YEAR 4 PROJECT ABSTRACTS 2018/19

Contents

Astrophysics Experiment and Instrumentation

Project Team Leader – Dr Denis Martynov

1.1: Looking deep into the LIGO detectors using machine learning techniques and Bayesian analysis

Supervisor: Dr Denis Martynov
Office: R8-224, Telephone: 43722
E-mail: dmartynov@star.sr.bham.ac.uk

Open to any MSci Student

The LIGO detectors are approaching their design sensitivity and have already observed more than ten coalescences of the compact objects. The key challenge to further improving the sensitivity comes from the optical losses in the interferometers. At the moment, the distribution of losses inside the giant machines is not well understood but the origin may come from absorption and scattering from the mirrors and mode mismatch between optical resonators.

The aim of the project is to build a software module which can estimate optical losses from different parts of the LIGO interferometers. We will use Finesse to simulate the detectors, machine learning techniques to analyse images of the optical modes, and Bayesian inference to estimate optical losses from subsystems of the LIGO detectors. Expertise or a strong interest in quantum optics and programming is recommended since we will use quantum properties of light to decouple losses from the interferometer subsystems and build our software module in Python.

1.2: Laser beam shape distortion in gravitational wave detectors

Supervisor: Prof Andreas Freise
Office: West G04
Telephone: 43565
E-mail: adf@star.sr.bham.ac.uk

Open to any MSci Student

Gravitational wave detectors, such as LIGO and VIRGO, are complex Michelson-type interferometers enhanced with optical cavities. Slight distortions to the laser beam shape, the eigen-modes of the optical cavities, can limit the performance of the detector. We are using numerical models to guide our design of the optical systems in the future GW detector, the Einstein Telescope.

The aim of the student project is to develop a computer model of a coupled three-mirror optical cavity and model the effect of mirror surface distortions on the beam shape of the cavity eigenmode. The student will study gravitational wave detection, laser interferometry and numerical modelling of electro-magnetic fields. Expertise or a strong interest in programming is recommended as the students will develop Python scripts to perform modelling tasks.

1.3: Laser interferometers and seismometers for gravitational waves

Supervisor: Dr Conor Mow-Lowry
Telephone: 43020
Email: c.m.mow-lowry@bham.ac.uk sdfsdf

Gravitational-wave observatories are the most sensitive devices ever built. We build crucial parts of the detectors and push the boundaries of measurement technology to allow them to 'listen' to events with greater clarity, and reaching deeper into the universe. We have combined laser interferometers with precision seismometers to upgrade LIGO's vibration isolation system, which is already the most sophisticated of its kind in the world.

The aim of this experimental year 4 project is to assemble and test these new sensors. Proving their performance will require creating a very quiet space in our basement laboratory and carefully analysing the sensor outputs. This will involve developing physical models of the seismometer and readout to understand their performance limitations. Depending on progress, students will then adapt the develop particle-swarm optimisation to optimally enhance the performance of LIGO using the new sensors.

1.4: Testing the inverse square law at 15 micrometres

Supervisor: Prof Clive Speake
Office: West 220
Telephone: 44679
Email: C.C.Speake@bham.ac.uk

Open to any MSci Student

Newton's Inverse Square Law of Gravitation has been tested to high precision on length scales from that of the solar system down to scales of centimetres. There do, however, exist theories which invoke modifications to the inverse square law at galactic or cosmological scales to explain the appearance of dark matter or dark energy. Some of these models, for instance involving Large Extra Dimensions, Axion-Like Particles or 'Chameleon' Fields, also predict modifications to gravity at small but potentially experimentally accessible scales, of the order a few microns. The ISL experiment aims to test some of these theories by measuring gravity at a range of order 10 microns. The current shortest range at which experiments are sensitive to gravity is about 60 microns. This is achieved by using a torsion balance, which allows very weak forces to be measured. Unfortunately, there are major difficulties, particularly associated with tilt instability, in extending this technique to shorter ranges. We aim to circumvent some of these problems by utilising a novel superconducting magnetic suspension system, which acts like a torsion balance, but with additional tilt stability.

The successful project in 2018-19 developed an air-bearing model of the superconducting suspension and demonstrated the novel principle of being able to tune both the natural rotational frequency and the centre of force due to the suspension versus the centre of mass. A possible project for 2019-20 is to extend this work to designing and building a seismometer or possibly a detector of gravitational forces based on the air-bearing principle.

Astrophysics Theory and Observation

Project Team Leader - Dr Patricia Schmidt

2.1: Planetary and binary star systems, with a twist

Supervisor: Dr Amaury Triaud
Office: G32, ground floor, Physics West
Email: a.triaud@bham.ac.uk

The more traditional approach to discovering exoplanets and studying binary stars is to measure their radial-velocity as a function of time. Usually, investigators then apply Keplerian orbits to the data, where a match measures the physical parameters of the system they study. However, sometimes, something strange happens and simple Keplerian laws are no longer sufficient. This is where the fun begins.

The goal of this project will be to first develop a tool to adjust Keplerian orbits to two different sets of Doppler velocity data, obtained on two stellar systems. These data remain unpublished to this day. The beginning of the project will identify the source of why a simple Keplerian is not sufficient, and then move on to apply the appropriate corrections. For one system the goal is to establish whether we are truly in the presence of a planet, and for the other, to extract the orbital elements of a tight triple star system.

To progress with this project, you will need to be comfortable with writing code (most preferably python), with handling statistical tools like Markov Chains, and of having some understanding of Keplerian motion and Newtonian dynamics.

Proposed reading:

http://dx.doi.org/10.1051/0004-6361/200912700

http://dx.doi.org/10.1051/0004-6361/201220779

2.2: High-precision stellar astrophysics: testing models of stellar structure using asteroseismic, astrometric and spectroscopic constraints

Supervisor: Dr Andrea Miglio & Dr Josefina Montalban
Offices: G35, ground floor, Physics West
Telephone: 44599
E-mail: miglioa@bison.ph.bham.ac.uk

The availability of precise and accurate seismic (Kepler, K2, TESS), astrometric (Gaia) and spectroscopic data allows us to test our understanding of stellar structure and evolution to the percent level. In this project you will choose a specific open problem in stellar physics (see below), use models of stellar structure and pulsation to predict properties of well constrained systems (e.g. stars in eclipsing binaries), and compare them to the available observational constraints (either from Kepler or from the TESS mission, if they become available in time).

Examples of specific projects are:

- Study the low-mass end of core-He burning stars, and the transition to the HB and the RR Lyrae instability strip (to inform mass loss rates),
- Use constraints on mode coupling to characterise the detailed structure of the evanescent region in red giant stars (to constrain transport processes in stellar interiors),
- Predict the expected number and pulsation spectrum of stars undergoing the He flash (to find direct observational evidence for the flash),
- Look for evidence of unresolved binaries coupling Gaia and seismic constraints (to constrain the properties of the underlying binary population),
- Use astrometric and asteroseismic constraints to put upper limits on fundamental physics (e.g. limits on axion properties)

The nature of the project is such that you should be happy analyzing and manipulating data, computing and interpreting results from numerical simulations of stellar evolution, and writing your own codes. Familiarity with asteroseismology and stellar evolution (e.g., from Y3 Group Studies, Life and the module Death of stars) would be beneficial.

Asteroseismology of Solar-Type and Red-Giant Stars
https://arxiv.org/abs/1303.1957

Asteroseismology of red giants: from analysing light curves to estimating ages
https://arxiv.org/abs/1601.02802

Constraining fundamental stellar parameters using seismology, application to α Centauri AB
http://adsabs.harvard.edu/abs/2005A%26A...441..615

MESA
http://mesa.sourceforge.net

2.3: Bayesian Hierarchical Modelling and Machine Learning of Stellar Populations

Supervisor: Dr Guy Davies
Office: West G34
Email: g.r.davies@bham.ac.uk

Open to any MSci student (Astro & Theory)

Astrophysics has entered the era of big data. Big data doesn't so much refer to the size of a data set but really it refers to the way in which the data set is treated: normally trying to discover properties of a population. This project is about bringing big data methods to astronomical data sets.

Big data methods can include machine learning or hierarchical modelling methods in order to learn about a population. In astrophysics, it is common to have data with large observational uncertainties that need to be properly accounted for. We can do this using the latest generation of statistical tools (probabilistic programming i.e., Stan of PyMC3) coupled to machine learning tools (i.e., TensorFlow).

I have a number of examples where I want to know about a population of stars and need to apply the above tools. Some examples are:

- Modelling stars found in eclipsing binaries
- Modelling stars found in open or globular clusters
- Modelling the old stars of the Milky Way
- Modelling Gaia's 1 billion stars (note we probably will not model all 1 billion but we could make a start)

  These projects contains a number of technically challenging methods. To make a success of this project you will need to be proficient in statistics and coding – if not at the start of the project, certainly by the end. Open to any MSci student. Excellent statistical skills and very strong programming skills would be very useful for this project.

2.4: Machine Learning Applications in Survey Astronomy

Supervisor: Dr Ian Stevens
Office: West 232
Telephone: 46450
Email: irs@star.sr.bham.ac.uk

Open to any MSci Student, but only do this project if you are proficient in Python programming.

With current astronomical surveys the number of detected sources is already large and with future telescopes the volume of data will become huge, so that machine learning techniques will be required to seek out the interesting objects.

This project aims to look at a couple of different angles of machine learning.

I. Source identification in radio/IR surveys - the Square Kilometer Array will be the premier radio telescope when it starts operating around 2020. In the meantime, precursor telescopes such as MeerKAT will generate impressively large datasets of radio objects. While that is the future, there already exist several large radio survey datasets (eg FIRST, NVSS etc). This project aims to take the data from these surveys and combine them with infrared (IR) surveys.
In principle, we could also take in optical/UV/X-ray data from a range of other surveys, but that may get a bit unwieldy. Most likely, we will use a Random Forest Algorithm, almost certainly from the Python Scikit package:
http://scikit-learn.org/stable/modules/ensemble.html
The goal will be to develop an efficient classifier of the objects (quasars, galaxies, HII regions, stars etc) and then, if time permits, focus in on a class of unusual objects detected by the analysis.

II. Image identification - here we wish to use image recognition as part of a neural network to recognise specific image features in data. The types of object of interest may be double-lobed radio galaxies, supernova remnants, stellar bubbles or bow shocks. Here we will make use of the Tensorflow neural network

https://www.tensorflow.org/

and the dataset we will probably use is the Spitzer GLIMPSE,

https://irsa.ipac.caltech.edu/data/SPITZER/GLIMPSE/

although, in principle, we could use a range of other surveys as well.

Reading List/Preparation:

1. Learn how to use Tensorflow (which has many good tutorials)
2. For an overview of some of the issues being faced, see https://arxiv.org/pdf/1612.00048
3. An artificial neural network applied to identifying radio galaxies https://arxiv.org/abs/1705.03413
4. The CAESAR algorithm to detect and parameterise extended sources in radio data http://adsabs.harvard.edu/abs/2016MNRAS.460.1486R
5. This paper shows what can be done by eye - a test will be how much better can a neural network do than this http://adsabs.harvard.edu/abs/2016ApJS..227...18K

2.5: The tidal destruction of local galaxies: Implications for galaxy formation and the origin of dark matter

Supervisor: Dr Sean McGee
Office: West 223
Telephone: 46459
Email: smcgee@star.sr.bham.ac.uk

Open to any MSci Student

The abundance and size of dwarf galaxies near the Milky Way is sensitive to a wide range of physics as well as the underlying cosmological model of the universe. In recent years, two problems have arisen: the ‘missing satellite problem’ - in which the number of satellite galaxies observed near the Milky Way is much smaller than a Cold Dark Matter universe should naively have - and the ‘too big to fail’ problem - in which the masses of satellite galaxies do not fit the expectations of our current cosmology. Among a wide range of possible solutions to these problems is that dark matter is not as we thought and instead acts, for instance, as a superfluid.

First, this project will use newly released data from the Gaia satellite, and will require making detailed maps of nearby dwarf galaxies, determining their member stars and measuring their physical extent. These measurements are direct constraints on the tidal gravitational field that the dwarf galaxies have felt in their recent history.

Secondly, the project will involve the construction of models for the expected tidal forces in a Milky Way like galaxy with different dark matter formulations, eg. Cold dark matter, BEC dark matter, etc. These models will be compared to the measurements of the size of dwarf galaxies to constrain our cosmological model.

This project can be adapted depending on the interests and skills of the students, but would be best suited to students with both analytic and computational skills.

The following papers may be of interest:

Summary of satellite problems with current cosmology:

Bullock & Boylan-Kolchin (2017) http://adsabs.harvard.edu/abs/2017ARA%26A..55..343B

Local galaxies with Gaia:

Helmi et al. (2018) http://adsabs.harvard.edu/abs/2018arXiv180409381G

Superfluid dark matter:

Mocz et al. (2017) http://adsabs.harvard.edu/abs/2017MNRAS.471.4559M

Berezhiani et al. (2015) http://adsabs.harvard.edu/abs/2015PhRvD..92j3510B

2.6: Modelling the Interaction of Space-Based Laser Interferometers with Gravitational Waves

Supervisors:
Dr Christopher Moore (office West 222; email cmoore@star.sr.bham.ac.uk)
Dr Antoine Klein (office West 238; email antoine@star.sr.bham.ac.uk)

Open to MSci or Theory students

The LIGO and Virgo detectors have just begun to regularly detect gravitational waves from neutron stars and stellar mass black holes here on Earth. In order to detect lower frequency gravitational waves, such as those generated in collisions between the supermassive black holes found in the centres of most galaxies, it is necessary to go to space in order to avoid the seismic noise sources ever present on Earth.

The European Space Agency is planning the LISA mission to do exactly that. LISA will consist of three satellites orbiting the sun with laser beams travelling the 2.5 million kilometres between each pair satellites. Carefully recombining the measured phases of laser beams in a process known as time-delay interferometry will allow the triangular constellation of three spacecraft to function as a set of low-frequency, space-based gravitational wave detectors.

However, space-based detectors are considerably more complicated than the current ground-based detectors. The signals that LISA will detect are long-lived, typically changing over timescales of months to years. The LISA constellation orbits the sun with a period of 1 year, and the orbital motions of the spacecraft will affect the signal that we measure; even a simple sinusoidal gravitational wave signal will manifest itself in our data as a relatively complicated, time-dependent signal due to the spacecraft motions. In order to detect and characterise incoming gravitational wave signals it is necessary to be able simulate the response of the LISA detector to such a wave both quickly and accurately. The first goal of project will be to construct a numerical model of the LISA response (this can be done in python, or any similar language with which the student is familiar, but some previous coding experience would be useful). Several computationally fast semi-analytic approximations to the LISA response already exist; the second goal of this project will be to test the accuracy of these by comparing them against our numerical model. This project is open to two students who will each focus on different approximations to the response designed for different types of gravitational wave sources.

We anticipate that the full numerical model of the LISA response, while extremely useful, will be too computationally expensive for many applications; therefore, the final goal of this project will be to explore the possibility of using neural networks and machine learning techniques to accelerate the modelling of the LISA response.

Christopher and Antoine are both members of the Institute of Gravitational Wave Astronomy in Birmingham and are involved in preparations for the LISA mission. For a broad overview of the LISA mission you may like to read https://arxiv.org/pdf/1702.00786.pdf. A detailed technical description of time-delay interferometry may be found here: https://arxiv.org/pdf/gr-qc/0409034.pdf; the project will use some results from this paper but it is NOT necessary to study this beforehand. If you have any questions about the project please don't hesitate to contact both of us by email.

2.7: Spinning black holes from formation to detection: cracking the "isotropic stays isotropic" puzzle

Supervisor: Dr Davide Gerosa
E-mail: dgerosa@star.sr.bham.ac.uk

Open to any MSci Student (Astro & Theory)

Black-hole (BH) binaries are the most promising sources of gravitational waves (GWs). BHs are key predictions of Einstein's theory of General Relativity and are fully characterized by two quantities: their mass and angular momentum, or spin. As two BHs orbit about each other in a binary system, couplings between the BH spins and the binary's orbital angular momentum introduce secular dynamical features on top of the binary's orbital motion: the two spins and the orbital plane precess about the direction of the total angular momentum of the system. Meanwhile, energy and momentum are slowly dissipated away in the form of GWs and the orbital separation consequently shrinks. GW-driven inspiral ultimately leads to the merger of the two holes, as observed by our instruments like LIGO and Virgo [1,2].

From a dynamical point of view, the evolution of spinning BH binaries is a daunting mathematical problem. The three phenomena highlighted above (orbit, precession, and inspiral) all take place on different timescales. The orbital timescale is very short compared to the spin-precession timescale which, in turn, is much shorter than the radiation-reaction timescale on which the orbit is shrinking due to GW emission. A great simplification arises if one studies the binary dynamics in an orbit-averaged fashion, where one only tracks the evolution of the orbit itself, not the instantaneous position of each BH. Effective potentials methods allow to further average over the precessional time, thus considering the spin precessional cones as a whole, without tracking the spins secular motion. These new solutions improve our understanding of spin precession in much the same way that the conical sections for Keplerian orbits provide additional insights beyond Newton's law [3].

An outstanding open problem is BH spin dynamics is the so-called "isotropic stays isotropic" puzzle: distributions of binary BHs with spin directions distributed isotropically at large separations (where BHs form) appear to remain isotropic as they inspiral towards merger (where BHs are detected by LIGO). This feature of General Relativity was pointed out more than 10 years ago and is now being exploited in current LIGO/Virgo parameter estimation pipelines. However, its full understanding is still elusive and a formal proof still lacking. Hints to the solution of the puzzle might lie in peculiar spin-orbit resonant configurations, which are empirically found to stay resonant.

The ultimate goal of this project is to solve the "isotropic stays isotropic" puzzle exploiting multi-timescale methods. This project provides a unique opportunity to combine astrophysics and theoretical physics in a mixture of analytical and numerical work. Key steps articulate as follows:

1. Students will first need to familiarize themselves with post-Newtonian BH binary spin precession and the python code "precession" [4].

2. Numerical evolutions will be used to quantify thoroughly how well these properties are preserved. The project can be carried on by two students in parallel, with one student exploring the degree to which resonant binaries are maintained resonant, while the second student explores how isotropicity is preserved in large samples of binaries.

3. Guided by such numerical explorations, analytical work on the spin precession equations will be required to prove or disprove that isotropic spin distributions are truly invariant under the post-Newtonian evolutionary equations.

Strong background in mathematical physics and solid python coding skills are required. Successful proof (or disproof) of the puzzle will lead to a refereed scientific publication.

Further readings:
[1] First observation of BHs and GWs by LIGO: https://arxiv.org/pdf/1602.03837.pdf
[2] Review on BHs and GWs by Nobel Laureate Kip Thorne (perhaps a bit outdated but still illuminating): https://arxiv.org/pdf/gr-qc/9706079.pdf
[3] Multi-timescale approach to BH binary spin precession:
https://arxiv.org/pdf/1506.03492.pdf
[4] Python module "precession": https://arxiv.org/pdf/1605.01067.pdf

2.8: Prospects for identifying spin misalignment in gravitational-wave observations of merging high-mass black hole binaries

Supervisor: Dr Patricia Schmidt
Office: West 235
Email: pschmidt@star.sr.bham.ac.uk

Open to any MSci student (Astro & Theory)

The Advanced LIGO and Virgo detectors have observed gravitational waves (GWs) from a total of ten merging black holes during their first and second observing runs. GWs carry information on the fundamental properties of the black holes, such as their masses and spins, which can be extracted by comparing observations to theoretical waveform models.

The majority of these binaries was found to be heavier than 50 solar masses. On the other hand, current constraints on the black hole spins are rather wide and no clear imprint of misalignment between the orbital angular momentum of the binary and the black hole spins, i.e. precession, has yet been identified. From theory is it expected that precession will leave stronger imprints in the GW signal for lower mass black holes than for heavy systems.

In this project, we will investigate the prospects for identifying precession in high-mass systems of varying mass ratio. To do so, we will analyse Numerical Relativity simulations in a fully Bayesian analysis and determine whether current state-of-the-art effective waveform models will allow us to make inferences on possible spin misalignment.

The successful completion of this project requires basic coding skills (Python preferred) and to perform statistical analyses (mostly Bayesian inference). It is important to have an understudying of the key concepts of general relativity and black hole physics in order to being able to interpret the results.

Further reading:

Summary of LIGO/Virgo GW observations: https://arxiv.org/abs/1811.12907

Precession in black hole binaries:
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.49.6274

Bayesian inference for GWs: https://arxiv.org/abs/1409.7215

2.9: Stellar interactions and transients

Supervisor: Dr Silvia Toonen
Email: toonen@star.sr.bham.ac.uk

Stars are the fundamental building blocks of galaxies and stellar clusters. They are often part of small stellar systems, such as binaries and triples in which the stars can interact with each other. These interactions give rise to some of the most energetic events in the universe, e.g. supernovae Type Ia explosions and gravitational wave sources.

In this project, we will model the evolution and interaction of stars in binary and triple systems. Using existing codes, we will study novel pathways for the formation of transients, mergers, or run-away stars. What are the properties of these events? How frequent do they occur? What sets them apart from other stars?

Examples of specific projects are:

- The effects of winds on wide orbits. Recently there have been many claims for gravitational wave sources and other transients from wide-orbit triples. However, they assume that the stellar winds have an adiabatic effect on the orbit, which is likely not correct for these wide orbits. In this project, we would study how the wide orbits change due to wind mass loss. Do the systems unbind? Or how eccentric do they become? And how does this affect the further evolution of the binary or triple? How should the previously-predicted rates of transients be adjusted?
- Mass transfer in triples. The basic theory of mass transfer in binaries has been accepted and tested for a long theory, but the systematic study of mass transfer in triples has just

started. Recently we have finished the first full population synthesis study of triple stars. This gives us a unique understanding of the properties of those triples that will experience mass transfer. In this study we will investigate what happens to triples after the mass transfer starts. Will the stars merge? Will the triple become unstable? With different methods, we will assess the future evolution of these systems.

- Another follow-up study of our population synthesis study of triple stars involves improved assumptions for tides and orbital braking. How do these affect the eccentricities and orbital decay? This is your chance to prove me and the previous results wrong!
- Runaway stars are stars that travel through the Galaxy with high velocities. In the coming data release of the Gaia mission these stars can be detected with much higher accuracy then was possible before. These run-away stars can be formed when a star is kicked out of a binary systems. Triple stars allow for the exciting possibility of runaway binaries! What are the properties of these systems? How fast are their velocities? How many will Gaia likely detect? What can we learn about winds and supernova from these systems?

Condensed Matter, Nanoscale Physics, and Metamaterials

Project Team Leader – Dr Wolfgang Theis

This project group combines three research groups, as shown in the table below. Note that within a given project number, there may be more than one alternative for the research to be carried out.

Research group	Projects
A) Condensed Matter	3.1
B) Nanoscale Physics	3.2-3.4
C) Metamaterials	3.5-3.6

A) CONDENSED MATTER RESEARCH GROUP

3.1: Understanding Quantum Magnetism in Low Dimensions

Supervisor: Dr Mingee Chung (Minki Jeong)
Email: M.Chung@bham.ac.uk

In this project, the student will investigate properties of (quasi-) low-dimensional quantum magnets. The student will first characterise experimentally a one or two-dimensional quantum magnet by measuring its thermodynamic and magnetic properties, and then analyse the data through developing Python codes. Quantum magnets (materials in which interacting spins are arranged on a lattice) represent one of the simplest physical settings of quantum many-body system; it allows close comparison between theory and experiment. The student will be encouraged to apply several theoretical models to compare with the experimental results. The experiments will provide an opportunity to learn cryogenic (down to 2 Kelvin) and measurement techniques. The student will learn forefront knowledge in the active field of quantum magnetism research, how to perform essential solid-state experiments and analyse the data.

B) NANOSCALE PHYSICS

3.2: Assembly of two-dimensional molecular frameworks

Supervisor: Dr Quanmin Guo
Email: Q.Guo@bham.ac.uk

This is an experimental project in the area of nano-fabrication and characterisation. It involves the preparation of a single layer of molecules on a solid substrate such as the (111) face of Au. Scanning tunnelling microscopy (STM) is used to image the molecular layer with atomic resolution. Based on the STM images, you will derive a structural model of the molecular layer by establishing the unit cell of the 2-D molecular lattice. You will also investigate the thermal stability of the molecular layer by observing how the structure of the molecular layer changes as a function of temperature.

3.3: Design and characterisation of solid-state far-IR modulator for signal and image processing

Supervisor: Dr Andrey Kaplan
Room: Physics East 121
Tel: 44690
E-mail: a.kaplan.1@bham.ac.uk

A modulator is the most crucial component in signal and image transmission and processing. There are commercially available modulators for almost any part of the electromagnetic spectrum. Yet, for the wavelength range between 4.5 and 10 microns there are none available. This range is very important for night and thermal imaging, free-space space communication, range-finding and numerous other applications. Currently the only modulator in this range available on the market is a mechanical one. It has a number of disadvantages: slow modulation speed; intermittently frozen image; not suitable in environments with high g-forces; no potential for 3D imaging, no capabilities of position and speed determination; no wavelength selectivity; bulky and power thirsty. Our lab works on the development of a new type all-optical solid-state modulator which aims to resolve this disadvantages and bring a shift in far-IR imaging.

This project offers to participate in this project developing optically active element for the modulator, one of the most important components. There are three main stages needed to be performed to develop the active element:

1) Design of the multilayer photonic structure optically active in the far-IR range. This will be done using simulation software such as Lumerix, Comsol or packages in Python or Matlab.

2) Fabrication of the photonic structure in our facilities according to a layout designed in a previous step.

3) Optical characterisation of the performance using available at the lab set-up.

3.4: Applying machine learning in scanning transmission electron microscopy (STEM)

Supervisor: Dr Wolfgang Theis
Room: Physics East 104
Tel: 44666
E-mail: w.theis@bham.ac.uk

Aberration corrected transmission electron microscopes (ac-STEM) are important tools in nano science providing 2D projections of 3D structures in atomic resolution. A current challenge in the field is to achieve fast throughput analysis of nanoparticle (NP) shape distributions in large ensembles. This would benefit tuning processes of NP fabrication, for example to yield certain target geometries in higher purity.

This project aims to develop machine learning approaches for the classification of NPs imaged by HAADF-STEM (high angle annular dark field STEM). One simple example would be to classify the shape as triangular pyramid or cube, however in applications typically classification between much more similar shapes would be of interest. The challenge in this is that the ground truth of the classification is not readily available for the experimental data. While the experimentalist could try to provide the ground truth by inspecting the thousands of images required for training a neural network, the aim is to try to avoid the need for this because it is both very labour intensive and subjective. Thus, it is proposed to divide the task into two separate steps. The first step is to record a dataset with multiple projections at different tilt angles from which the ground truth can be reliably derived using a network to be trained on simulated data. Taking multiple projections is fairly time consuming because each NP has to be kept in the field-of-view and brought into focus individually. Therefore, taking such detailed data is not viable for the intended high-throughput measurements. Instead, this labelled experimental data will be used to train a second network which takes a single projection as its input. This network can then be used to classify single tilt data sets which can be measured at high throughput.

To carry out the project the student(s) need(s) to have a good working knowledge in python. The “experimental data” referred to above would most likely be provided or it could be simulated by the student(s) as well to make this a fully computational project without reliance on any experiments.

C) METAMATERIAL RESEARCH GROUP

3.5: Computational THz imaging for liquid samples

Supervisor: Dr Miguel Navarro-Cía
Room: Medical Physics Building (R11), G05b
Ext: 44664
Email: m.navarro-cia@bham.ac.uk

Sandwiched between microwaves and infrared in the electromagnetic spectrum, THz radiation (ca. 0.1 – 3 THz) holds promise for medical diagnosis, security applications (chemical fingerprinting and standoff screening) and industrial control processes [1]. The potential of THz in these realms arises from the ability of THz radiation to pass through many optically opaque materials (e.g., clothing, paper, etc.), and the fact that specific rotations, vibrations or librations of molecules and molecular aggregates occur in this frequency range. In addition, THz radiation is non-ionizing and safe, unlike X-rays. Unfortunately, THz cameras (i.e. array of pixels) are scarce and expensive. To circumvent this, one can look at computational imaging techniques exploiting single-pixel detection [2].

In Life Sciences applications, where specimens stay in an aqueous environment, THz spectroscopy and imaging meets a special challenge: 1 mm of water attenuates a THz signal by a factor of ~1000 times! To tackle this problem, THz imaging and spectroscopy should be done in reflection [3] or in the low part of the THz spectrum (i.e. <0.5 THz).

The students will design and test a microscope system (working preferable in reflection) that is suitable (1) to integrate with the existing TERA K15 all fiber-coupled Terahertz Spectrometer [4] or TeraSense IMPATT diode source + ultrafast detector system [5] in the Metamaterials Research Group, and (2) for liquid sample inspection. To this end, students will first have to familiarize themselves with the abovementioned systems and calibrate them [6]. With this information, they will design the quasi-optical system (that enables imaging without the need of raster-scanning the liquid sample or the detector) and they will liaise with the workshop to fabricate the system. The project is suitable for students with a strong interest in optical systems that like a good mixture of modelling and hands-on tasks.

[1] D. M. Mittleman, Opt. Express **26**, 9417-9431 (2018).

[2] M. P. Edgar *et al.*, Nature Photonics **13**, 13-20 (2019).

[3] J.-H. Son, Terahertz: Biomedical Science & technology, CRC Press, 2014.

[4] https://www.menlosystems.com/en/products/thz-time-domain-solutions/all-fiber-coupled-terahertz-spectrometer/

[5] http://terasense.com/

[6] J. F. Molloy *et al.*, IEEE J. Sel. Topics Quantum Electron. 19, 8401508–8401508 (2013)

3.6: Reciprocity in plasmonic nano-antennas

Supervisor: Dr Angela Demetriadou
Email: a.demetriadou@bham.ac.uk

When light illuminates nano-sized metallic structures, the free electrons in the metal collectively oscillate, creating `plasmons’. By specifically designing the geometry and arrangement of the nano-metallic structures, one can create plasmonic nano-antennas that can enclose even single molecules or quantum emitters. Quantum emitters absorb plasmons to excite electrons at higher-energy states, and electron relaxations produce photons that excite plasmons. Hence, the light (plasmon) and quantum emitters (matter) continuously exchange energy, creating a hybrid system where light and matter blend together.

Nanoplasmonic antennas have the ability to specifically direct light emitted by the molecules and/or quantum emitters to the far-field, where it can be measured experimentally. Due to reciprocity, the reverse is also true, which means that external illumination can be concentrated at very small volumes to strongly interact with quantum emitters.

In this project, we will theoretically investigate reciprocity in nano-plasmonic antennas, and propose designs where reciprocity breaks. The new nano-antenna designs will exhibit unique and counter-intuitive properties, which significantly influence the interaction between light and matter.

To carry out the project, the student needs good command on Electromagnetism and Electrodynamics and he/she will use a commercial software with a user-friendly interface to numerically calculate the properties of nano-plasmonic antennas.

Nuclear Physics

Project Team Leader – Prof Peter Jones

4.1: Nuclear Deformation in Gadolinium from Isotope Shifts and Hyperfine Structure

Supervisor: Dr D. Forest
Offices: Poynting PB2h / East 303
Telephones: 44579 / 44685
Emails: D.Forest@bham.ac.uk

The energies of atomic states can be explained to a high degree of precision by assuming the nucleus to be an infinitely massive, point-like charge. However, we know that the nucleus has a finite size and a finite mass, and these create small differences in the atomic energy levels for different isotopes of the same element. These energy differences lead to the wavelength of the same atomic transition in different isotopes varying by a few parts-per-million [1]. These small changes – the isotope shifts – can be measured using high resolution laser spectroscopy techniques with a few parts-per-billion precision.

The isotope shift arises from two effects; changes in nuclear size – the field shift – and the other from changes in nuclear mass – the mass shift – between isotopes. Each of these contributions is itself a combination of nuclear and atomic factors, as the observed isotope shift depends on how the changes in nuclear properties influence the atomic structure. As nuclear masses are known to high precision from other techniques, the nuclear parameter of interest is the change in nuclear size. If the atomic contributions are known, then these size variations can be extracted from the isotope shifts, even for radioactive isotopes far from the valley of nuclear stability [2]. The nuclear size depends not only on the number of nucleons, but also the shape of the nucleus, allowing the deformation to be inferred.

As well as the isotope shift, isotopes with an unpaired neutron or proton (or both) will have a magnetic dipole moment and possibly an electric quadrupole moment. These electromagnetic moments interact with the atomic electrons giving rise to hyperfine structure in atomic spectra [1]. Measuring this hyperfine structure can thus give information on the magnetic properties of the nucleus – which depend on which single particle orbitals are occupied – as well as the shape of the nuclear charge distribution – which depends on the degree of deformation of the nucleus [2]. This measure of nuclear deformation is slightly different from that extracted from the nuclear size, allowing the influence of dynamic effects to be deduced.

This project aims to determine the isotope shifts and hyperfine structures for a range of transitions in the stable isotopes of atomic gadolinium. This will involve using a continuous-wave tunable dye laser to excite atomic transitions in the visible and/or UV portion of the electromagnetic spectrum. The data will be analysed to determine the degree of deformation in the Gd isotopes, and whether it is predominantly static or dynamic in nature.

The project requires good practical skills, and brings together aspects of nuclear physics, atomic physics, laser physics, optics, vacuum technology and electronics.

References

[1] Woodgate, G K 1992 *Elementary Atomic Structure* (Oxford).
[2] Cheal B and Flanagan K 2010 *J. Phys. G: Nucl. Part. Phys.* **37** 113101

4.2: Exploring quark deconfinement with jets at the Large Hadron Collider

Supervisor: Prof Peter Jones
Room: Physics East 306
Telephone: 44677
Email: p.g.jones@bham.ac.uk

ALICE is one of four experiments at the Large Hadron Collider (LHC) designed to study particle interactions under conditions similar to those that would have existed a fraction of a second after the Big Bang [1]. ALICE has been optimised to study high-energy collisions involving heavy nuclei where normal nuclear matter is expected to undergo a phase transition into a plasma of quarks and gluons. This novel state of matter is extremely short-lived and cannot be observed directly. Instead, we rely on studying observables that are sensitive to the existence of the quark-gluon plasma during the early stages of the collision.

Jets are collimated sprays of hadrons, formed when a quark or, more often, a gluon is scattered sideways out of a high energy nucleus. The rate at which jets are observed in heavy-ion collisions is much lower than expected because they are partially quenched by the surrounding quark-gluon plasma. Although the experimental evidence for jet quenching is unequivocal, the underlying mechanism is not well understood. Recently, a new picture was put forward based upon a phenomenon known as colour decoherence [2]. This model treats jets as radiating antennas. To test this model, we want to look for jets that are composed of two subjets, so that they look like a colour antenna. The complication is that the jets are obscured by a large and almost overwhelming background. This project will investigate how well we can deal with the background to extract information on the structure of jets. We'll do this by simulating jets and then embedding them into a synthetic background made to look like the data.

This project gives students practical experience of some of the methods, techniques and tools used in high-energy physics data analysis, as well as providing insight into state-of-the-art detector systems and the physics of the strong interaction. This project primarily involves analysing existing data and you will spend a significant fraction of your time developing analysis code using C++. The project will make use of software tools that have been developed by the ALICE collaboration and build on the ROOT C++ analysis framework [3]. You will be provided with a class template for your analysis task that will handle the I/O and give access to the data objects you need but the rest of the code will be written by you. To get the most out of this project you need to be competent at programming in C++ and have a good general appreciation of classes. Above all, you need to enjoy programming and thinking of ways to check that your code works the way you think it should.

[1] ALICE web page: http://aliceinfo.cern.ch
[2] J. Casalderrey-Solana *et al.*, New picture of jet quenching by color decoherence, Phys. Lett. B725 (2013) 357-360.
[3] ROOT web page: http://root.cern.ch

4.3: Production of multistrange particles in pp collisions at √s = 7 TeV from the ALICE experiment

Supervisors: Dr R. Lietava and Prof. D. Evans
Room: Physics East 307 / 303
Email: rl@hep.ph.bham.ac.uk, de@hep.ph.bham.ac.uk

Multistrange particles, Ξ^- and Ω^-, are very sensitive probes of the overall level of strangeness in a proton-proton collision [1,2]. It was proposed by J.D. Bjorken that in a proton-proton collision of sufficiently high multiplicity (number of particles produced in a collision) a Quark-Gluon Plasma (QGP) might be formed [3], but, till now, such very high multiplicity collisions have not been accessible. The LHC provides a new regime where much higher multiplicity collisions are seen to occur. Should a QGP be created, a thermal system is produced in which strangeness abundances could be much higher than in normal hadronic reactions [4], as has already been seen in heavy ion interactions. In this project, the relative production rates for multistrange particles will be examined as a function of multiplicity to look for possible changes from the values expected for hadronic interactions.

This project gives students practical experience of some of the methods, techniques and tools used in high-energy physics data analysis, as well as providing insight into state-of-the-art detector systems and the physics of the strong interaction. This project primarily involves analysing existing data and hence is a computing based project. The project will make use of software tools that have been developed by the ALICE collaboration and build on the ROOT C++ analysis framework. You will be provided with a working program for your analysis task but will have to make changes to it. Hence, you need to enjoy programming and thinking of ways to check that your code works the way you think it should.

Further reading

1. J. Rafelski and B. Mueller, *Phys. Rev. Lett.* **48** (1982) 1066; Erratum Phys. Rev. Lett. **56,** 2334 (1986); J.Rafelski and M. Petráň, *Phys. Rev.* **C82** (2010) 011901
2. H. Caines J. Phys. G **32** (2006) 171
3. J.D. Bjorken, Fermilab Report Fermilab-Pub-82/59-THY (1982)
4. Z.L. Matthews, J. Phys. G. **37** (2010) 094048.

4.4: Developing novel proton radiotherapy modalities at the MC40 cyclotron

Supervisors: Dr T Price and Dr F Romano (National Physical Laboratory)
Room: East 310
Telephone: 44681
Email: T.Price@bham.ac.uk, Francesco.romano@npl.com.uk

Over the last 20 years there has been an explosion in the number of proton radiotherapy centres due to the potential of delivering a lower dose to healthy tissue, thus reducing the risk of secondary cancers in later life. In more recent times, studies have shown that delivering the dose to the tumour at dose rates much higher than used currently, known as FLASH radiotherapy, can have a sparing effect on the healthy tissue. In addition, there are signs that delivering the radiation as a grid of microbeams, known as microbeam radiotherapy, rather than one large beam can stimulate the body's immune response and increase the effectiveness of the cancer treatment. Both of these emerging modalities require intense study to understand the mechanism involved. There are very few sites worldwide that have the potential to deliver these emerging modalities and the MC40 cyclotron at the University of Birmingham is one such site. In this project, one student will work with us to develop the systems required on the cyclotron to accurately deliver the required dose, over timescales of less than a second, and ways to monitor the beam during FLASH treatments. Working with technologies developed for the nuclear and particle physics communities and now applied to radiotherapy, the other student will run Monte Carlo simulations to optimise the collimator design for microbeam treatments. Both of the students will then work together on experimental days at the cyclotron to test their designs and integrate them into the already available systems. Depending on the timescales of the project, there is also the potential that these systems could be used to irradiate cell cultures towards the end of the project. The dosimetry experts at NPL will assist with solving some of the complexities that arise when performing accurate dosimetry on such modalities. The ideal students will need to have a mixture of both computational and experimental skills due to the nature of work involved in the project.

Particle Physics

Project Team Leader - Dr Nigel Watson

5.1: Top quark measurements using ATLAS data from the LHC

Supervisors: Dr CM Hawkes / Dr MF Watson
Room: Physics West 212 / 314
Extension: 44622 / 44618
Email: C.M.Hawkes@bham.ac.uk, Miriam.Watson@cern.ch

During the period 2015-2018, the ATLAS experiment collected data from proton-proton collisions with a centre-of-mass energy of 13 TeV at the Large Hadron Collider (LHC) at CERN, the world's highest energy particle collider. The Birmingham Particle Physics group is contributing both to the running of the experiment and to the physics analysis of the data.

The main goals of ATLAS are to search for the production of new particles and for signs of physics beyond that expected from the Standard Model of particle physics. Many of the particles produced in the proton-proton collisions originate from the decays of the heaviest known fundamental particle, the top quark. Measurements of top-quark events allow us to investigate their production and to test Standard Model predictions. In this project you will study the identification of collisions where top quarks are produced and use these to make measurements of their properties. Examples of possible measurements are the correlation between the spins of top and antitop quark pairs [1], the charge asymmetry of top and antitop quarks [2] or the mass of the top quark [3].

You will investigate different ways of selecting the relevant signatures and evaluate other background processes which might fake the signal. In the course of the project you will need to gain a good understanding of the basic features of the Standard Model of particle physics, high energy proton-proton collisions and detection methods used in the most recent collider experiments. You will gain a strong insight into the techniques used in current particle physics experiments at the energy frontier.

This project will involve programming in Python or C++, and will be based on a Linux operating system.

Further reading:

1. Measurement of spin correlation in top-antitop quark events and search for stop quark pair production in proton-proton collisions at $\sqrt{s}$ = 8 TeV using the ATLAS detector, Phys. Rev. Lett. 114, 142001 (2015), http://arxiv.org/abs/1412.4742.

2. Measurements of the charge asymmetry in top-quark pair production in the dilepton final state at $\sqrt{s}$ = 8 TeV with the ATLAS detector, Phys. Rev. D 94, 032006 (2016), https://arxiv.org/abs/1604.05538.

3. Measurement of the top quark mass in the $t\bar{t} \rightarrow$ dilepton channel from 8 TeV ATLAS data, Phys. Lett. B 761 (2016) 350, https://arxiv.org/abs/1606.02179.

5.2: Large Hadron Collider (LHCb)

We will run one of Projects 5.2a or 5.2b:

Either 5.2a: Studies of jet physics with the LHCb experiment

Supervisors: Dr Phil Ilten / Dr Nigel Watson
Room: Physics West W320 / W215
Phone: 48684 / 44699
Email: Philten@cern.ch / Nigel.Watson@cern.ch

LHCb [1] is a general purpose forward detector on the Large Hadron Collider at CERN, but unlike the ATLAS and CMS detectors, has ring imaging Cherenkov detectors which allow for full particle identification. Leveraging this capability and the unique trigger system designed for low transverse momentum physics, LHCb is an ideal experiment for understanding the structure and composition of jets in the high energy LHC environment.

Due to the interactions of quantum chromodynamics (QCD), bare quarks and gluons are not observed in nature. Instead, only colourless bound states such as the proton or pion are observed. Jets are clusters of these colourless states, including leptons, and are an emergent property of QCD radiation. Consequently, while the fundamental interactions of QCD cannot be directly observed, phenomenological techniques can be applied to jets to further understand QCD, see [2].

In this project you will explore these techniques, both with data and Monte Carlo simulation [3]. Possible projects include expanding on [4] and measuring the momentum fraction and polarization of heavy flavour quarkonia in jets. More phenomenological paths can also be taken, such as comparing theory results from Pythia and DIRE [5] to data. Other measurements include measuring particle production properties in jets, e.g. kaon momentum fractions.

[1] http://lhcb.web.cern.ch/lhcb/
[2] https://arxiv.org/abs/1702.02947
[3] https://arxiv.org/abs/1410.3012
[4] https://arxiv.org/abs/1701.05116
[5] https://arxiv.org/abs/1506.05057

Or 5.2b: Searching for Novel Signatures for new Physics at the LHC with CODEX-b

Supervisors: Dr Phil Ilten / Dr Nigel Watson
Room: Physics West W320 / W215
Phone: 48684 / 44699
Email: Philten@cern.ch / Nigel.Watson@cern.ch

The experiments at the Large Hadron Collider (LHC) are designed to look for standard model signatures: electrons, muons, photons and hadrons with lifetimes less than a nanosecond, and jets of these particles. Searches at the LHC with these conventional signatures, including missing energy, have failed to yield any new physics. Consequently, new unconventional signatures are being explored, pushing the current detectors to their limits. Long-lived particles (LLPs) are a particularly challenging unconventional signature, as they will often decay outside the detector and have very low transverse momentum signatures. Several new experiments have been proposed at the LHC to search for LLPs: MATHUSALA [1], FASER, and CODEX-b.

The CODEX-b proposal is a low-cost addition to the LHCb detector that would be implemented before run 3 of the LHC. In this project, students will improve the CODEX-b proposal. This includes expanding phenomenological studies to understand the potential of the experiment. Additionally, students will develop a full GEANT4 simulation and event reconstruction framework for the proposal, providing more robust predictions than current studies.

We ran a Y4 project on CODEX-b for the first time in 2018/19. This produced new results that improved our understanding of the parameter space regions that are accessible with this proposed detector for dark photons and emergent jets [4], as well as setting up a first simulation and pattern recognition/track finding algorithm for muons and electrons [5]. In 2019/20, students will enhance these areas further, working with us and one of our PhD students.

[1] https://arxiv.org/abs/1606.062984
[2] https://arxiv.org/abs/1708.09389
[3] https://arxiv.org/abs/1708.09395
[4] P.Swallow, CODEX-b mini-workshop, 26-27 March 2019, https://indico.cern.ch/event/806481/
[5] G.Gibbons, CODEX-b mini-workshop, 26-27 March 2019, https://indico.cern.ch/event/806481/

5.3: Higgs Boson Production in Future ep Collisions at the LHeC

Supervisors: Dr PD Thompson / Prof PR Newman
Room: Physics West 218 / 210
Telephone: 44570 / 44617
Email: pdt@hep.ph.bham.ac.uk, p.r.newman@bham.ac.uk

Following its discovery and first studies at the LHC, the Higgs boson appears to be fully consistent with the predictions of the Standard Model of Particle Physics. On the other hand, many models for new physics predict only small and subtle variations of the Higgs properties from the Standard Model version. It is therefore reasonable to ask whether other new facilities might be able to produce and study Higgs bosons in ways that are different from the LHC. One possibility is to use electron-proton collisions, where Higgs bosons are produced via WW and ZZ fusion decay channels that are hard to observe at the LHC, such as b bbar and c cbar, might be accessible. A possible cost-effective realisation is the so-called 'LHeC,' a proposed high energy, high luminosity, facility in which Birmingham is deeply involved, colliding the existing LHC proton beams with electrons from a new accelerator.

In this project we will be analysing simulated data to confirm whether the LHeC can give complementary Higgs information to the LHC and to estimate the precision with which it might be able to measure some of the Higgs couplings. The studies will be done using standard (root) software tools used in most particle physics experiments to implement the techniques required to reconstruct the signal, separate it from the background and quantify the expected measurement precision. Some knowledge of the linux operating system and of the C++ programming language would be an advantage.

For more details, see eg the LHeC web page at http://lhec.web.cern.ch and the links therein.

5.4: Photodiodes as beam probes for ATLAS irradiations

Supervisors: Prof K Nikolopoulos / Dr A Chisholm
Room: Physics West 325 / 315
Telephone: 44627
Email: k.nikolopoulos@bham.ac.uk / asc@hep.ph.bham.ac.uk

In testing materials and detectors for the upgraded ATLAS experiment at the CERN High Luminosity Large Hadron Collider (HL-LHC), we are using the University of Birmingham Medical Physics cyclotron to expose devices to particle fluences (numbers of incident particles per unit area) equivalent to those expected after several years of operation at the HL-LHC.

For comparison reasons, all radiation damage studies worldwide report findings scaled to an equivalent fluence of 1 MeV neutrons. For this conversion a crucial, energy dependent, factor is needed, the exact value of which is debated in literature. Thus, in-situ measurements at Birmingham and at overseas laboratories are necessary.

Within the project state-of-the-art Hamamatsu Photonics K.K. MD diodes will be irradiated at Birmingham, in collaboration with Prof D. Parker and his cyclotron team, and in overseas laboratories. For the study of the diode characteristics before and after irradiation, the facilities of the Birmingham Instrumentation Laboratory for Particle Physics and Applications will be used.

Within the ATLAS High Luminosity LHC (HL-LHC) upgrade project, Birmingham has the unique international responsibility for the routine proton irradiation and testing of test devices during the production of the ~20,000 silicon strip detectors need for the replacement tracker, the largest single order of the entire upgrade programme. Checking for radiation hardness is vital to ensure survival for well over ten years in the unpredicted radiation environment at the HL-LHC. The work of the next year to fully commission the procedures for irradiation and testing of diodes from the chosen vendor for the final production is vital to the success of this programme.

Furthermore, the project has attracted significant interest within the CERN RD50 Collaboration working towards developing radiation hard semiconductor devices for very high luminosity colliders.

Overall the project will be hardware based, with some data analysis, and will involve understanding an interesting mixture of particle, nuclear, and solid state physics, starting at a level familiar to all 4th year students.

5.5: Testing readout electronics of the ATLAS tracker upgrade

Supervisors: Prof PP Allport / Dr JP Thomas
Room: Physics West 217 / 213
Telephone: 44680
Email: ppa@hep.ph.bham.ac.uk / jpt@hep.ph.bham.ac.uk

The Silicon Laboratory (BILPA) at the Birmingham Particle Physics group is participating in the production of the new silicon tracking detector ('Inner Tracker Strip Detector: ITk') for the ATLAS experiment, which is required for operating the detector at the High-Luminosity Large Hadron Collider (HL-LHC) planned to start data-taking in 2026. This system will replace the existing tracking detector of ATLAS, the 'SCT' and 'TRT'. The production effort involves assembling 'hybrids' build from custom-designed readout and controller chips which are glued onto thin printed-circuit boards, and 'modules' where one or two such hybrids are glued onto 10x10cm sized silicon sensors. In the UK, Birmingham is one of only two groups involved in both the microelectronics circuits (hybrid) and overall silicon strip module production. An important aspect of this production is to ensure the required quality of those builds. This involves functional testing under different environmental conditions.

In this project, students will initially run the last generation of such modules, called '130 Short Strip Module' within a thermal-cycling setup between very low temperature (eg -40C), room temperature and higher temperatures, at controlled humidity. The data collected during this test will be analysed to derive the characteristics of each channel of the module esp the 'input noise' levels, and how they change with the running conditions, esp temperature and the bias voltage to the sensors. This requires developing and working with object-oriented analysis code ('ROOT' package, C++ or Python). Comparisons between the 10 or 20 chips on one module as well as between different modules should be derived.

The next step will then be to compare those results with a new and likely final generation of chips, hybrids and modules, the 'Star Short Strip Module', which will arrive in summer 2019. The project will be largely software-based. The data will be recorded at dedicated 'data taking days', where the system will be run under supervision at the BILPA clean-room suite in the Physics West building.

We hope the project will appeal to someone who enjoys working with object-oriented analysis software, and also has an interest in digital electronics. Experience with the operating system Linux is advantageous.

References:

For overviews of the ATLAS Tracker Upgrade Project:
http://epweb2.ph.bham.ac.uk/user/thomas/tracker/yr4project/
Full details of the Tracker Upgrade project:
'Technical Design Report for the ATLAS Inner Tracker Strip Detector',
CERN report number: CERN-LHCC-2017-005 and ATLAS-TDR-025
https://cds.cern.ch/record/2257755?ln=en
Document at: http://cds.cern.ch/record/2257755/files/
Birmingham Silicon Laboratory
(BILPA): http://www.ep.ph.bham.ac.uk/general/SiliconLab/index.html
Tutorials of the analysis software package:
Python ('pyroot'): https://root.cern.ch/doc/v612/group__tutorial__pyroot.html

C++: https://root.cern/doc/v612/group__Tutorials.html

5.6: NEWS-G: Searching for Light Dark Matter with a Spherical Proportional Chamber

Supervisors: Prof K Nikolopoulos / Dr R Owen
Room: Physics West 325
Telephone: 44627
Email: k.nikolopoulos@bham.ac.uk / reo@hep.ph.bham.ac.uk

Given the absence of any deviation from the Standard Model (SM) of particle physics, the Dark Matter (DM), an essential ingredient for understanding our Universe, appears as one of the only evidence for new physics. The University of Birmingham is a member of the NEWS-G experiment, dedicated to direct searches for very-low mass (0.1-10 GeV), Dark Matter particles. This experiment particularly timely, as in a number of new models the preferred DM candidates are much lighter than the Electro-Weak scale.

The NEWS-G experiment is built around a large diameter radio-pure spherical gaseous detector that will operate at SNOLAB (Canada) underground environment with the aim of reaching a much higher sensitivity for light Dark Matter search than any other experiment. The proposed detector brings many advantages in the searches for Dark Matter, including: sub-keV energy threshold, fiducialisation and background rejection by pulse shape analysis, ability to operate at pressures up to 10 bars, tens of kg of gas with various light targets such as H, He and Ne nuclei.

An existing, 60 cm in diameter, detector is currently operating at the Laboratoire Souterrain de Modane (LSM) in France. Currently, the next generation, 130 cm in diameter, detector is being assembled in LSM, and will be commissioned with physics data-taking, before it is transferred to SNOLAB for the main stage of the experiment.

In this project, novel constraints on Dark Matter particles will be placed through a mixture of data analysis and simulation-based work. Data from the experiment will be analysed with state-of-the-art techniques and simulations developed by the Birmingham group, potentially leading to the most stringent Dark Matter constraints to-date. Standard analysis tools used in most modern particle and astro-particle physics experiments will be employed, thus providing particularly relevant experience for future involvement in research. Familiarity with the Linux operating system and a programming language (ideally, C/C++ or Python) would be beneficial for this project.

The students will be part of the NEWS-G at Birmingham group and will make original contributions to the experiment. More information on the NEWS-G at Birmingham activities can be found here:

http://www.ep.ph.bham.ac.uk/index.php?page=exp/NEWS-G/index

5.7: Calorimeter Trigger Algorithms for the LHC Upgrade

Supervisors: Dr AT Watson / Dr SJ Hillier
Room: West 214 / West 322
Telephone: 44619 / 44235
Email: Alan.Watson@CERN.CH / sjh@hep.ph.bham.ac.uk

The first-level calorimeter trigger of ATLAS (L1Calo) is responsible for analysing all collisions and rapidly identifying energetic electron, photon, tau and jet candidates, as well as measuring the total and missing transverse energy, so use in selecting potentially interesting events which should be read out for subsequent analysis. The Birmingham group have particular responsibility for the processor which identifies electron/photon and tau candidates, but have involvement in most parts of the system's physics algorithms and performance. For Run 2 of the LHC (2015-18) the algorithms have been upgraded and new hardware added to allow the trigger to continue to operate at luminosities higher than it was originally designed to do. However, the LHC plan is to increase the luminosity even further for Run 3 (2019 onwards), and for this a new, more powerful system is being designed to replace the current L1Calo hardware. The new system will have better energy resolution, finer segmentation of inputs and greater processing power, allowing algorithms which will provide better discrimination between the signal (e.g. real electrons, photons or taus) and the backgrounds (mainly jets with topologies which resemble the signal), as well as improved jet identification and measurement, and thus should allow ATLAS to maintain physics sensitivity despite the rising luminosity and increasing numbers of proton-proton collisions per bunch-crossing.

Although the outline of the hardware design is decided, there is a lot of work to do to optimise the algorithms which will be used to identify trigger signatures, and to understand the sensitivity of the performance to the choices made and the detector performance.

The project would be to join the L1Calo team studying the algorithm design and physics performance of the upgraded trigger system, and to work on optimising the design. The work could focus on electron/photon, tau or jet identification and measurement. Study of algorithms for the Phase II upgrade, where the full detector granularity will be available, is also possible. The objectives would be to use simulated high-luminosity LHC data to identify optimal algorithms and estimate their performance in discriminating interesting events from the mass of collisions and possibly in assessing the sensitivity of key LHC physics processes to this performance.

References

1. ATLAS Trigger/DAQ Phase-1 Upgrade Technical Design Report: https://cds.cern.ch/record/1602235/files/ATLAS-TDR-023.pdf

2. ATLAS Phase-1 Upgrade Letter of Intent: http://cds.cern.ch/record/1402470?ln=en
(less specific, older, but maybe easier for an overview)

5.8: Searches for new physics in rare kaon decays

Supervisors: Dr E Goudzovski / Dr A Romano
Room: Physics West 321
Email: eg@hep.ph.bham.ac.uk / angela.romano@cern.ch

At present, the primary challenge of particle physics is the search for New Physics underpinning the Standard Model (SM) and responsible for such phenomena as the Dark Matter. The “energy frontier” experiments at colliders such as the LHC aim at discovering new particles produced directly in interactions at the highest energy that can be possibly achieved. A complementary “precision frontier” approach involves precision studies of very rare processes at low energies. New physics at high mass scale would manifest itself as higher order corrections to the basic SM processes, due to contributions involving new virtual heavy particles.

One of the major precision frontier facilities, with a significant UK involvement, is the NA62 experiment at CERN. It has collected a large data set in 2016–18, and is performing precision measurements of ultra-rare kaon decays, providing a range of unique opportunities to probe the nature of new physics at the multi-TeV energy scale. The primary NA62 goal is the measurement of the rate of the $K^+ \to \pi^+ \nu\nu$ decay, which is one of the rarest decays of a subatomic particle ever detected. Other NA62 goals are searches for lepton flavour and number violation, lepton universality violation, and feebly interacting Hidden Sectors of particle physics.

The project is focused on searches for rare and forbidden kaon decays using the NA62 data. It will involve studies of the signal selections, detector resolutions and backgrounds using real data as well as detailed Monte Carlo simulations. The computations will be performed within a ROOT-based data analysis framework using a Linux computer cluster of the Particle Physics group, as well as CERN computing facilities.

Familiarity with basics the Linux operating system and programming languages (C/C++, as well as scripting languages) is required for this project.

Reference

http://na62.web.cern.ch/NA62/Documents/ReferenceDocuments.html

5.9: Optimisation of current monitoring and beam quality at the high intensity irradiation line at the MC40 cyclotron

Supervisors: Dr L Gonella / Dr T Price
Rooms: Physics West 318 / Physics East 310
Email: l.gonella@bham.ac.uk / pricet@bham.ac.uk

The high intensity irradiation line at the MC40 cyclotron is heavily used to characterise detector components for the HL-LHC upgrade with 27 MeV protons. This project will look at developing a better current monitoring device and investigate beam composition.

Precise beam current monitoring is crucial to deliver the target fluence. Currently, a Faraday cup at the end of the irradiation line is used to setup the beam current and monitor current stability during irradiation. Depending on the thickness and material of the sample to be irradiated, the current monitored by the Faraday Cup might decrease to the point where it is not measurable anymore, making it impossible to monitor beam stability during irradiation. An ionisation chamber has been developed to measure the beam current right after the collimator, i.e. in front of the sample. Calibration has shown however that due to recombination and saturation effects, this device cannot provide an accurate measurement. In this project the design of the ionisation will be modified to increase the sensitive volume in order to reduce these effects. The device will then be tested and calibrated at the cyclotron.

If the development is successful, the device could also be used to measure the total fluence delivered to the sample. If time allows, an alternative method of current beam and fluence measurement using thin aluminium foils could also be investigated.

Irradiations of silicon strip sensors developed for the ATLAS inner Tracker (ITk) upgrade have shown that alongside the 27 MeV protons, a low energy component is present in the beam, leading to significantly increased radiation damage for a given fluence. Previous investigations have shown that this component has an energy below 6 MeV, and it is most likely made of electrons or negative ions, generated by the interaction of the protons with either the titanium window, the tantalum collimator, or air. A Geant4 simulation will be used to investigate the origin, nature and energy of the component. Once this is understood, irradiations of prototype ITk strip sensors will be performed at the cyclotron with different thickness of absorbing material. The charge collection efficiency of the sensors will be tested before and after irradiation, and compared to expected values to assess the effectiveness of the shielding.

We are looking for students interested in doing experimental work to optimise equipment, perform measurements and analyse the data of the experiments. This project will increase your knowledge of interactions of particles with matter and radiation detection, starting from particle and nuclear physics concepts familiar to all Y4 students.

5.10: Upgrade of the NEWS-G experiment for operation in SNOLAB

Supervisors: Prof K Nikolopoulos / Dr I Katsioulas
Room: Physics West 325
Telephone: 44627
Email: k.nikolopoulos@bham.ac.uk / i.katsioulas@bham.ac.uk

Given the absence of any deviation from the Standard Model (SM) of particle physics, the Dark Matter (DM), an essential ingredient for understanding our Universe, appears as one of the only evidence for new physics. The University of Birmingham is a member of the NEWS-G experiment, dedicated to direct searches for very-low mass (0.1-10 GeV), Dark Matter particles. This experiment particularly timely, as in a number of new models the preferred DM candidates are much lighter than the Electro-Weak scale.

The NEWS-G experiment is built around a large diameter radio-pure spherical gaseous detector that will operate at SNOLAB (Canada) underground environment with the aim of reaching a much higher sensitivity for light Dark Matter search than any other experiment. The proposed detector brings many advantages in the searches for Dark Matter, including: sub-keV energy threshold, fiducialisation and background rejection by pulse shape analysis, ability to operate at pressures up to 10 bars, tens of kg of gas with various light targets such as H, He and Ne nuclei.

An existing, 60 cm in diameter, detector is currently operating at the Laboratoire Souterrain de Modane (LSM) in France. Currently, the next generation, 130 cm in diameter, detector is being assembled in LSM, and will be commissioned with physics data-taking, before it is transferred to SNOLAB for the main stage of the experiment.

In this project, a number of ideas for the upgrade and improvement of the NEWS-G detector at SNOLAB will be tested using the new gaseous detectors laboratory set-up in Birmingham. Overall, the project will be hardware-based, with some data analysis. Standard analysis tools used in most modern particle and astro-particle physics experiments will be employed, thus providing particularly relevant experience for future involvement in research. Familiarity with the Linux operating system and a programming language (ideally, C/C++ or Python) would be beneficial for this project.

The students will be part of the NEWS-G at Birmingham group and will make original contributions to the experiment. More information on the NEWS-G at Birmingham activities can be found here:

http://www.ep.ph.bham.ac.uk/index.php?page=exp/NEWS-G/index

5.11: Testing the electroweak theory at the LHC

Supervisors: Prof D Charlton / Dr A Chisholm
Room: Physics West 315 (AC)
Telephone: 46462 (AC)
Email: Dave.Charlton@cern.ch / Andrew.Chisholm@cern.ch

Following the discovery of the Higgs boson by the ATLAS and CMS experiments in 2012, the Standard Model of particle physics is apparently complete. However, many questions are unanswered, and this project will address one of them which can only be explored at the LHC.

The Brout-Englert-Higgs ("BEH") mechanism, postulated in 1964 and rewarded by the 2013 Nobel prize in physics, provides an explanation how particles can gain mass without destroying the mathematical symmetry of the electroweak theory. It is not known, however, if the single Higgs boson observed so far provides a complete explanation of this sector of physics, or if there is more to be found. In addition to studying directly the properties of the Higgs boson at the LHC or looking for more Higgs bosons directly, a sensitive further way to attack the problem is study how the electroweak force-carrying particles – the photon, W and Z – interact with each other directly.

This project will look into rare, high-energy, processes at the LHC which probe these boson-boson interactions, using a process known as "vector-boson scattering". The very first observations of one of these processes are being made at the moment by ATLAS and CMS, but with the much larger data samples to come, they should be amenable to more detailed measurements, allowing either the discovery of new physics, or constraints to be placed on the properties of the particles. This project will look into the prospects for this physics in the coming years at the LHC.

Overall the project will be analysis based and will involve understanding an interesting mixture of particle physics theory and analysis, starting at a level familiar to all 4th year students who have taken the Y3 Particle Physics course. It is recommended that students also take the Y4 Particle Physics courses along with this project. The studies will be performed using the standard analysis tools used in most modern particle physics experiments. Familiarity with the Linux operating system and a programming language (ideally C++ and/or Python) is required for this project.

The project is directly relevant to the ATLAS research programme of the Particle Physics group.

5.12: Physics and detector R&D for a future e+e- collider

Supervisor: Dr Nigel Watson
Room: Physics West W215
Phone: 44699
Email: Nigel.Watson@cern.ch

Most physicists think experiments at high energy e^+e^- colliders are easy: well-defined centre-of-mass energy; negligible backgrounds and simple detector design. The reality for future designs is less clear, with large beam-related backgrounds and a very broad spectrum of initial state energies, which pose challenges both for detector design and for physics measurements [1]. This project will extend our current work in one of two directions:

(a) Detailed simulations for the CLIC (Compact Linear Collider) project, a 3 TeV centre-of-mass machine in the design phase at CERN [2], with recent highlights of the planned programme available [3]. Following our recent analyses of top quark [4] and Higgs [5] physics within the CLICdp Collaboration [6], we will develop improved ways of 'tagging' top quarks, investigating jet-clustering methods so far not applied to high energy e^+e^- physics;

(b) New R&D for a CMOS-based 'digital' electromagnetic calorimeter, where we will build on our leading expertise in this field [7] to develop analysis and simulation of 'testbeam' prototypes for a digital electromagnetic calorimeter, e.g. as in [8].

[1] NK Watson, *Future experiments (colliders): New Detectors, YETI'2019, Durham,* https://conference.ippp.dur.ac.uk/event/723/sessions/939/#20190108.detailed
[2] http://clic-study.web.cern.ch/; http://clicdp.web.cern.ch/content/updated-staging-baseline
[3] NK Watson, *News on the CLIC Physics Potential, Moriond QCD 2018,* http://moriond.in2p3.fr/QCD/2018/WednesdayMorning/Watson.pdf
[4] H. Abramowicz *et al.*, *Top-Quark Physics at the CLIC Electron-Positron Linear Collider*, https://cds.cern.ch/record/2629403/.
[5] Eur. Phys. J. C77 (2017) 475,http://dx.doi.org/10.1140/epjc/s10052-017-4968-5
[6] http://clicdp.web.cern.ch/
[7] R. Bosley *et al., Digital Calorimetry for Future Colliders, CALICE Collaboration/Utrecht, April 2019,* https://agenda.linearcollider.org/event/8109/contributions/43631/attachments/34430/53117/Utrecht_11_04_2019_robert_bosley.pdf
[8] A.P. de Haas *et al.*, *The FoCal prototype—an extremely fine-grained electromagnetic calorimeter using CMOS pixel sensors*, *JINST* **13** P01014, https://doi.org/10.1088/1748-0221/13/01/P01014

Quantum Light and Matter

Project Team Leader - Dr Giovanni Barontini

The Quantum Light and Matter research area combines several research teams within the larger Birmingham Cold Atoms group, as listed below. Note that within a given project number, there may be more than one alternative for the research to be carried out.

Background

The last few decades have seen a revolution in atomic physics, as reflected by the Nobel prizes in 1997 (for laser cooling and trapping of atoms), 2001 (achievement of Bose-Einstein condensation), 2005 (laser-based precision spectroscopy), and 2012 (manipulation of individual quantum systems). These systems offer an unprecedented degree of control over the quantum behaviour of light and matter. Particular advantages of atomic systems are their pure and practically defect-free nature, in combination with direct optical detection and tuneability of their parameters. The Quantum Light and Matter group targets leading edge developments in this field including experimental quantum simulation in optical lattices, quantum memories and entangled images, collective light-atom interactions, and precision atomic magnetometers.

We expect students who like to engage in hands-on experiments and energetically drive project work. We aim to tailor the projects to fit your ambitions and abilities, so please discuss with us to find out more about the project possibilities in our group.

6.1: Making a Bose-Einstein Condensate

Supervisor: Dr G. Barontini
Email: g.barontini@bham.ac.uk

Using laser cooling and evaporative cooling it is possible to cool small ensembles of atoms down to some tens of nK above absolute zero. In this regime, if the gas is made of Bosons, a phase transition to a Bose-Einstein condensate (BEC) occurs. A BEC is a macroscopic quantum matter wave that features many extraordinary properties like superfluidity and long range phase coherence.

In this project you will evaporatively cool a gas of rubidium (^{87}Rb) atoms with an optical dipole trap and you will measure the critical temperature of the BEC transition. You will further characterise the dependence of the condensate fraction on the temperature below the transition point. You will repeat your measurement for different shapes of the trapping potential. You will use your data to design the optimal cooling ramp across the transition and to retrieve important information about the BEC, like the effect of the atom-atom interactions on the transition temperature.

During this project you will have the unique opportunity to work on a state-of-the-art cold atoms experiment, you will learn how to acquire and analyse data using scientific methods and you will become familiar with the basics concepts of cold atoms Physics. This project is particularly recommended for students aiming at pursuing a PhD in cold atoms. We advise to contact the project supervisor before choosing this project.

6.2: Building and characterising a position detector for quantum optics measurements

Supervisor: Dr V. Boyer

Quantisation of light is responsible for the fluctuations that are recorded when measuring the intensity of a laser beam with a very sensitive photodetector. Quantum mechanics says that a beam can be seen as a stream of randomly distributed photons, which generates on a photodetector noise similar to the sound of the rain on a tin roof. This is called the shot noise. Until now people have mostly focused on the overall noise but there is now a growing interest in understanding the spatial (transverse) distribution of photons in light beams. This is because the spatial noise limits the optical resolution in imaging.

Here we focus on the impact of the spatial shot noise on the determination of the position of a laser beam and we propose to compare two variants of specialised photodetectors: the split detector and the position-sensitive detector (PDS). Both can measure the position of a beam but they are subtle (quantum) differences in what they measure. The goal of the project is to analyse and measure these differences in order to better understand the behaviour of photons inside a laser beam and gain a better understanding of what constitutes a quantum measurement.

You will first update and optimise a transimpedance amplifier circuit quiet enough to "see" the quantum fluctuations (this is hard but you will get plenty of help). Next, you will characterise and evaluate the performance of the detectors by shining a laser beam onto it. You will measure the noise of the detected photocurrents and with the proper "algorithm" extract the shot noise on the beam position. If time allows, you will measure the position quantum noise on the output of an experiment designed to reduce the quantum fluctuations by introducing correlations between the photon positions (this would be like ordering raindrops in the rain!).

The project involves electronics, optics, and a good dose of quantum mechanics and quantum optics. This is the continuation of a project that has run during two previous years. You will build on our previous designs and accumulated experience. Two of the previous students have chosen to stay with us for a PhD. Successfully led, this project could lead to a scientific publication.

6.3: Adventures in light-matter interactions

Supervisor: Dr J Goldwin
Room: Physics East 204
Email: j.m.goldwin@bham.ac.uk

We are offering any **one of the following three projects**, all of which study aspects of light-matter interactions which may be new to you. These projects require a sense of adventure and a willingness to dive into the unknown. Success will be measured more by the spirit of investigation than the achievement of any specific end result.

Either 6.3a: Frequency-shifted feedback laser

We would like to develop a light source which has spatial coherence (it propagates in a beam, like a laser, rather than being diffuse, like a light bulb), but is spectrally broadband (the light intensity is distributed over a wide range of wavelengths or frequencies, rather than being monochromatic). We aren't quite there yet, but last year's project pair discovered an interesting light source known as a frequency-shifted feedback (FSF) laser. The spectrum of such a laser does not fill a continuum of wavelengths, but it does produce a 'moving comb' of narrow lines which are distributed over a large wavelength range, but varying in time.

In this project, you will build an FSF laser and study its spectral characteristics. Last year's students have left a home-built Michelson interferometer and a few other bits and bobs to help you build and characterise the laser. Possible directions for this year include:

- Can you broaden the comb teeth enough to realise our original dream of a broadband continuous source? You might add electronic noise onto the frequency shifter, insert an intra-cavity optical filter, or otherwise adjust the laser design to maximise the linewidth.
- What happens if you go to extreme values of the key design parameters? Normally the frequency shift is small compared to the rate that light makes round trips through the laser cavity – what if you make them equal, or even invert the situation?
- Tune the FSF laser to resonance with some atomic transitions and see what happens. Use the source to pump a ring resonator made from optical fibre. Can you achieve Brillouin lasing in the fibre? If so, what does the output tell you?

This is an open, exploratory project for a pair of students who would like nearly free reign over a photonics bench. In addition to managing the experimental work with the laser and photonics, you will need to tackle some Fourier analysis and aspects of nonlinear optics/laser theory.

References:

"Tapered amplifier laser with frequency-shifted feedback," https://scipost.org/10.21468/SciPostPhys.1.1.002

"Spectral characteristics of a frequency-shifted feedback ring laser using a semiconductor optical amplifier," https://doi.org/10.1143/JJAP.47.3483

Or 6.3b: Spin noise magnetometry

Atomic spins interact with magnetic fields to produce measureable shifts to atomic energy levels. This is the basis of optical magnetometry, which maps the state of spins in a material system onto the state of light. For example, the Faraday effect causes polarisation rotation of light transmitted through a circularly birefringent medium. A measurement of the polarisation angle reveals information about the ambient magnetic field and the properties of the medium.

If the spins fluctuate (and they *must!*), then these fluctuations are transferred to the light. Normally we try to reduce noise in high-precision measurements, but in this project *the noise is the signal*. You will study spin noise magnetometry in a room temperature rubidium vapour. You will set up a tuneable diode laser which was built as part of a previous project, and build a high-speed dual photodetector for use in a polarimeter.

This project involves a combination of atomic physics, lasers and photonics, electronics, and Fourier analysis.

References:

“Spectroscopy of spontaneous spin noise as a probe of spin dynamics and magnetic resonance,” https://doi.org/10.1038/nature02804

“Measurement of transverse spin-relaxation rates in a rubidium vapor by use of spin-noise spectroscopy,” https://doi.org/10.1103/PhysRevA.75.042502

“Analyzing atomic noise with a consumer sound card,” http://dx.doi.org/10.1119/1.3663275

Or 6.3c: Pushing the limits of tight focusing in optical cavities

We are generally interested in increasing the coupling strength between single atoms and photons. There are two common strategies for this: (1) focus the light down to a size on the order of its wavelength, or (2) increase the duration of the interaction using an optical cavity. Technical challenges make it difficult to effectively combine these two strategies. Here you will design optical cavities which are specifically optimised for extreme focusing. One option is to use diffraction-limited focusing lenses within a pair of ‘standard’ mirrors; another option is to use a square or ‘bow-tie’ geometry for the cavity. What is the smallest focus you can achieve with realistic parameters?

This is primarily a design project, requiring a good grasp of Gaussian beam propagation. The theoretical side will involve a combination of analytical and numerical work, with the balance largely up to you. Depending on your design(s), it may be possible build and test a prototype in the lab.

References:

“Increased atom-cavity coupling and stability using a parabolic ring cavity,” https://doi.org/10.1088/1361-6455/aaddd1

“Operating a near-concentric cavity at the last stable resonance,” https://doi.org/10.1103/PhysRevA.98.063833; “Single atoms coupled to a near-concentric cavity,” http://www.qolah.org/thesis/Thesis_NguyenChiHuan.pdf

“Design and Characterization of a Custom Aspheric Lens System for Single Atom Imaging,” http://atomoptics-nas.uoregon.edu/publications/matt-briel-thesis.pdf

Quantum Sensing and Timing with Cold Atoms

Project team leader: Dr Michael Holynski m.holynski@bham.ac.uk, 48303

Staff: Prof Kai Bongs, Dr Michael Holynski, Dr Yeshpal Singh

The UK National Quantum Technology hub in Sensors and Metrology is a new initiative, formed of six universities and over seventy industrial partners, which aims to bring quantum science to a new and diverse range of applications – ranging from magnetometry for brain imaging to being able to locate underground features using gravimetry. The sensors are all based on upon cold atoms, and a key focus is improving the portability and robustness of these systems such that they can be taken outside of the lab, and into a real application environment. The Birmingham teams focus on three areas: quantum gravity sensing, quantum clocks, and quantum squeezing.

In addition to the quantum hub, we are also part of MUARC and the Birmingham Cold Atoms group. You may find projects from the rest of the group also to be of interest.

For more information, please contact us or see:

http://www.birmingham.ac.uk/research/activity/physics/quantum/cold-atoms/index.aspx

http://quantumsensors.org/

http://mpa.ac.uk/muarc/

Projects

Our projects are divided amongst the quantum technology teams at Birmingham, who all work together as part of the quantum sensors hub and MUARC. Our projects are student driven, and research orientated, with each contributing directly to our research activity. The projects are focused either on contributing directly to one of our research projects, or are aiming to create novel research in their own right. As such, we expect a high standard of work but also provide the framework for students to both achieve and learn a significant amount.

If you identify interest within an area, or would be interested in related projects, make sure to discuss with the relevant supervisors or team leader. We may be able to offer additional or alternative projects. Students must discuss with supervisors prior to making their project choices.

7.1: High quality beam delivery for atom interferometry

Supervisors: J. Vovrosh and M. Holynski (contact m.holynski@bham.ac.uk)

Atom interferometry uses pulses of light to manipulate atoms in a format analogous to an optical interferometer, but with the roles of light and matter interchanged – with light pulses now representing the mirrors and beam splitters. Such a system can then be used to perform precision measurements, for example of inertial effects such as acceleration, rotation or gravity and gravity gradients. However, realising a high sensitivity and accuracy relies upon having high quality optical pulses. In particular, as the phase of the light is imprinted upon the atoms the system is impacted by errors in the optical wavefront. Furthermore, as the transfer, or "reflectivity" in the analogue of the optical interferometer, of the atom optics is related to optical intensity and the atom cloud has a finite size, it is important to have a clean optical intensity distribution. While these are priorities in reaching a high performance, often sacrifices need to be made in practical implementation.

In this project you will learn how to design, build, characterise and optimise optical telescopes for use in an atom interferometer – aiming to ultimately use them to within an atom interferometer to assess their performance. This will include optimising the intensity profile, perhaps including investigation of non-Gaussian beam profiles such as flat-top beams, beam geometry and polarisation.

7.2: Simulation and modelling of atom interferometry

Supervisors: A. Lamb, S. Lellouch, and M. Holynski (contact m.holynski@bham.ac.uk)

Atom interferometers can be used to perform precision measurements of, for example, inertial effects using atoms as test-masses. Since the first demonstration of atom interferometry over 25 years ago, the technique is now being investigated for a wide variety of practical and fundamental applications. While sensitivities of the order 1 in 10^9 have been demonstrated in laboratories, future experiments are aiming at beyond 1 in 10^{15} sensitivity to gravity. The practical limit is determined by a wide range of experimental factors, such as the achievable temperature of the atom cloud or intensity noise on the lasers used to detect the atoms. For example, the interaction between the thermal expansion of the atom cloud and the non-uniform intensity profile of the laser beams leads to decoherence in the atom interferometer. Designing and optimising an atom interferometer requires a clear understanding of such systematics and noise sources in order to set appropriate specifications and to understand limitations.

In this project you will learn about atom interferometry and how to use modelling and data analysis to understand experimental data. You will simulate and model the key experimental steps in an atom interferometer before adding a sub-set of noise and systematic effects. You will then then validate your model through applying it to experimental datasets with known parameters, ultimately aiming to describe the limiting experimental factors with your model. If time permits, you will use your model to derive requirements for future fundamental physics missions, such as would be performed using atom interferometry in space.

This project is focused upon applying modelling and analysis to experimental data, initially through building simple models.

7.3: Advanced quantum control pulses in atom interferometry

Supervisors: Y-H. Lien and K. Bongs (contact k.bongs@bham.ac.uk)

Atom interferometry is a key tool in the area of Quantum Technology, as it is the most precise method to measure quantities such as gravity and rotation. It relies on the ability to manipulate the internal and external quantum states of atoms with laser beams, letting atoms travel along different trajectories at the same time. Current laser pulse sequences only allow basic manipulation and are sensitive to small fluctuations in beam power, phase and frequency. This project aims to investigate advanced laser pulse sequences to allow precise and robust quantum state manipulation. It will consist of an intense literature research on current pulse shaping techniques, a simulation of the effect of different pulse shapes on the atoms during the interferometer sequence and the implementation of advanced pulses in our laboratory atom interferometer.

This project is aimed at students, who are skilled in atom-light interaction theory, computer simulation and want to demonstrate their ability to deliver a complex project at the leading edge of research with the aim to create a significant publication at the end. Do not chose this project, if you are not prepared to put some extra time and effort into it.

7.4: High flux atom sources

Supervisors: Y-H. Lien and K. Bongs (contact k.bongs@bham.ac.uk),

All cold atom experiments and related quantum technologies rely on the reliable preparation of an ensemble of atoms at temperatures just a few millionth of degree above absolute zero. In this project, you will learn about advanced atom cooling and trapping techniques and develop an atom source with unprecedented flux/compactness ratio. In addition to traditional Zeeman slowing, you will also investigate novel techniques such as bichromatic laser cooling, which could be over 1000 times more powerful than traditional laser cooling. You will design an atom source, simulating all relevant design parameters and realise it in practise, working with lasers, vacuum and magnetic field generators. Experience in atomic physics and atom-light interactions will be beneficial.

7.5: Slowing atoms using Rydberg states

Supervisors: Yogeshwar Kale and Y. Singh (contact y.singh.1@bham.ac.uk),

QT Hub is committed to use quantum technology for the development of really portable quantum sensors. Optical clocks have reached unprecedented precision of 10^-18. Laser cooling and trapping of atoms is the underpinning concept enabling such a mind boggling precision. In conventional setup, people normally use Zeeman slower to primarily slow atom down. A Zeeman slower utilise the Zeeman effect while atom interacts with laser light field. In this project, we aim to use novel approach based on Rydberg states of the atom. This approach has the potential to reduce the form factor of an optical setup. We will use Sr atoms for our project and the project will build upon the work done during the last year's project. This is a lab-based project and we are looking for the students who are self-driven and ready to do hard work.

7.6: Setting up a GPS disciplined atomic clock in the lab

Supervisors: J. Jones and Y. Singh (contact y.singh.1@bham.ac.uk)

We are looking to setup a GPS disciplined atomic clock in our lab. Such a clock is very useful for many timing applications such as computer networks or precise instruments. In our lab, we have bought a commercial Cs frequency standard. There are two 10 MHz and one 5 MHz outputs with exceptionally low phase noise of (-130 dBc/Hz at 10 Hz offset) and one second Allan Variance of (< 2×10^{-11}). The clock can be phase-locked to an external 1 pps reference like GPS. Using the provided software, one can easily monitor and control 1 pps timing, and determine the instrument's operational status. One of the first applications in our lab for such a clock will be to measure the beat frequencies between the two high finesse optical resonators that we have setup. Such clocks can also be used to build a high spec source of frequency generation. We are looking for the students who see electronics as their hobby and ready to put up some hard work.

Theory

Theory projects are different. You do not have a specific list of proposals from which to choose. You have to discuss with individual supervisors, compare your interests (abilities) with theirs, to decide what you would like to work on during 2019/20. Contact Martin Long for more information.