Bloch electrons. If successful we will scan a variety of simple metals as well as more complicated alloys in order to predict ideal materials for applications in magnetic random access memory devices (MRAM).

Key References

1. M. Gradhand et al.; J. Phys. Cond. Matt. 24, 213202 (2012)
2. V. Chernyaev, No. CERN-CN-95-17. (1995)
3. G.M.Nielson and B.Hamann, Proceedings of Visualization, IEEE ComputerSociety Press, pp. 83-90, (1991)

Skills

- introduction to solid state physics, including Bloch electrons, bandstructure, Fermi surfaces as well as semiclassical transport theory
- introduction to spin-dependent and topological transport
- introduction of the density functional theory (DFT) method
- Mathematical background of the underlying Greens function method
- Fortran95 programming including parallel coding
- Testing of visualization tools
- Implementation of a marching code algorithm in Fortran95 DFT code

TP-M11: Statistical mechanics of foreign exchange markets

Supervisor: Dr. Thomas Machon (Theory)

MSci
60/30

Description

The foreign exchange markets are the highest volume and most liquid financial markets in the world, operating 24 hours a day, five days a week. Participants on these markets exchange currencies, and so determine the relative value of, for example the Euro and Pound Sterling (quoted as EURGBP).
While the value of EURGBP will be driven by economic factors, news and the actions of large financial institutions, its value is correlated with other currency pairs, since similar factors often affect the entire market, or entire sectors. As an example, EURUSD and GBPUSD are two positively correlated currency pairs.
The goal of this project will be to analyse these correlations using models and ideas from statistical physics. We will use a computational technique, known as inverse Ising inference, to analyse the network of correlations between a set of currencies, and to ascertain whether these have changed over time.
Inverse Ising inference fits an Ising model – a simple model of magnetism – to a data set, and has applications in neuroscience, condensed matter physics, machine learning and other areas. The project will fit an Ising model to historical datasets from financial markets, and then analyse the resulting fitted models.

Key References

1. Nguyen, H. Chau, Riccardo Zecchina, and Johannes Berg. “Inverse statistical problems: from the inverse Ising problem to data science.” Advances in Physics 66.3 (2017): 197-261.
   https://doi.org/10.1080/00018732.2017.1341604

2. Aurell, Erik, and Magnus Ekeberg. “Inverse Ising inference using all the data.” Physical review letters 108.9 (2012): 090201.
   https://doi.org/10.1103/PhysRevLett.108.090201

Skills

- Advanced models in statistical mechanics
- Applications of statistical mechanics to finance, data science and machine learning
- Computational methods and data analysis (Python)

TP-M12: Singularities and symmetries in the structure of classical mechanics

Supervisor: Dr. Thomas Machon (Theory) | MSci 60/30

Description

Many physical systems are described by Hamiltonian mechanics. The ingredients for a Hamiltonian system are a phase space equipped with a Poisson structure, and a Hamiltonian. Recently, it has been shown that the space of all Poisson structures has, itself, a Poisson structure. This allows you to study the 'classical mechanics of classical mechanics'. This mathematical structure has not yet been fully explored, and the goal of this project will be to further understand its properties.
In the same way a particle moves through phase space, we will study how theories can move through 'theory space'. The goal of this project will be to investigate whether this flow in theory space admits finite-time singularity formation in low dimensions, and whether there exist any Noether currents – symmetries and conservation laws.
This is a challenging theoretical project, and will suit mathematically inclined students interested in the formalism of theoretical physics.

Key References

1. Machon, Thomas. "A Poisson bracket on the space of Poisson structures." arXiv preprint arXiv:2008.11074 (2020).
   https://doi.org/10.48550/arXiv.2008.11074
2. Machon, Thomas. "Poisson structures on sets of Maurer-Cartan elements." arXiv preprint arXiv:2203.02310 (2022).
   https://doi.org/10.48550/arXiv.2203.02310

Skills

- Geometry and mathematics
- Classical mechanics formalism

TP-M13 : Simulating the Dynamics of Knotted Molecules

Supervisor: Dr. Simon Hanna (Theory)

MSci
60/30

Description

Recent developments in both scanning probe microscopy and optical tweezers mean that it is now feasible to manipulate single polymer molecules, for example, by pulling them off surfaces, stretching them or to pull them through nanopores. Because the experiments involve only a single molecule, they lend themselves to simulation in the computer. In the current project we are interested in the tendency of polymer molecules to form knots – knots have been found in many biological polymers including proteins and DNA.

The aim of this project will be to construct a model polymer chain in the computer, and then perform numerical simulations to explore the dynamics of the molecule under different conditions. The Brownian dynamics method will be employed, which includes the effects of thermal motion of the fluid, and hydrodynamic interactions and drag. The molecule will be represented by a set of beads and springs.

Ultimately, we will aim to study the dynamics of knots in single polymer chains i.e. how they move, under different conditions. Parameters to vary will include the solvent quality, the dimensions of any confinement, the solvent flow rate (if any) and in particular the complexity of the knot. The project will partly involve adapting existing computer programs, and partly writing new code. It will make extensive use of the University supercomputer.

Key References

1. Katritch V, Bednar J, Michoud D, Scharein R G, Dubochet J and Stasiak A (1996). Geometry and physics of knots. Nature 384, 142-145. https://www.nature.com/articles/384142a0

2. Orlandini E and Whittington S G (2007). Statistical topology of closed curves: Some applications in polymer physics. Reviews of modern physics 79(2), 611-642. https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.79.611

3. Michieletto D, Marenduzzo D and Orlandini E (2015). Topological patterns in two-dimensional gel electrophoresis of DNA knots. Proceedings of the National Academy of Sciences 112(40), E5471-E5477. https://doi.org/10.1073/pnas.1506907112

Skills

- Learn principles of Brownian dynamics simulations.
- Review methods for implementing polymer-solvent interactions and hydrodynamic interactions.
- Learn the rudiments of knot theory as required for the description of open knots.
- Computational coding skills required

TP-M14 : Modelling Swarms of Active Particles

Supervisor: Dr. Simon Hanna (Theory)

MSci
60/30

Description

Active particles are particles that have a capability to drive themselves through a fluid. Examples in nature would include bacteria, but many synthetic active particles have been created that use optical fields or chemical reactions to propel themselves. Typically, active particles may be designed to follow a stimulus e.g. a food gradient in the case of bacteria, but when a lot of similar particles all follow the same stimulus, the result is a swarm.

Swarm of bird-like active particles

Swarms attract much interest for a variety of reasons. The particles are interacting, and may demonstrate interesting phenomena including collective behavior and phase transitions. Swarms of rod-like bacteria may behave like liquid crystals (so-called active nematics). Examples of swarming in nature, such as the motions of shoals of fish or flocks of starlings, are visually striking and sometimes newsworthy. However, apart from the visual appeal, there are some fascinating potential applications, involving swarms of smart particles working cooperatively towards a common goal. An emotive example would be the proposed use of swarms of nanoparticles to deliver targeted therapies to cancer cells via the bloodstream.

The aim of this project will be to develop a computer model to describe the motion of swarms of interacting active particles. The model will be quite simple; the complexity will arise in the emergent behaviour when 1000s of simple particles are interacting with each other and with an external stimulus. This project will require programming skills; extensive use will be made of the University supercomputer.

Key References

1. Craig W. Reynolds, “Flocks, Herds, and Schools: A Distributed Behavioral Model”, Computer Graphics, 21(4)(1987) https://dl.acm.org/doi/pdf/10.1145/37401.37406
2. Mach, R; Schweitzer, F (2003). “Multi-Agent Model of Biological Swarming”. *Advances In Artificial Life.* Lecture Notes in Computer Science, 2801, 810-820. doi:10.1007/978-3-540-39432-7_87.

Skills

- Learn about Brownian dynamics techniques.
- Review literature on modeling of swarms in physical and biological systems.
- Computational coding skills required

TP-M15 : Modelling flexible threads and vesicles in optical tweezers

Supervisor: Dr. Simon Hanna (Theory)

MSci
60/30

Description

Holographic optical tweezers (HOT) may be used to assemble micron-sized particles into complex microstructures and micromachines. Focussed laser beams are steered by computer generated holograms, and used to manipulate particles with sub-micron resolution. Laser beams can be used to push, pull and twist different component particles; the particles interact with each other both through their scattered light, and through the hydrodynamics of the fluid in which they are immersed. The forces generated are in the pico-Newton range, which is more than adequate to generate useful work at the micron scale.
As part of the drive to fabricate complex optically-driven micromachines, it is necessary to manipulate flexible structures. These might include threads and vesicles, which will deform when held in an intense optical field. The aim of the present project is to develop a method for computing the shape and Brownian motion of flexible structures held in focussed laser beams. The threads or vesicles will be represented by a series of beads joined by springs, with each bead interacting with the optical field through dipole interactions. We will use the coupled dipole method to evaluate the optical forces on each particle, and iteratively move and deform the structure in response. In this way, we will study the spontaneous deformation of flexible structures in intense optical fields, and assess the usefulness of such structures as components in optical micromachines. This project will make extensive use of the University supercomputer.

Elongated flexible particles in optical fields

Key References

1. A. Ashkin and J.M. Dziedzic. "Optical trapping and manipulation of viruses and bacteria," Science 235, 1517 (1987). https://opg.optica.org/ol/abstract.cfm?uri=ol-11-5-288
2. S.M. Block et al. "Compliance of bacterial flagella measured with optical tweezers," Nature 338, 514 (1989). https://www.nature.com/articles/338514a0
3. M.D. Wang et al. "Stretching DNA with optical tweezers," Biophys. J. 72, 1335 (1997). https://www.cell.com/biophysj/pdf/S0006-3495(97)78780-0.pdf

Skills

- Learn principles of Brownian dynamics simulations including hydrodynamic interactions
- Learn about coupled dipole techniques.
- Review literature on applications of coupled dipoles to optical tweezers and general light scattering and optical force calculations.
- Computational coding skills required

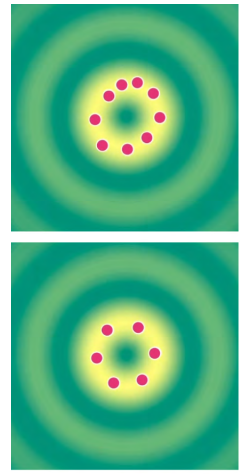
TP-M16 : Binding and dynamics in optical vortices

Supervisor: Dr. Simon Hanna (Theory)

MSci
60/30

Description

Optical binding is a phenomenon that occurs when light scattering from one microscopic particle falls upon another, and exerts a force. The behaviour of colloidal particles in a cluster will depend therefore on the incident beam, and all of the other particles present; this system must be solved self-consistently and the result is generally that stable configurations will be found, known as optical binding. If a bound cluster is placed in a circularly polarised beam, it will interact with the angular momentum of the beam and the whole cluster will rotate. Bessel beams are a class of laser beam that have an extended focus, but can carry both spin and orbital angular momentum, increasing the types of interactions that are possible. A zero-order Bessel beam is sometimes referred to as a pencil beam, due to its narrow central maximum which extends for 10s of μm along the propagation direction. Higher order Bessel beams are hollow and referred to as doughnut beams, or optical vortices.
The aim of this project will be to simulate a cluster of spherical nanoparticles in various orders of Bessel beam, with a view to exploring the binding between the particles and the subsequent dynamics of the bound cluster. Early indications are that particular configurations couple both to the light field and the fluid, such that extremely rapid rotations may be observed. Optical interactions will be modelled using a couple-dipole model; dynamical behaviour will be followed using a Brownian dynamics approach with hydrodynamic interactions. Analogies will be drawn with macroscopic systems of particles in fluid vortices. This project will require the University supercomputer.



Six particles form a bound state

Key References

1. M. M. Burns, J.-M. Fournier and J. A. Golovchenko, "Optical binding", Phys. Rev. Lett. 63, 1233 (1989) https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.63.1233
2. M. M. Burns, J.-M. Fournier and J. A. Golovchenko, "Optical Matter: Crystallization and Binding in Intense Optical Fields", Science, 249, 749-754 (1990). https://www.science.org/doi/10.1126/science.249.4970.749

Skills

- Review the literature on optical binding and on Bessel beams.
- Review literature on applications of coupled dipoles to optical tweezers and optical force calculations.
- Computational coding skills required

TP-M17 : Modelling and optimisation of rocket engines

Supervisor: Dr. Simon Hanna (Theory)

MSci 60

Description

Falcon 9

As the development of space systems continues to gather momentum, with millions being invested in researching new propulsion systems, gaining a deeper understanding of their optimization will only serve to further accelerate future research. This project represents an opportunity to delve into the thermodynamics of cutting-edge space systems, developing a computer model for a practical rocket engine, with the aim being to optimise for the most efficient system given real-life design parameters.

The goal of this project is to build a computational thermodynamic model of a full flow staged combustion engine, similar to the Raptor engine currently under development by SpaceX. This model will study the pressure, temperature and energy of different parts of the system relying on ideal thermodynamic processes. Monte Carlo optimisation will be used to alter the parameters of the model and record performance of key performance indicators (KPIs) such as total specific impulse, generated thrust and chamber pressure. The entire model will have to perform within set parameters of the theoretical materials involved e.g. the use of carbon fibre fuel tanks limits the cryogenic temperature that propellants can be stored at compared to other potential materials. Potential failure points will be monitored in parallel with the KPIs with a successful optimisation being one that generates the best KPIs without exceeding the failure point limits.

The project will make use of Matlab and Simulink for the modelling. The modular nature of Simulink allows a convenient work share between project partners with each developing different parts of the system. For example, work could be divided between the fuel system and the engine nozzle, with collaboration on the combustion chamber.

Key References

1. "Rocket Propulsion Elements", G.P. Sutton and O. Biblarz (Wiley, 8th Ed. 2010)
2. "Concepts in Thermal Physics", S.J. Blundell and K.M. Blundell (OUP, 2nd. Ed. 2009)
3. "Thermodynamics, an engineering approach", Y.A. Cengal, M.A. Boles and M. Kanoglu (McGraw Hill / Asia, 9th Ed. 2019)

Skills

- To understand the principles behind a rocket engine and the design limitations involved when developing one
- To develop computational modelling skills to enable rapid optimisation of a real system through a computer model
- Working with MatLab and Simulink, the industry standard for engineering modelling work

TP-M18 : How much entanglement?

Supervisor: Dr. Alan Reynolds (Theory) | MSci 60/30

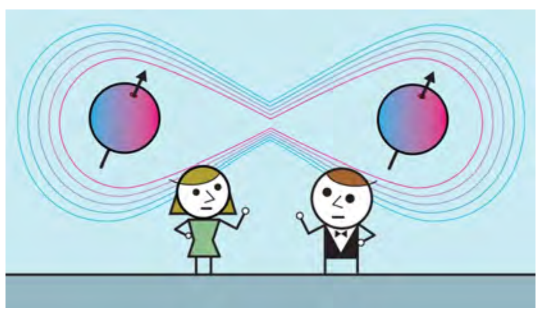
Description

Loosely speaking, quantum entanglement describes the notion that one might not be able to fully describe the quantum state of a single particle in a system of particles, without reference to the rest of the system, despite knowing the quantum state of the system as a whole. This has at times been considered as problematic. The EPR paradox, or "spooky action at a distance", encapsulates some of these concerns, with the measurement of a particle in such a system seemingly affecting the whole system and hence the properties of a distant entangled particle. Today, however, entanglement is also thought of as a resource that can be exploited, for example in quantum computation and communication.

While we can divide quantum states of, for example, two particles into a class of entangled states and a class of unentangled (seperable) states, can we go further and describe one entangled state as being 'more entangled' than another? Can we quantify entanglement?

In short, yes we can. However, there are number of different measures that are used to do this, each corresponding to subtly different notions of entanglement. Moreover, the task becomes more challenging when we consider 'mixed' states, whereupon some measures of entanglement that work well with pure states confuse entanglement with the impurity of the state.

For this project, you will be expected to compare and contrast a range of different measures of entanglement. In doing so, you may also find that you also explore related concepts in quantum information, such as entanglement distillation and bound entanglement.



Entangled particles (not to scale). (Image from "What is Quantum Entanglement", IEEESpectrum, (2022))

Key References

1. V. Vedral, M.B. Plenio, M.A. Rippin, P. L. Knight, "Quantifying Entanglement", Physical Review Letters **78**, pp2275-2279 (1997)
   `https://doi.org/10.48550/arXiv.quant-ph/9702027`
2. M. A. Nielsen, I. L. Chuang, "Quantum Computation and Quantum Information"
   `https://doi.org/10.1017/CBO9780511976667`

Skills

- An interest in quantum information.

TP-M19 : Dissipation Learning in Active Matter

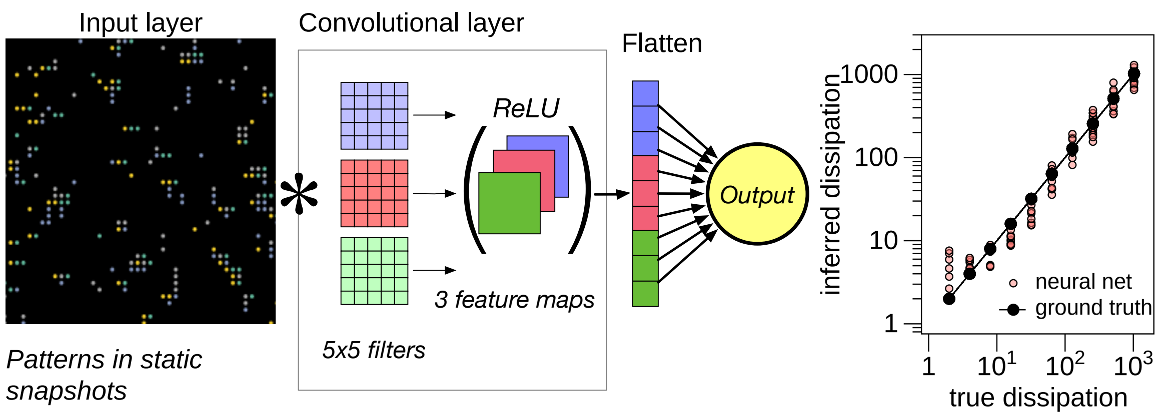
Supervisor: Dr. Francesco Turci (Theory) | MSci 60/30

Description

Flocks of birds, bacterial colonies as well as swarming robots are examples of systems that achieve complex spatial organisation through local energy dissipation. Collectively, these systems are referred to as *active matter*, distinct from the ordinary soft and hard condensed matter [1]. Nonequilibrium, disorder, sensing and communication are key characteristics of active systems, leading to rich patterns and phase separation. Using suitably designed deep neural networks, recent progress has shown that we can link spatial patterns and local dissipation (e.g. entropy production) [2]. This opens several questions:

- what degrees of freedom are most important to control dissipation?
- how much information is required to learn dissipation accurately?
- how does the architecture of the networks linking structure and dissipation depend on the specific model under consideration?

The project is theoretical and computational: we will simulate on-lattice and off-lattice active models, analytically design structural metrics to link to dissipation, embed them in convolutional networks using state-of-the-art deep-learning APIs (e.g. Keras) and compare their performance for different minimal models.



Static snapshots of the Persistent Exclusion Process model (left) feed a convolutional network (middle) to predict the dissipation. Ground truth vs prediction on the right (preliminary work).

Key References

1. G. Gompper, et al. J. Phys.: Condens. Matter **32**, 193001 (2020) https://doi.org/10.1088/1361-648X/ab6348
2. G. Rassolov, et al. J. Chem. Phys. **157**, 054901 (2022) https://doi.org/10.1063/5.0097863

Skills

You will acquire

- Expertise in convolutional neural networks in Python
- A general knowledge of nonequilibrium statistical mechanics

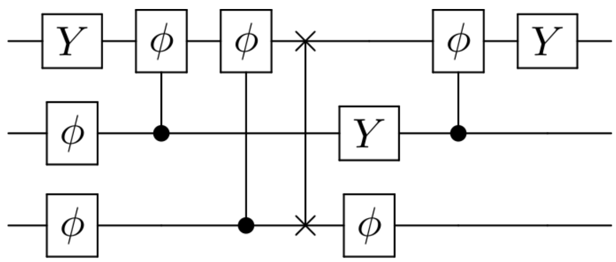
TP-M20 : Quantum computer simulation

Supervisor: Dr. Alan Reynolds (Theory)

MSci
60/30

Description

While public access to quantum computers is becoming available, there are still good reasons for simulating quantum computers on their classical counterparts. Most likely, the simulation of a quantum computer can never be truly efficient — indeed quantum computing would be far less appealing if such efficient simulation were possible. However, this should not prevent us from attempting to make such simulations as efficient as possible.
In this project, you will learn the fundamentals of quantum computing and write software (e.g. in C++) to simulate quantum circuits. You will also learn about methods for making such simulations more efficient and consider applications of such simulators, Finally, you may choose to compare the use of such simulators with the use of public accessible quantum computers.



Schematic of a simple quantum circuit

Key References

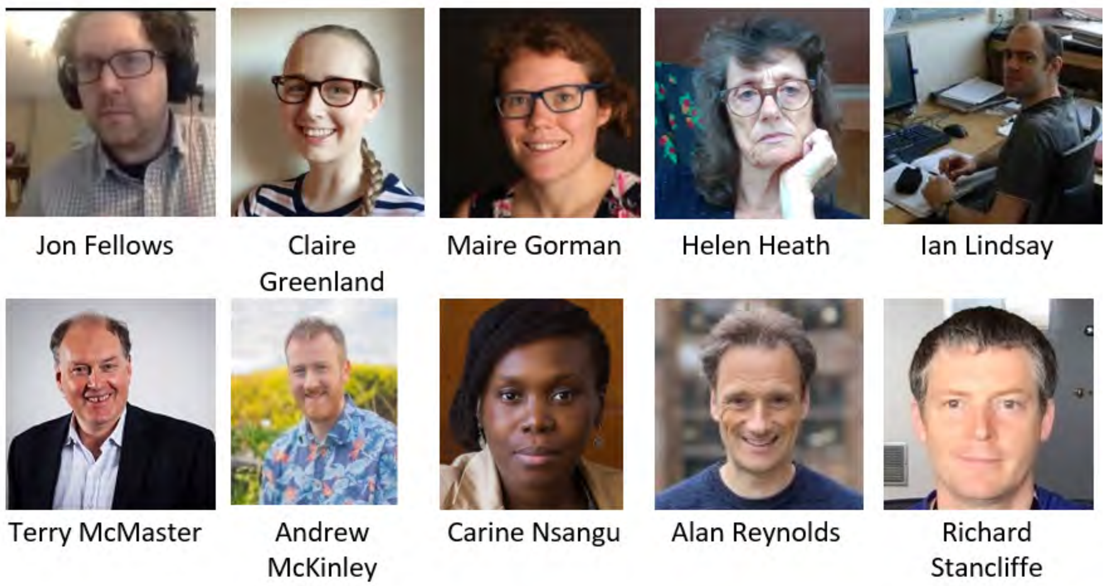
1. I. L. Markov and Yaoyun Shi, "Simulating quantum computation by contracting tensor networks", SIAM Journal on Computing **38**, 3, pp963-981 (2008)
   https://doi.org/10.1137/050644756
2. M. A. Nielsen and I. L. Chuang, "Quantum Computation and Quantum Information", Cambridge University Press (2010)
   https://doi.org/10.1017/CBO9780511976667

Skills

- Computer programming ability
- An interest in quantum computation

PHYSICS EDUCATION GROUP

The Physics Education Group (PEG) is the group of staff who have a teaching focus to their role. Our aims are to engage in pedagogic research to inform the teaching of Physics at the University of Bristol and beyond and to help ensure that undergraduate teaching, in terms of both delivery methods and content, is informed by the latest research evidence. The School of Physics is undergoing a major curriculum review so the outcomes of your project or dissertation could have a long-term impact on teaching in the School.



We have a range of interests including, but not limited to the topics below.

Threshold Concepts

Threshold concepts are concepts that are transformative; once grasped, students are able to move on in their understanding. Exactly what constitutes a threshold concept in Physics is the subject of some debate; therefore projects can consider what are threshold concepts as well as methods for aiding students to understand them and methods of assessment to test conceptual understanding.

Assessment

A live topic in the University is the appropriate amount of assessment and the variety of assessment methods that are appropriate in a degree programme. Assessments should test the learning outcomes of units and programmes and must assess the achievements of individuals. An MSci student project this year is looking at Quantum Mechanics teaching from years 2-4 and how the concepts discussed in the courses are assessed in examinations and coursework

Transition to University

We are also interested in the transition from school to university. For example, you may have participated in the BEST study, which we are contributing to, that looks at the factors enabling successful transition to university. A project investigating how well-prepared students were in terms of their mathematical background was presented at the national conference on University teaching in Chemistry and Physics (VICE/PHEC) in summer 2022.

Outreach

Outreach and engagement with schools and the public is a vital part of our work as a university. Within PEG we have a wide range of physics research experience enabling us to support outreach projects in several areas. These could involve developing experimental workshops or online materials for schools.

Our projects are very adaptable, and we encourage students to use their expertise in the learning of Physics at University, which you have all gained through taking our courses, to suggest topics for study or outreach projects.
If you have a novel idea for a project. Please contact Helen Heath (helen.heath@bristol.ac.uk) who can put you in contact with a suitable supervisor.

PEG-M1 : How difficult are Physics exams? Cognitive load in assessments.

Supervisor: Prof. Helen Heath (PEG)

MSci
60/30

Description

Students are often puzzled at the start of the course as to how lecturers can answer complex questions with ease. Educational literature talks about cognitive load, which is about the number of pieces of information that can be dealt with simulataneously. The literature also distinguishes between expert and novice problem solvers. One of the differences between the two groups is that expert problem solvers tackle complex problems in larger chunks, reducing the number of piece of information needed to solve the problem. This project aims to investigate the cognitive load in physics examinations.

Exams are usually set with the aim of starting with straightforward questions with small numbers of intermediate steps (and therefore low cognitive load) and moving on to more complex questions. This project would review examinations papers and worked solutions to evaluate the load as seen by the setter of the paper. Worked solutions woudl be compared with some student responses to try and determine the load as seen by the students.

The cheat sheets that were used for examinations could form another source of information. What level of chunking of information is included in the cheat sheets?

A further line of investigation would be to review the papers in the light of Bloom's taxonomy, which is a heirachy of educational goals.

Key References

1. https://bloomstaxonomy.net
2. J.Sweller, Cognitive Load During Problem Solving: Effects on Learning, URL

Skills

- Methods of physics education research
- Managing qualitative data
- Ethical approval

PEG-M2 : Assessments that adapt to student needs

Supervisor: Prof. Helen Heath (PEG)

MSci
60/30

Description

You are almost certainly familiar with the Mobius toll that can be used to provide formative and summative assessment in an online environment. Mobius is able to handle adaptive assignments - that is those that adjust as the student progresses. This means it has the capability to either repeat basic questions, for students who haven't grasped a concept, or move quickly on to more challenging material for those who find the first questions easy.

So far the School of Physics has not made much use of the adaptive capabilities. This project would involve developing adaptive assessments to be used in conjunction with the 1st year Core Physics lectures- this is timely as we adopt a new curriculum and gives you the possibility to help develop materials that might be used for some time. You would develop and deploy the materials and then monitor student engagement with and progress through the assignments with the aim of producing a guide to good practice with exemplars of good adaptive assessments.

The aim of the project would be to develop formative, adaptive assessments for some basic materials from either the 1st or 2nd year of the physics programmes. These would ideally be designed for the TB2 units and would be deployed during TB2. Student progress through the formative work would be analysed to understand how successful the formative tests were at developing understanding and fluency in answering simple questions. The initial stage of the project would involve discussions with lecturers to identify priorities for development of questions and understanding how writing adaptive assignments in Mobius works. You will also need to consider how to evaluate the success of the project. At what point have students been succesful in completing the formative asessment?

The project would involve becoming familiar with the Mobius software, developing content that aim to increase in sophistication through an adaptive assignment. This will probably also involve becoming familiar with Maple-TA which underlies the mathematical capabilities of Mobius.

Key References

1. D.Challis,Committing to quality learning through adaptive online assessment,Assessment and Evaluation in Higher Education, 20,3,519-527,2005 URL (this is an example paper but in a very useful journal)

2. Mobius Instructor Creator Guide URL

Skills

- Methods of physics education research
- Use of Mobius and MapleTA software
- Ethical approval

PEG-M3 : The Shadow of COVID: Long-term effects on learners

Supervisor: Dr. Andrew McKinley (PEG)

MSci
60/30

Description

The COVID19 pandemic caused global disruption to almost every aspect of life. In the context of our work, the pandemic forced us to move all our teaching online immediately, with little change to consider the learning opportunities this might afford. As the pandemic developed however, we were afforded a unique opportunity to review how students learn and how we could use educational technology to support learning in an inclusive manner, reaching more students and being more flexible to the individual needs of the learner.

The academic year of 2022/23 is the first which can be considered a return to "normal" operation, however it is clear there are still lingering effects. We wish to consider whether these effects will persist further, and how we can make the most of what we learned about education to build a curriculum and learning environment which is inclusive and accessible, and helping to improve the interactions between students and academic staff.

Key References

1. J. Lennox et al, International Journal of Educational Development **85**, 102429 (2021)
   https://www.sciencedirect.com/science/article/pii/S0738059321000821
2. COVID-19 Global Coalition: Lessons from Evaluations
   https://www.oecd.org/dac/evaluation/lessons-from-evaluation-ge-education.pdf
3. Education Development Trust: Learning Renewed: Ten lessons from the Pandemic
   https://www.educationdevelopmenttrust.com/our-research-and-insights/research/learning-renewed-ten-lessons-from-the-pandemic

Skills

- Literacy and library skills
- Critical evaluation
- Reflection and research ethics

PEG-M4 : Programmed learning - self-generated feedback for better understanding

Supervisor: Dr. Andrew McKinley (PEG)

MSci
60/30

Description

“Programmed learning” is a strategy of encouraging self-directed “learning by doing”, focussing on small, managable exercises with rapid feedback, allowing the learner to progress at their own pace. The small exercises provide a constant programme of reinforcement to the learning and the feedback generates motivation to continue.

In this project you will explore opportunities for implementation of such strategies in the Physics curriculum and to evaluate the efficacy of such exercises in the context of undergraduate learning and to determine the level of feedback needed to ensure appropriate progression through such exercises.

Key References

1. N. Seel et al, Encyclopedia of the Sciences of Learning, pp 2706
   https://link.springer.com/referenceworkentry/10.1007/978-1-4419-1428-6_671
2. Programmed Learning overview
   https://psychology.jrank.org/pages/505/Programmed-Learning.html

Skills

- Literacy and library skills
- Critical evaluation
- Reflection and research ethics

PEG-M5 : Integrating Data Science in the Physics Curriculum

Supervisor: Dr. Andrew McKinley (PEG)

MSci
60/30

Description

The field of “Data Science” has become increasingly prevalent, with “Big Data” becoming one of the buzzwords of recent years. Research councils increasingly require that data are open and accessible for all to interpret, and with their Juno project, NASA released the raw data for citizen scientists to analyse and interpret. However, all of this relies on those creating the data understanding how to work with it and how to ensure the integrity of the data, right from creation through its analysis and subsequent publication. This MSci project is an education project with the intended output of integrating data science into the physics curriculum. Through the project it is expected that methods will be established for automating data collection in undergraduate laboratories where possible, the appropriate archival and access of such data, together with the creation of informed educational resources to guide UG students through the process of appropriate management of data and its eventual analysis.

Key References

1. UoB research data management bootcamp:
   https://data.blogs.bristol.ac.uk/bootcamp/
2. Arduino and LabVIEW-based remote data acquisition system for magnetic field of coils experiments
   https://iopscience.iop.org/article/10.1088/1361-6552/ab5ed6/meta

Skills

- Literacy and library skills
- Critical evaluation
- Reflection and research ethics
- Coding in an education setting

PEG-M6 : Threshold Concepts on Core 2nd - Year Physics

Supervisor: Dr. Carine Nsangu (PEG) | MSci 60/30

Description

The idea of threshold concept was first introduced by Meyer and L [1] and, is defined as a name for those concepts which, when understood by a student, mark a fundamental milestone in their learning. Identifying those threshold concepts in CORE materials will be helpful with the course delivery as and they can form a benchmark in students understanding.

With the view of past projects where Threshold concepts were investigated in other different specific areas of Physics, this one will concentrate on the 2nd year Core Physics material, namely Classical physics I and classical physics II. This will certainly include conducting investigations from teaching academics and from Focus groups with student cohorts across the Years. This is further essential given the current curriculum review the School is undergoing.

Key References

1. Meyer J.H.F. and Land R. Threshold concepts and troublesome knowledge (2): epistemological considerations and a conceptual framework for teaching and learning. Higher Education 49 (3), 373-388, 2005.
   https://link.springer.com/article/10.1007/s10734-004-6779-5
2. Yusaf F. Stokes' Theorem: A candidate threshold concept. Practice and Evidence of Scholarship of Teaching and Learning in Higher Education, 2017.
   https://www.pestlhe.org/index.php/pestlhe/article/view/183

Skills

- How to run focus groups
- Pedagogic literature research
- Effective online questionnaire development
- Effective Data analysis

PEG-M7 : Understanding the transition to University from School: what does it mean for the first-year Physics courses and students?

Supervisor: Dr Terry McMaster (PEG)

MSci 60/30

Description

It is a common experience that making the transition from School to University is a challenging and sometimes difficult experience for students. The change in working pattern, different styles of teaching, a greater emphasis on practical work - these are just some of the features that contribute to the challenge. It is arguable that whilst most, if not all, students are full of enthusiasm to study Physics at University, they are simultaneously not fully prepared for the transition. Nor is the University fully understanding of the nature and scale of the challenge and what students are going through.
This project will examine the interface between School and University Physics. You will employ a mixture of methods including a systematic literature review of education research on this topic. You will complement the literature review with information-gathering from students using interviews and questionnaires. The aim would be to understand more fully the precise nature of the challenge in making the transition, and to suggest educational strategies and practices that could be incorporated in the first-year Bristol Physics curriculum in order to help students at this interface. .

Key References

1. Briggs, A. R. J. et al. (2012) Building Bridges: understanding student transition to university, Quality in Higher Education, 18, pp 3-21.
   https://DOI:10.1080/13538322.2011.614468

Skills

- How to conduct and write a literature review
- correlative data analysis
- analysing qualitative and quantitative data
- Design and utilisation of questionnaires and interviews as a research method

PEG-M8 : What does it mean to do ‘Interdisciplinary Research’ and why is it important?

Supervisor: Dr. Terry McMaster (PEG)

MSci
60/30

Description

The nature of research is constantly changing, and Physics is no exception. All of the “disciplines” that we are familiar with no longer fully or comprehensively describe the emergent challenges we face. There are still many opportunities for “pure” Physics research, although many of the challenges facing us today – climate change and environmental collapse, the emergence and rise of AI, new methods of energy production, quantum computation – have a footprint in Physics but require a multidisciplinary, or more accurately an interdisciplinary, approach in order to have any hope of understanding and a basis for progress.
In this project you will investigate the meaning of Interdisciplinarity using analysis of citations and databases of publications. You will identify patterns of published work and develop an understanding of trends in interdisciplinary publishing and impact. You will look at the research being carried out in the School of Physics and develop an “interdisciplinary map” of the work – this will provide us with a tool to communicate the importance of Physics to interdisciplinary research and challenges.
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Key References

1. Szell, M. et al. (2018) Nature Physics, 14, 1075 URL
2. Okemura, K. (2019) Palgrave Communications, 5,141

Skills

- Developing an understanding of metrics for scientific literature
- Searching of scientific publishing databases
- High-level data analysis
- Scientific writing