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Department of Physics PhD Projects Available for October 2012

Physics @ Heriot-Watt University

The Physics Department at Heriot-Watt is strongly research oriented with approximately 30 Postdoctoral Research Associates and 40 PhD students at any one time. The research interests are wide ranging from semiconductor physics, optoelectronics, material science and nonlinear physics.

PhD Research Studentships

Many of our research projects are identified as potentially having EPSRC studentship support, which is restricted to home students only. The Physics Department had 10 such studentships available in 2011, with similar availability expected for 2012. Although the usual start date is in October, we can take students at other times of year.

The projects could equally run with students supported by other means, which in many cases have no nationality restrictions. However, the number of studentships in this category is very limited and the competition is high. The studentships available include:

1) **Scottish Universities Physics Alliance (SUPA) Prize Studentships**: These are prestigious and competitive awards that are intended to attract outstanding students from around the world. Please visit the SUPA website for further information: http://www.supa.ac.uk/ **Note: submission deadline for this is 20th January.**
2) **Scottish Doctoral Training Centre in Condensed Matter:** Fully funded PhD studentships are available in Condensed Matter research. For further information please visit http://cm-dtc.supa.ac.uk/
3) **James Watt (ORSAS) Scholarships:** These are University awards providing full university postgraduate fees and a contribution to maintenance costs of £8,500 per annum for a maximum of three years. For further information please visit: http://www.postgraduate.hw.ac.uk/scholarships/ **Note the submission deadline for this is 31st March**.
4) **Partial Scholarships:** The scholarships provide full fees and a contribution towards maintenance for up to three years. Please also visit http://www.postgraduate.hw.ac.uk/scholarships/ for further information.
5) **Fees Only Scholarships:** These scholarships provide full fees for up to three years. Further information can also be found in http://www.postgraduate.hw.ac.uk/scholarships/

Please note that each studentship award scheme has different closing dates and you should check carefully the websites before you submit an application.

In addition, there may be EPSRC project studentships available in the Department, which can support UK, EU and possibly Overseas students. Some of the projects may be advertised in www.findaphd.com

Industrially-based doctoral studies in photonics are also available in the Photonics Engineering Doctorate Centre, see www.photonics-engd.hw.ac.uk for details.

How to apply

If you are interested in doing a PhD with us, either through one of above studentships or your own financial resources, please complete our online postgraduate application form. The form can be found in http://www.postgraduate.hw.ac.uk/apply/

Applicants for the Condensed Matter DTC studentships, or for SUPA studentships should make their application via the relevant websites (listed above).

Ultrafast Optics Research

Prof. Derryck Reid

Frequency-comb spectroscopy in the mid-IR to THz region

Femtosecond OPOs can be operated as versatile frequency combs, with coverage from 1.0 – 5.0 µm. Two approaches will be pursued in which such OPO combs will be developed for high-resolution spectroscopy. The first is in partnership with NPL, and will develop two asynchronous OPO combs to implement broadband FTIR spectroscopy in the 2 - 4 µm wavelength band with rapid acquisition rates, high sensitivity, 0.01 cm^{-1} resolution and with no moving parts. The second approach takes a single high-repetition-rate OPO comb and will use mode filtering to achieve a near- to mid-infrared output at ~10 GHz mode-spacing, allowing femtosecond Fourier-transform spectroscopy developed at HWU to be applied for full-comb spectroscopy at Hz-level acquisition rates.

The project builds on earlier results from the Ultrafast Optics Group which, in 2007, was the first group worldwide to achieve carrier-envelope-offset locking of a femtosecond OPO, and subsequently reported a nearly 3-octave spanning comb from a synchronously-pumped Ti:sapphire-pumped OPO. Uniquely, OPO frequency combs allow access to the important fingerprint region of many molecules with resolutions better than any conventional FTIR system. The potential of such combs remains unrealised for spectroscopy, therefore motivating the development of OPO combs for this purpose. This project will develop a comb-based alternative to environmental DIAL gas sensing, which unlike DIAL offers simultaneous sensing of multiple gas species.

The project is based in Heriot-Watt's Ultrafast Optics Group (http://www.ultrafast.hw.ac.uk), working under the supervision of Prof. Derryck Reid. Enquiries may be addressed to Prof. Derryck Reid at D.T.Reid@hw.ac.uk

This PhD position is fully funded by a departmental Doctoral Training Account (DTA) award (fees + living allowance), which is available only to well-qualified UK nationals. DTA awards are issued competitively. Overseas and EU nationals of exceptional quality will also be considered.

High-energy ultrafast optical parametric oscillators

The extension of synchronously-pumped femtosecond optical parametric oscillators to µJ energy levels via cavity-dumping represents a promising new source for nonlinear spectroscopy and ultrafast-laser waveguide inscription in the near- to mid-infrared. Current tunable optical parametric oscillators and amplifiers lie on either side of a technological gap in repetition frequency between around 100 kHz and 100 MHz. This project will explore technical approaches to achieving efficient, µJ-energy pulses via cavity dumping which can fill this gap, producing pulses up to a few MHz.

In 2011 HWU reported the highest energy pulses from a fs OPO, achieving 650-nJ pulses at 250-fs durations up to 3 MHz repetition frequency. The generation of such pulses in the mid-IR presents exciting opportunities for ultrafast laser waveguide inscription in semiconductors (Si, Ge), where the high repetition rate is expected to be necessary because of the high thermal conductivity of these materials. The combination of high energy and high repetition rate implies applications in laser-scanning microscopy and nonlinear spectroscopy.

The project is based in Heriot-Watt's Ultrafast Optics Group (http://www.ultrafast.hw.ac.uk), working under the supervision of Prof. Derryck Reid. Enquiries may be addressed to Prof. Derryck Reid at D.T.Reid@hw.ac.uk

This PhD position is fully funded by a departmental Doctoral Training Account (DTA) award (fees + living allowance), which is available only to well-qualified UK nationals. DTA awards are issued competitively. Overseas and EU nationals of exceptional quality will also be considered.

Ultrafast Optics Research

Prof. Derryck Reid

Two-photon Ultrafast LADA for Defect Localization in Integrated Circuits

Applications are invited for a PhD position to work in the area of optical stimulation of integrated circuits using two-photon absorption. The position is closely related to an industrially-funded project which concerns the development of a 1530-nm femtosecond laser, a 1250-nm femtosecond optical parametric oscillator, and the application of these sources to develop resolution-enhancing techniques in the context of two-photon microscopy and laser-probing of integrated circuits.

The project is based in Heriot-Watt's Ultrafast Optics Group (http://www.ultrafast.hw.ac.uk), working under the supervision of Prof. Derryck Reid. The position is available from January 2011. Enquiries may be addressed to Prof. Derryck Reid at D.T.Reid@hw.ac.uk

This PhD position is fully funded by a departmental Doctoral Training Account (DTA) award (fees + living allowance), which is available only to well-qualified UK nationals. DTA awards are issued competitively. Overseas and EU nationals of exceptional quality will also be considered.

Optical Diagnostics

Prof. Andrew Moore and Dr. Wei Wang

Optical techniques for vibration measurement

The project will investigate novel optical techniques for vibration measurement. We have pioneered multi-point optical vibrometers that enable vibration amplitude and phase to be measured at many points simultaneously. The data obtained are used to determine experimental mobility matrices for modal analysis, structural dynamics modification and sub-structure synthesis. Current experimental techniques do not enable all components of the mobility matrix to be measured. This project will therefore investigate optical approaches to recover these unmeasured components, including (but not limited to) optical phase singularities and vortices.

The project will involve experimental research in optics and vibration measurement, underpinned by a strong theoretical understanding. It is suitable for students who have (or expect to obtain) a first class degree in physics, engineering or a relevant subject. Some experience with optics or vibration measurement, and hardware-software interfacing (LabView/MatLab), is desirable although not essential. The successful candidate will work as part of Heriot-Watt's Optic Diagnostics Group (http://www.mec.hw.ac.uk/optical-diagnostics/), working under the supervision of Prof. Andrew Moore and Dr. Wei Wang.

Applications with a detailed CV, covering letter and the names and addresses of two referees should be e-mailed to Prof. Andrew Moore at a.moore@hw.ac.uk. Enquiries may also be addressed to Prof. Moore.

Funding Notes

Applications are invited for a fully-funded EPSRC PhD studentship starting by October 2012. The studentship is open to UK and EU nationals only, in accordance with Research Council eligibility criteria (www.epsrc.ac.uk/funding/students/pages/eligibility.aspx). The studentship will cover tuition fees and a maintenance grant of £13,590 p/a for 3.5 years (subject to satisfactory performance).

For further information, please contact Prof. Andrew Moore (email: a.moore@hw.ac.uk *).*

Single Photon Sources and Detectors

Prof. Gerald Buller

Near Infra-red Single Photon Detection Using Ge-on-Si Heterostructures

Semiconductor-based photon-counting detectors have risen to prominence in the last decade as new application areas, such as quantum information processing, have emerged. In the near-infrared, there are substantial issues with single-photon avalanche diode (SPAD) detectors, as their performance deteriorates at higher wavelengths due to the increased noise levels associated with the narrow bandgap semiconductors normally used. This project aims to establish a new class of germanium/silicon SPADs that will operate efficiently in the near-infrared, particularly at the strategically important telecommunications wavebands, and combine the advantages of low-noise Si single-photon avalanche multiplication with the infra-red sensing capability of Ge. This PhD project is part of a £1M+ EPSRC-funded consortium comprising Heriot-Watt University, University of Surrey, University of Leeds and University of Warwick, and is part of the wider UK Silicon Photonics consortium (UKSP).

This new class of detectors will take advantage of recent advances in epitaxial Ge/Si growth and will be developed in conjunction with the UKSP, which has world leading expertise in silicon photonics research and is pursuing a comprehensive research programme of active and passive device development with access to state-of-art growth, processing and characterisation facilities. The detectors will be validated on existing state-of-art testbeds for gigahertz quantum key distribution and kilometre-range time-of-flight ranging/depth imaging.

The PhD position will involve design, fabrication and characterisation of single-photon detectors and their use in single-photon applications areas. The PhD will involve interaction with other academic groups within the consortium, which also has excellent industrial contacts. The PhD is available from September 2010 and is funded by an EPSRC project studentship open to UK and other EU applicants.

Funding Notes

Fully funded studentship (all fees and stipend supplied), available to all qualified UK and EU applicants

For further information, please contact Prof Gerald Buller (email: G.S.Buller@hw.ac.uk).

Diffractive Optics

Prof. Mo Taghizadeh

Novel Nano-structured Optical Device Fabrication and Modelling

The development of our unique nano-structuring technology, based around the stack-and-draw techniques used in the fabrication of photonic crystal fibre, allows the design and fabrication of micro-optical devices with highly customised optical properties. The micro-optical devices which can be produced by this technology include arbitrary profile micro-lenses, polarisation sensitive focussing and beam-shaping devices, super-continuum generation structures, optical meta-materials, photonic crystals and double-negative nanostructures.

Our initial work in this area, in the fabrication of arbitrary profile microlenses, has given us a simulation code base which is highly optimised for simple soft-glass dielectrics. In addition, the commissioning of our in-house fibre drawing facility has allowed us to successfully fabricate a wide range of micro-optical devices. We are now expanding the breadth of both our design and fabrication capabilities to include nonlinear, active and metallic materials within the designed nanostructures. These materials exhibit significantly more complex electromagnetic behaviour compared to simple dielectrics and will require the expansion of our code base to handle highly dispersive and negative materials.

Some initial work on this expansion has been performed on the Finite Difference Time Domain portion of the code base and the successful candidate would develop and implement similar device models for the Fourier Modal Method portion. The successful candidate will also undertake fabrication of the designed nanostructured micro-optics using our fibre drawing and micro- and diffractive optics fabrication facilities.

Recent relevant publications

- F. Hudelist, J. Nowosielski, R. Buczynski, A. Waddie and M. Taghizadeh, “Nanostructured elliptical gradient-index Microlenses”, Optics Letters 35, 130-132 (2010).
- J. Nowosielski, R. Buczynski, F. Hudelist, A. Waddie and M. Taghizadeh, “Nanostructured GRIN microlenses for Gaussian beam focusing”, Optics Communications (in press 2010)
- F. Hudelist, A. Waddie and M. Taghizadeh, “Analysis of crossed gratings with large periods and small feature sizes by stitching of the electromagnetic field”, JOSA-A, 26(12), 2648-2653 (2009)
- F. Hudelist, A. Waddie and M. Taghizadeh, “Design of all-glass multilayer phase gratings for cylindrical microlenses”, Optics Letters, 34(11), 1681-1683 (2009)
- F. Hudelist, R. Buczynski, A. Waddie, and M. Taghizadeh, "Design and fabrication of nano-structured gradient index microlenses," Optics Express 17, 3255-3263 (2009).
- F. Hudelist, A. Waddie, J. Nowosielski, R. Buczynski, and M. Taghizadeh, "Nanostructured graded index materials," in CLEO/Europe and EQEC 2009 Conference Digest, (Optical Society of America, 2009), paper CK8_4.

For further information contact Professor Mo Taghizadeh on +441314513067 or M.Taghizadeh@hw.ac.uk

Superconducting Single-Photon Detectors Research

Dr Robert Hadfield

Contact: r.h.hadfield@hw.ac.uk
Web: http://www.eps.hw.ac.uk/departments/physics/SuperconductingDetectors.htm

Infrared single-photon detectors based on small energy gap superconductors

One of Einstein's key contributions to modern science was the insight that light, at a fundamental level, is comprised of packets of energy known as photons. A century later, a host of new applications at the frontiers of science hinge on the ability to detect these individual quantum objects. Superconducting single-photon detectors based on superconducting nanowires are a highly promising new technology for low-noise, high speed photon counting in the infrared. At long wavelengths (in the mid infrared spectral region), the sensitivity of these devices typically drops dramatically. This project targets a promising solution to this problem, namely the use of small energy gap superconducting materials, which are triggered more readily by low energy photons. We aim to create a new generation of nanostructured superconducting single-photon detectors based on small energy gap amorphous superconducting materials (such as W-Si, Mo-Si, Nb-Si). These devices would be suitable for advanced photon counting applications in the mid-infrared, such as atmospheric remote sensing of greenhouse gases. This project will encompass nanofabrication (employing newly opened state-of-the-art facilities at Heriot-Watt) and electrical and optical device testing down to milliKelvin temperatures.

This project is suitable for a first class student with an interest in nanoscience, optics and low temperature physics, and will run in conjunction with the SUPA graduate school and the Scottish Doctoral Training Centre in Condensed Matter Physics.

Superconducting single-photon detector arrays

Superconducting nanowire single-photon detectors are a highly promising infra-red photon counting technology. Current device active areas are limited to 10's of micrometres diameter, suitable for single-mode fibre coupling but not well matched to the demands of many other photon counting applications. This project aims to develop highly uniform large area arrays of superconducting nanowire single-photon detectors. Nanofabrication will be carried out using a newly-commissioned state-of-the-art electron beam lithography faciltity at Heriot-Watt University which includes a laser interformeter controlled stage for ensuring 10's of nanometer precision over millimetre length scales. The devices developed in this project will be tested using low temperature electrical and optical characterization facilites at Heriot-Watt and optically coupled for use in advanced photon-counting applications.

Potential applications for these next generation detector arrays include atmospheric remote sensing, infrared astronomy and quantum communication using orbital angular momentum states. In addition such arrays provide the sought-after ability to resolve the number of photons per optical pulse.

This project is suitable for a first class student with an interest in nanoscience, optics and low temperature physics, and will run in conjunction with the SUPA graduate school.

Applied Optics and Photonics

Prof Duncan Hand & Dr Jon Shephard

Novel laser-based manufacturing processes enabled by adaptive optics

Although the laser is widely used in modern manufacturing, it has the potential to become even more powerful if the effective 'tool shape' (i.e. the laser beam shape at the workpiece), can be readily altered for a particular process or stage of a process. Adaptive optics (AO) technologies offer a solution here; however commercially-available devices capable of handling high laser powers have significant limitations, in particular due to their large diameter (typically at least 30 mm) and with a limited number of actuators (typically 37 or fewer). An alternative is the spatial light modulator (SLM), which can provide high resolution control of the phase across the wavefront of the beam, and hence the beam shape at focus. We have been carrying out research in this area for the past 2-3 years, and have demonstrated the feasibility of controlling high power beams in this way, including some demonstration machining. This PhD project will build on our earlier results, and will concentrate on the novel processes which are enabled by the degree of beam flexibility provided by an AO. It is planned to investigate surface modification techniques (both to achieve controlled roughening and polishing); laser drilling at a very shallow angle to the workpiece; and sub-surface machining.

The project involves:

(a) Operation of high peak power pulsed lasers;

(b) Laser-machining trials and development of an understanding of laser-materials interaction;

(c) Use of microscopy for analysis of laser-generated parts; microscopes include optical, scanning electron, and atomic force microscopes;

Studentship

EPSRC DTA (full funding for UK students, with tax-free stipend of at least £13,600 / partial funding for EU students)

Supervision

The PhD student will work alongside a postdoctoral Research Associate. The project will be supervised jointly by Prof Duncan Hand and Dr Jon Shephard.

Further information

The student will be a member of the Applied Optics and Photonics Group (www.aop.hw.ac.uk). This large group will provide considerable support for the project in the form of equipment and expertise over a range of high power lasers and fibre optic applications. The project also forms one of the components of the James Watt Institute of High Value Manufacturing.

Molecular Dynamics

Dr Dave Townsend

Tel: 0131 451 3794, E-mail D.Townsend@hw.ac.uk

Relaxation Dynamics in Biomolecules

The interaction of certain biologically relevant molecules with ultraviolet light has been attracting much attention in recent years. The very rapid (i.e. femtosecond timescale) redistribution of electronic energy into vibrational degrees of freedom is often of key importance to the stability and biological function of these types of molecules. Using femtosecond laser pulses in conjunction with time-resolved photoelectron spectroscopy and spatial imaging methods, one is able to observe such redistribution processes in real time, following the creation and subsequent relaxation of an electronically excited state. This offers a great deal of mechanistic insight into the fundamentally important underlying physical processes.

Initial work will focus on the DNA bases adenine, thymine, guanine and cytosine as well as melanin, the molecule responsible for the body's 'first line of defence' against ultraviolet radiation. Work will be carried out primarily at Heriot-Watt, although there is also the possibility of spending time at the National Research Council in Ottawa, Canada.

Previous experience with lasers and optics, ultrahigh vacuum systems and hardware-software interfacing (LabView/MatLab) is desirable, although not essential.

For further information, contact Dr Dave Townsend (Tel: 0131 451 3794, E-mail D.Townsend@hw.ac.uk)

Nonlinear Optics, Dynamics and Complexity

Dr Weiping Lu
Tel: 0131-4513065, Email: w.lu@hw.ac.uk

Cooling of Molecules in Optical Cavities

Inspired by the great success in laser cooling of atoms, physicists and chemists now want to create cold molecules to study their applications that have already realized for cold atoms. However, a simple extension of laser cooing techniques fails for molecules because complex energy structure of most molecules makes a closed multi-level system impossible. Buffer gas cooling is a general scheme that can produce cold paramagnetic molecules at temperatures of hundreds mK. The next requirement for this field to be successful is to develop new and complementary techniques that can break the mK bottleneck and produce a dense molecular samples in μK region. We are currently studying a number of schemes that use optical fields to produce large densities of stable cold molecules.

This PhD project will theoretically investigate one of these techniques, which will cool molecules using optical dipole forces in an optical cavity. This work follows on from our recent results in this subject. You will develop the present technique to be a general cooling scheme that can cool many polarisable molecules and other species.

Development of nonlinear and spatio-temporal image processing algorithms for biological applications

Despite recent advances in light microscopy revolutionizing live cell imaging, the full potential of the increasing high sensitivity and resolution of modern microscopes has yet to be realised. A key barrier is the limited power and scope of image analysis techniques currently available to cell biologists. A major improvement would be to exploit advanced image processing and analysis algorithms to deal with complex time-lapse live cell data.

In this project, you will research and develop a nonlinear partial differential equation (PDE) method as a new approach to tracking biological particles in live cells. The method builds on the recent development of spatio-temporal nonlinear dynamics systems. A key advantage of this method over all commercial software currently available is to make full use of temporal and spatial relationships in time-lapse data to assist in overcoming severe noise effects and recognition of targets in real biological conditions. Specifically, you will develop a spatio-temporally integrated and nonlinear particle tracking system based on the PDE approach.

The project is part of a collaborative programme with colleagues in Oxford University, which has recently received a funding of £700K from the UK research council EPSRC.

For further information, contact Dr. Weiping Lu (tel: 0131-4513065, email: w.lu@hw.ac.uk)

Quantum Communications

Prof Gerald S Buller and Dr Robert Hadfield

Quantum Imaging

In the early 1980s Aspect et al. demonstrated the non-locality of quantum mechanics, by measuring correlations between polarisation states. Since then, using photon-pairs generated by down-conversion, entanglement has been observed for many variables, including the transverse position of one photon with the linear momentum of its partner. One variant of these experiments is “ghost diffraction” and “ghost imaging” in which an aperture placed in one beam of a pair of entangled beams creates its diffraction pattern or image only in the coincidence count rate recorded between the two beams.

Quantum entanglement is a coherent process, the coincidence count rate depending on both the intensity and phase structure of the detected photons. Spatial phase entanglement was demonstrated, for example, by Zeilinger et al. who observed correlations in the orbital angular momentum of down-converted photons (c.f. polarization and spin angular momentum). While this work used fixed holograms to control the phase-structure of the light, Glasgow and Strathclyde have recently achieved dynamic control of the holograms using spatial light modulators (SLMs). These devices can be rapidly reconfigured to observe entanglement in both angular and linear states and their conjugate variables.

This PhD project is part of a major new EPSRC-funded collaboration between Heriot-Watt, Glasgow and Strathclyde Universities in quantum or ghost imaging. This challenging project will research many aspects of this fascinating phenomenon, including the construction of a full demonstrator quantum imaging system. This PhD project offers exciting opportunities for experimental work in close collaboration with the other partner institutions, as well as a chance to explore the theoretical possibilities presented by this remarkable and practical example of photon correlation and entanglement.

A talented and motivated student is required for the EPSRC studentship associated with this project, which is available from March 2009. This studentship is also open to appropriately qualified non-UK residents.

High-speed Quantum Cryptography

In recent years quantum information research has led to the discovery of a number of remarkable new paradigms for information processing and communication. These developments include, for example, quantum cryptography schemes that offer unconditionally secure information transport guaranteed by quantum-mechanical laws and quantum computers that, if realised, would make today’s public-key-based data security systems obsolete. Evidently these new, and potentially disruptive, security technologies could be of high strategic and economic value in the future. An important challenge for the scientific and engineering community, therefore, is to develop practical quantum communication and processing systems in order to achieve credibility for these advanced new concepts.

We offer a PhD studentship in the area of high-speed quantum key distribution research. The successful candidate will join a successful group which has collaborations with other major groups in the UK and Europe. Although not guaranteed initially, there is a good possibility of a CASE studentship with industry. The PhD research will lead to an understanding of lasers, optical systems, cryptography, telecommunications systems, quantum concepts and state-of-the-art single-photon detection technologies.

For further information, please contact Dr Gerald Buller (email: G.S.Buller@hw.ac.uk).

Open Quantum Systems & Entanglement

Dr. Sabrina Maniscalco
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Information Flow and Quantum Technologies

The theory of open quantum systems studies quantum systems interacting with their environment. It is well known that, in many cases, the environment destroys quantum properties such as entanglement or quantum coherence, which are crucial for quantum technologies. Such loss of quantumness (decoherence) is generally viewed as the effect of the environment monitoring the quantum system and therefore leading to a loss of information on the state of the system [1]. Decoherence is the major enemy of all quantum technologies, from quantum computers, to quantum cryptographers and quantum sensors.

Open quantum systems can be broadly classified into two different categories, Markovian and non-Markovian [2]. The first class refers to cases in which on can neglect correlations between the system and the environment and the environmental energy spectrum is approximately flat. The second class refers to cases in which correlations between system and environment are dominant and the energy spectrum of the environment is structured.

Very recently non-Markovian open quantum systems have attracted a lot of attention for at least three reasons. The first one is the incredible technological advances in the coherent control of systems, such as Josephson junctions, atom lasers, photonic crystals, quantum dots, and even (quantum) biological systems, which cannot be described by Markovian methods. The second reason is the increasing interest in reservoir engineering, allowing for example to modify the spectral properties of the environment inducing a non-Markovian dynamics. The third reason is of more fundamental nature: Markovian systems are always the result of approximations and a non-Markovian description is required to describe, e.g., phenomena like the Quantum Zeno effect.

The research project stems from very recent developments in the non-Markovian theory of open quantum systems, focussing on current fundamental questions in this field: What are the key physical features of non-Markovian systems [3,4]? How can we define non-Markovianity in a way that is independent from specific mathematical models? Can we measure the degree of non-Markovianity and what is the best way of doing it [3,5]?

Aim of the project will be the study of the connection between non-Markovianity, quantifying information flow between the system and the environment, and the functionality and optimization of quantum technologieas in the context of impurities in ultracold atomic gases [6].

The student will work together with a Research Associate and will collaborate with Dr. Gabriele De Chiara at Queens University Belfast, with Prof. Dieter Jaksch's group at Oxford University, and with Prof. H.-P. Breuer at the University of Freiburg.

References

[1] W. H. Zurek, Rev. Mod. Phys. 75, 715–775 (2003).
[2] H.-P. Breuer and F. Petruccione, The Theory of Open Quantum Systems (Oxford University Press, Oxford, 2001).
[3] H.-P. Breuer, E.-M. Laine, and J. Piilo, Phys. Rev. Lett. 103, 210401 (2009).
[4] J. Piilo, S. Maniscalco, K. Härkönen, and K.-A. Suominen, Phys. Rev. Lett. 100, 180402 (2008).
[5] B.-H. Liu, Li Li, Y.-F. Huang, C.-F. Li, G.-C. Guo, E.-M. Laine, H.-P. Breuer & J. Piilo, Nature Physics (11 September 2011), doi:10.1038/nphys2085.
[6] P. Haikka, S. McEndoo, G. De Chiara, G. M. Palma, and S. Maniscalco Phys. Rev. A 84, 031602(R) (2011).

Quantum Simulators

Quantum computers were originally conceived by Richard Feynman as devices able to simulate efficiently quantum systems. It is known, indeed, that to simulate systems of five hundreds quantum bits with a classical computer would require a time longer than the age of the Universe. A quantum computer, however, would be able to perform a massive parallel computation exploiting the existence of quantum superpositions. It has been shown that there exists algorithms, based on quantum correlations, which can solve problems that no classical computer can solve. A quantum computer is a universal quantum simulator, and it is therefore able to simulate any quantum system. However, the presence of environmental noise makes the realization of real scale quantum computers a very difficult task. It turns out that quantum simulators of specific quantum systems may be easier to realize experimentally. Indeed, very recently, experiments demonstrating a quantum simulator of an open quantum system, that is a quantum system interacting with the environment, have been successfully performed [1]. This research project focuses on the extension of the results of Ref. [1] to a wider class of open quantum systems, known as non-Markovian open quantum systems. The project will be conducted in collaboration with CM-DTC student Massimo Borrelli and with the experimental group of Prof. Jonathan Home at ETH-Zurich.

The candidate needs to have a very good knowledge of quantum physics and a strong motivation to do research in this field.

References

[1] J. T. Barreiro, M. Müller, P. Schindler, D. Nigg, T. Monz, M. Chwalla, M. Hennrich, C. F. Roos, P. Zoller, R. Blatt, "An open-system quantum simulator with trapped ions", Nature 470, 486 (2011).

For further information, please contact Dr. Sabrina Maniscalco, S.Maniscalco@hw.ac.uk

webpage: www.OpenQuantum.co.uk

facebook page: www.facebook.com/OpenQuantum

Quantum Information Science

Dr Erika Andersson

Open quantum systems

A master equation is used to describe an "open" physical system, that is, a system which is coupled to an environment. Markovian behaviour arises when the environment is essentially "memory-less", and this case is fairly well understood. An example is exponential decay. There are, however, many situations where we cannot make the Markov approximation. The project will investigate what general forms a non-Markovian master equation can take, and the use of such master equations to describe quantum systems used for quantum information processing. In this project, there is scope for collaboration with experimentalists.

An open quantum system refers to a quantum system which is interacting with an environment [3]. This is obviously a very general concept, and can refer e.g. to an atom coupled to a cavity field, or to an electron spin in a quantum dot, coupled to nuclear spins and external fluctuations. The time evolution of the system plus environment is described by the Schrödinger equation. One is however often unable to solve for the exact dynamics of the whole system plus environment, or not interested in the detailed behaviour of the environment, only in that of the system. In such a situation it makes sense to describe the dynamics of the system using a master equation, which is essentially obtained by tracing over the degrees of freedom of the environment and usually making various other approximations.

Markovian dynamics, where the environment is essentially "memory-less", is fairly well understood and leads to a master equation in the so-called Lindblad form [1]. The non-Markovian case is less well understood, but is becoming increasingly relevant as our ability to experimentally manipulate quantum systems develops. Already simple systems, such as a driven damped two-level atom, display non-Markovian behaviour. Non-Markovian dynamics also seems to be essential for understanding error-correction in quantum computers, a quantum dot coupled to two different reservoirs, quantum state transfer through a chain of coupled quantum dots subject to decoherence, etc..

There are various techniques for obtaining non-Markovian master equations describing a particular physical situation. Depending on the approximations made, the resulting master equation may sometimes display non-physical features, such as probabilities for certain states becoming negative for short initial times. It is not known exactly what form a non-Markovian master equation must take in order to preserve the positivity of the density matrix. This project will continue work done together with Dr James Cresser and Dr Michael Hall on finding the general form of a "physical" non-Markovian master equation [2]. It turns out that the condition that the time-evolution be trace-preserving leads to a generalised Lindblad form. Additional conditions must then, however, be imposed to guarantee that the time evolution is also completely positive. The form these conditions take is presently unknown.

The project will also look at whether there are experimentally easily measurable signatures which would indicate whether the behaviour of a system is Markovian or not. It would also be interesting to know whether it is always possible to describe a large environment using a smaller "effective" environment. Another question is whether density matrix renormalisation group (DMRG) techniques [3] would be useful in modelling the system and its reservoir. DMRG is a technique for numerically solving for the lower-lying eigenstates and also the dynamics of large composite quantum systems. This is done by successively building up the system size, only retaining the most probable states in the description. In quantum information theory, DMRG has been applied to the description of entanglement in large composite quantum states.

For further information, please contact Dr Erika Andersson (DB 1.26, telephone 0131 451 8184, email E.Andersson@hw.ac.uk).

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[2] E. Andersson, J.D. Cresser and M. J. W. Hall, Obtaining the Kraus decomposition from a master equation and vice versa, J. Mod Opt. 54, 1695 (2007) (special issue for QEP-17, Manchester, UK, 2006).

[3] S. R. White, Phys. Rev. Lett. 69, 2863 (1992); S. R. White, Phys. Rev. B 48, 10345 (1993).

Quantum information with finite resources

The objective of this project is to investigate aspects of extracting information from quantum systems, or realising a desired time evolution of a quantum system, given that only finite resources are available. We will look at the estimation of properties of quantum states using different types of quantum measurements, and at efficient characterisation of processes by which quantum states are transformed. If one wants to implement any quantum communication protocol, or a calculation using a quantum computer, one needs to be able to efficiently characterise and implement the involved states and processes. Particular emphasis will be given to finding strategies that are experimentally viable, as this is crucial in order to make real use of the advantages offered by quantum information processing.

Quantum information science is a new and interdisciplinary field that has rapidly become very active due to the fundamental implications it has for the way we process information. This applies both to communication, where quantum cryptography has been shown to yield a level of security unparalleled by classical cryptography, and to information processing, where quantum computers can perform certain tasks, such as searching a database, faster than any classical computer which does not exploit quantum mechanical effects.

Quantum information science is an interdisciplinary research field, combining aspects of physics, particularly quantum mechanics, including experimental realisations, with information theory. With higher communication data rates, smaller processors, and more precise standards, noise control and information extraction at the quantum level becomes necessary. This requires us to carefully tailor the measurement used to decode the information. The quantum state constitutes a finite resource from which as much information as possible has to be extracted. Different optimal measurement strategies may be used for this, such as maximum confidence measurements [1]. We might also ask, if several copies of the quantum system we want to measure are available, whether we should make the same measurement on each quantum system or not [2]. The project will look both at the estimation of properties of quantum states using different types of quantum measurements, and at efficient characterisation and realisation of processes (completely positive maps) by which quantum states are transformed. As an example, any such map can, for a finite-dimensional quantum system, be realized by coupling the system in question to a qubit-sized ancillary system, measuring the ancillary qubit, and then repeating this process [3]. Emphasis will be given to finding strategies that are experimentally viable, as this is crucial in order to make use of the advantages offered by quantum information processing.

[1] S. Croke, E. Andersson, S. M. Barnett, C. L. Gilson, and J. Jeffers, Maximum confidence quantum measurements, Phys. Rev. Lett. 96, 07401 (2006).
[2] T. Brougham, and E. Andersson, Estimating the expectation values of spin-1/2 observables with finite resources, Phys. Rev. A. **76**, 052313 (2007).
[3] E. Andersson and D. K. L Oi, Binary search trees for generalized measurement, arXiv:0712.2665.

Quantum digital signatures

Digital signatures is an important and widely used application of public key cryptography, and allows one party to securely sign documents so that other parties can be sure of their origin and authenticity. Classical public key cryptography unfortunately relies on unproven assumptions regarding the computational difficulty of reversing a so-called one-way mathematical function in order to break the code. Quantum public key cryptography, on the other hand, can be made unconditionally secure based on information-theoretical limits. The main objective of this project is to perform theoretical work relating to a proof-of-principle experiment for quantum digital signatures. The protocol is an adaptation of the scheme by Gottesman and Chuang [1], modified to use coherent states and linear optics [2]. Essentially, the security is guaranteed because it is impossible to perfectly determine the state of a quantum system, if its possible states are non-orthogonal.

This PhD project is related to an EPSRC proposal related to a project involving Dr Erika Andersson and Prof Gerald Buller at Heriot-Watt and Dr. John Jeffers at Strathclyde. It builds on the expertise the group of Prof Buller already has in quantum cryptography experiments, and the theoretical work of Dr Andersson and Dr Jeffers. Depending on the preferences of the student, it should also be possible to do some experimental work. The theoretical work in the project will start with planning optimal experimental setups, and performing a performance and security analysis of the actual experimental setups.

For further information, please contact Dr Erika Andersson (DB 1.26, telephone 0131 451 8184, email E.Andersson@hw.ac.uk).

[1] D. Gottesman and I. L. Chuang, Quantum digital signatures, quant-ph/0105032 (2001).
[2] E. Andersson, M. Curty and I. Jex, Experimentally realizable comparison of coherent states and its applications, Phys. Rev. A 74, 022304 (2006).

Quantum Optics and Cold Atoms

Dr. Patrik Öhberg

When atoms are trapped and cooled to temperatures only one millionth of a degree above absolute zero, their behaviour becomes dominated by their wave-like quantum nature. How they behave depends on their intrinsic spin. Bosons, having integer spin, tend to occupy the same quantum state and behave coherently. The most striking example being the atomic Bose-Einstein condensate. Fermions, having half-integer spin, are forbidden from occupying the same state and behave very differently.

The main theme here is to investigate the effects of light propagating through an extremely cold gas. The light will have some peculiar properties. It can for instance propagate very slowly through the cloud of atoms. In vacuum the speed of light is 300 000 km/s, but when the light propagates through a cold gas the situation can be strikingly different. If the frequency of the light is carefully chosen, then the velocity of the light pulse can be as slow as a walking pace. The light can also have an orbital angular momentum associated with a propensity to induce rotation. This means that the incoming light will have a phase profile which resembles a helical spiral. The combination of light with orbital angular momentum propagating through a quantum gas has some remarkable consequences. It turns out that the interaction between such light beams and the atoms is of the form of a vector potential which in turn opens up a whole new playground for the cold atoms. A vector potential is typically encountered when describing the interaction between charged particles, such as electrons, and magnetic fields. In our case the atoms are neutral and do not feel the presence of a magnetic field likeelectrons would do. But since the interaction between the atoms and the light is of the same mathematical form as the vector potential for charged particles, we can introduce an effective magnetic field in our neutral cloud of atoms. This has some profound consequences in allowing us to explore fundamental systems with charged particles and magnetic fields, but using neutral atoms. It makes it much easier to control parameters, such as the density, or even interaction strengths between the atoms, compared to standard solid state "charged particle systems". Another remarkable consequence of the effective vector potential is a direct analogy between ultracold quantum gases and gauge theories encountered typically in high energy physics. This will give us a new tool and allows us to study phenomena known from a wide range of different fields, but now with all the advantages the cold atoms are giving.

The following projects are currently available:

1) Effective magnetic fields in ultracold neutral quantum gases

In this project we will explore the effect of strong vector potentials in neutral ultracold atomic quantum gases. In particular phenomena such as the atomic quantum Hall effect will be investigated and topological excitations in the quantum fluid. The applied effective magnetic field is created by optical means, which is a highly versatile technique. This means we are in a position to study truly exotic states of the quantum gas where the applied effective magnetic field can be chosen to take forms that are not easy to create with real magnetic fields. The applied light field/effective magnetic field, will force the quantum fluid to behave in a nontrivial manner. The goal here is to understand the ground state properties and excitations of the quantum gas.

2) Non-Abelian dynamics: From Wave Packets to Quantum Information processing

Electromagnetism is an example of an Abelian gauge theory where the vector potential describes the interaction between charged particles. A non-Abelian situation is very much different! It is often encountered in theories describing the interactions between elementary particles. Now we do not have a vector potential, but a matrix instead. We are going to work with ultracold atoms, which opens up a number of interesting possibilities. In this project we will study the non-Abelian wave packet dynamics using the properties of multi-component Bose-Einstein condensates. The goal here is to understand the dynamics of the Bose-Einstein condensate and the role the non-Abelian gauge potential plays. A promising direction in this respect is the possibility to device quantum phase gates based on the geometric phases, which indeed are the source of the non-Abelian gauge potential in our case. This concept has the promising feature of making it, to a large extent, possible to avoid decoherence in our system.

3) Slow light

Light pulses can be slowed down to a walking pace by using for instance electromagnetically induced transparency. In this project we will study slow light pulses which carry an orbital angular momentum. The orbital angular momentum of the light will manifest itself as slow moving optical vortices. We will study the induced rotations in the cloud of ultracold atoms. In particular in the superfluid regime we hope to shed some light on the transfer of angular momentum between light and matter, a concept which has puzzled scientists for decades.

4) Exotic lattices

Recent techniques to shape and control light beams using holograms makes it possible to create atomic traps with an unprecedented controllability. In this project we will investigate the properties of ultracold atoms in optical lattices where the shape of the lattice structure is highly nontrivial. In particular dynamical lattices will be studied and their influence on the macroscopic quantum states of the trapped atoms. We will develop numerical techniques to handle the dynamics. One of the mainobjectives in this project will be to device systems which rely on spatial quantum effects, but which actually mimics the physics we see in quantum optics where the internal degrees of freedom of atoms is manipulated.

5) Atom optics

A Bose-Einstein condensate is a giant coherent matter wave. In this project we will do optics with matter. Atom optics has the added interesting concept of being nonlinear. There are collisional interactions between the atoms. This makes life more complicated, but also more interesting. The project will focus on quantum state engineering. The key points will be the dynamics of the quantum fluid or superfluid. We will use techniques known from optics (Fourier transforms, phase and intensity holograms, focusing etc.) in order to shape the Bose-Einstein condensate as freely as possible. The work will be mainly numerical and involve nonlinear dynamics.

For more information please visit:

http://www.eps.hw.ac.uk/departments/physics/POhberg.htm
http://www.eps.hw.ac.uk/~po15/Site/Home.html

Theory of Quantum Nanomaterials

Dr Brendon Lovett

Quantum dynamics and energy transfer in driven nanosystems

This theoretical project is about the quantum properties of nanomaterials, which have atom-like discrete quantum energy levels. Examples of such systems include semiconductor quantum dots and molecular materials. We will be interested in how an optical driven field can create quantum coherence in these solid-state systems and how long this coherence can be maintained. We will go on to look at how energy can transfer between connected nano-materials and whether this influences the efficiency of the process. The results of the work could impact on a diverse range of fields, from quantum computing to solar cell design.

The project will involve collaboration with both theorists and experimentalists at Imperial College London and the Universities of Queensland and Sheffield. It will build on the work discussed in [1] and [2].

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[2] A . J. Ramsay, T. M. Godden, S. J. Boyle, A. M. Fox, M. S. Skolnick, E. M. Gauger, B. W. Lovett and A. Nazir, Phys. Rev. Lett. in press (2010)

Measurement based quantum computing

One can regard quantum entanglement as the fundamental resource needed in order to execute quantum algorithms. Certain kinds of entangled states exist which are universal resources, in the sense that any quantum algorithm can be performed simply by performing a prescribed series of quantum measurements. Moreover, even the entangled state itself can by created by making measurements [1]. These insights have led to many new possible implementations of quantum computers, for example: one that uses only photons, one exploiting crossed atomic beams and others based on optical measurements on colour centres in diamond.

In this project, you will develop enabling theory that will allow the creation of entangled electronic states of remote nanostructures such as quantum dots, molecules, or crystal defects. Our aim is devise robust protocols that rely simply on the observation of emitted photons from the nanostructures following optical excitation. There will be opportunities for collaboration with experimentalists and theorists both locally in Scotland, at the University of Oxford, Imperial College London and the National University of Singapore.

[1] S. C. Benjamin, B. W. Lovett and J. M. Smith, Laser and Photonics Reviews **3** 556 (2009)

Quantum biology: magnetic field detection and avian navigation

Established experiments find that birds navigate by detecting the orientation of the Earth's magnetic field, and this is enabled by optical excitation of molecules in the retina. Quantum coherence is now believed to play a key role in the navigation process [1].

We have suggested [2] that the detection mechanism relies on molecules whose electric dipole changes depending on the magnetic field orientation, and that this influences colour-sensitive retinal molecules in the eye. The aim of this theoretical project is to generate enabling calculations that establish the model and, together with experimentalists at the London Centre for Nanotechnology, to develop artificial systems that can exploit this effect for new sensor technologies.

[1] T. Ritz, P. Thalau, J. B. Phillips, R. Wiltschko, and W. Wiltschko, Nature **429** 177 (2004)

[2] A. M. Stoneham, E. M. Gauger, K. Porfyrakis, S. C. Benjamin, and B. W. Lovett, http://arxiv.org/abs/1003.2628 (2010)

Quantum memories for quantum computing applications

We are investigating a range of systems in order to produce a robust quantum memory. For example, we recently showed how to store a quantum state in a nuclear spin for over three seconds [1], in a solid state system. We are now looking at ways of extending this coherence time, and at making the memory more versatile [2].

In this project, we aim to design improved quantum memories in both single spins and spin ensembles. There will be opportunities for collaboration with experimentalists both locally, and at the University of Oxford.

[1] J. J. L. Morton et al., Nature 455 1085 (2008)

[2] M. Schaffry et al., Phys. Rev. Lett. 104 200501 (2010)

A quantum model for photosynthesis: towards efficient solar cells

Many living systems harvest the sun's energy through photosynthesis, a process that has three main steps. First, sunlight is absorbed by a protein-pigment complex, and converted into electronic excitation. Second, the electronic excitation moves through a network of excitation sites in a directed fashion, until it reaches a reaction centre. Third, charge separation at the reaction centre facilitates the production of ATP, which leads to the conversion of carbon dioxide to sugar.

This project will focus on developing models of the second of these steps, and will investigate the role of the protein's vibrational modes (phonons) in determining the efficiency of energy transport through the system.

There is a strong parallel between how photosynthesis works and how organic heterostructure solar cells operate. By exploiting the results on photosynthetic systems, we aim to develop new design principles for artificial energy harvesting devices.

Semiconductor Physics

Prof. Ian Galbraith

Quantum Monte Carlo of Realistic Semiconductors Nanostructures

Recent progress in growth of semiconductor materials has enabled the growth of semiconductor quantum dots. In such dots, electrons (and holes) are confined into a small volume (having ~10nm radius) which determines the quantum states which the electrons can occupy. Similarly quantum rings can be grown (like a polo-mint!) which also display very novel physical properties. Experiments on such dots and rings are underway (in the Nano-optics group Prof. Richard Warburton here at Heriot-Watt) but the results require sophisticated microscopic modelling before they can be reliably interpreted. What makes this fascinating is that the electrons and/or holes interact strongly via the Coulomb interaction as well as being localized by the material structure. So a dot with two electrons inside shows a different energy-level structure than a dot containing only a single electron because of their mutual repulsion. From a practical point of view quantum nanostructures are widely used in making semiconductor lasers and are prime candidates for implementation of quantum information processing systems. As such, understanding the underlying physics of how electrons and holes behave in these dots is of both theoretical and practical importance. Since there are many energy scales in the problem which are rather similar; the Coulomb interaction energy between two carriers in the dot is about 30meV, the thermal energy at room temperature is about 25meV, the phonon energy of lattice vibrations is about 35meV and the separation of the energy levels for a single carrier in the dot (like the particle-in-a-box problem) is also about 25meV. So we need a non-perturbative technique which can handle these interactions without approximation and deal with the complex geometry of the quantum dot or ring..

One technique which meets these conditions is Path integral - Quantum Monte Carlo (PI-QMC), a powerful tool used for solving many-body quantum problems in a wide range of physical situations from Liquid He to semiconductors. Based on Richard Feynman's Path integral formulation of quantum mechanics it involves the numerical sampling of interacting quantum trajectories for each particle. Specifically this project will build on our existing PI-QMC simulations for a few particles with simple interactions to move them into the realm of more realistic simulations. To achieve this we need to make progress in two areas. Firstly when two indistinguishable particles (say two electrons with the same spin) are being modelled the overall wavefunction of the system must be anti-symmetric in the exchange of the co-ordinates of the two particles. However this leads to a numerical difficulty, called the fermion sign problem, as the contribution of a given path and its anti-symmetric partner have opposite signs and almost (but not quite) cancel. One of the aims of this project would be to address this issue. Secondly, and related to the above, the sampling of the differing paths is most efficiently done using non-trivial changes to the locations of more than one particle at a time. This leads to a better coverage of the required 'path-space' than simple schemes. The second aim of the project would be to explore the influence of such approaches on the quantum dot simulations. Tackling both of these issues will involve understanding the theoretical foundations of the QMC method and computer coding of the simulations, where possible exploiting parallel processing on our new 320 CPU cluster. All the while we would expect to be in close collaboration with the experimental team in helping to interpret their results and in suggesting fresh experiments.

Physics and modelling Organic Semiconductor Devices

Great strides have been made over the last ten years in realising the enormous potential of organic semiconductor materials in that they are cheap, flexible and easily processed. The development of early polymer lasers and amplifiers today is following a similar trajectory to that of *inorganic* optoelectronic devices in the 1980's. At that time the first generation of bulk lasers had given way to a second generation based on quantum well heterostructures. Key to this development was a quantitative theoretical understanding of the influence of the underlying microscopic physics such as electronic bandstructure and carrier-carrier scattering losses. This led, for example, to the incorporation of strained hetereostructure layers into lasers which greatly enhanced their performance. Organic (Polymer) photonics devices are currently sufficiently developed that we can credibly begin to search for the same level of understanding and potentially reap similarly high rewards.

To model the optical response of the system requires knowledge not only of the population of any excitations in the system but also of the induced polarisations, as these are the sources for the propagating electric field.

In inorganic semiconductor devices these can be calculated using a so-called Equation of Motion approach. This approach has been extremely successful in providing a quantitative description of inorganic semiconductor lasers and amplifiers. It has been widely adopted in academic research and increasingly, in the commercial sector. The Heriot-Watt Semiconductor Theory group has substantial experience with this Equation of Motion techniques.

The major objective of this project is to develop an analogous set of physically appealing equations applicable to *polymer* semiconductor devices and test them against experiment. Clearly the usual periodic Bloch-like states are an inappropriate set of basis states to use for the localised excitations involved in the optics of polymer chains. Thus one of the challenges is to identify which basis states are best suited to this problem. A second challenge is to quantify, in the chosen basis, the dominant scattering mechanisms that determine the relaxation between the states and the damping of the optically induced polarisation. Inclusion of the light propagation involves coupling the equation for the induced polarization to the wave equation and thereby following the evolution of a real pulse as it transits the device. The resulting pulse will be directly comparable to the measured pulses obtained by our experimental collaborators at the University of St. Andrews (Prof I. Samuel & Dr G. Turnbull).

Success this ambitious project would lead to equations which are as key to modelling, understanding and optimising polymer devices as the semiconductor Bloch equations have proven to be in inorganic ones.

Semiconductor Physics

Dr Kevin A Prior

II-VI growth and characterisation

The Heriot-Watt Molecular Beam Epitaxy (MBE) group has excellent facilities for the growth and characterisation of semiconductors. Our MBE facilities have recently been upgraded with an improved MBE growth chamber to produce new and more complex structures and a new clean room facility.

Unlike all other UK MBE groups, we grow wide bandgap II-VI semiconductors, and this has traditionally meant ZnSe and its alloys with sulphur, magnesium and cadmium. We have also developed advanced characterisation techniques for electrical (CV profiling) and structural (AFM, X-ray) characterisation. Other structural characterisation techniques, including TEM and x-ray reciprocal space mapping measurements are obtained via our collaborators.

Currently our work falls into three main areas:

1. Growth of complex structures containing traditional II-VI compounds and alloys.

   These are usually structures containing multiple quantum wells or quantum dots. Typically, these structures would be supplied to other groups, both within Heriot-Watt (Quantum Electronics Lab and Non-linear optics group) and elsewhere.

2. Growth of novel semiconductors.

   We have developed a new variant on the usual MBE growth technique, which has enabled us to grow epitaxial layers of some new semiconductors, including MgS, which is an ultra-wide bandgap material (~5eV). It is a material which we have developed and recently we have produced several alloys based on this material. These have found a large number of uses in optoelectronic devices, many deriving from the enormous confinement. A recent development of the MgS is the demonstration of epitaxial lift off, where the semiconductor is etched away and the remaining layers can be transferred to other substrates.

3. Growth of magnetic semiconductors.

   We have also demonstrated that the same growth technique works with other semiconductors, such as MnS, which is antiferromagnetic, and CrS, which was grown for the first time in our laboratories. CrS is of particular interest as theoretical calculations have suggested that it is a ferromagnetic semiconductor and should have interesting spintronics applications. Currently our magnetic materials, including MnS, CrS and the alloy MnCrS (which has only been produced by our group) are being investigated by a number of our collaborators, in particular the group of Prof Wolfram Heimbrodt at Phillips University, Marburg.

Currently we are looking for a student who can work in two of the areas described above, with two main projects currently being developed. First, we are looking to develop methods of growing conventional semiconductor structures, but incorporating ultra-low doped materials in order to produce widely separated dopant atoms which can be individually addressed. The application here is in single photon sources.

A second project area is the development of new materials, in particular chromium containing alloys, including lightly chromium doped ZnSe and also chromium selenide, a material which is predicted to be not just a ferromagnet, but also a half metal. Incorporating CrSe with other semiconductor structures would produce a range of exciting new structures, such as spin injectors and possibly a memristor.

Both projects will entail using a variety of electrical and structural characterisation techniques and growth of a range of semiconductor materials and alloys. They are suitable for any student with a good knowledge of Physics, Chemistry or Electrical Engineering.

Waves and Fields Research Group

Prof. Alan Greenaway

Bio-medical Imaging/Fluid flow

Summary: We are looking for a postgraduate student to work on our programme for 3-dimensional imaging of dynamically-changing objects under a Bio-photonics programme funded by EPSRC. The studentship is part funded by this EPSRC programme and the remaining funds will be found from other sources, dependent on the student appointed to the project.

The work is based on the use of diffractive optical elements that, combined with a conventional lens, provide ‘snapshot’ 3-dimensional data. The recorded data can be in the form of simultaneously-recorded images of different slices through a 3-dimensional object or in the form of data from which the accurate position of tracer particles can be tracked in 3-dimensions, with either data set recorded as a time series.

This post is most suitable for home or EU-based students, but overseas students are not necessarily excluded. The post is suitable for students with a good degree (1st or 2.1-class Honours) in Physics, Applied Mathematics, Electrical or Mechanical Engineering, but mathematically-strong students from the Life Sciences would also be considered for this position.

Single Photon Sources and Detectors

Prof. Gerald S Buller

email: G.S.Buller@hw.ac.uk

Photon Counting Technologies for Time-of-Flight Ranging and Remote Imaging.

Summary: Laser detection and ranging systems have been widely applied to distance measurement and 3D imaging in a wide range of applications including industrial metrology, environmental survey and remote target characterization. Typically, such systems use a single laser source which emits short pulses and a detection system which analyses the light reflected back to the instrument by the target.

Over the past few years the research team at Heriot-Watt University has developed transceiver systems which have utilised time correlated single photon counting (TCSPC) in an innovative way, and developed sophisticated software algorithms for analysis of the return data, in order to enhance the sensitivity and accuracy of such detection and ranging systems. We have built a multiple wavelength system which widens the scope and functionality of photon counting, allowing issues such as: the wavelength dependence of temporal resolution, simultaneous multichannel data acquisition, atmospheric propagation, the wavelength dependence of speckle, and the wavelength dependence of target reflectivity to be studied in a single integrated system. Research on further enhancements is planned.

We offer a PhD studentship in this exciting research area. The student will join a successful group which has collaborations with other major groups in the UK and Europe. There is a good possibility of a CASE studentship with industry although this is not guaranteed initially. The PhD research will lead to an understanding of lasers, optical systems, and state-of-the-art single-photon detection technologies.

For further information, please contact Prof Gerald Buller (email: G.S.Buller@hw.ac.uk).

Quantum Photonics Laboratory

Dr Brian Gerardot

There are two projects available within the Quantum Photonics Laboratory (http://gerardot.eps.hw.ac.uk/). The research takes place within the framework of a £1M Challenging Engineering grant from EPSRC. Please note that we currently can offer full funding for any EU national. Non-EU students are eligible for a prestigious SUPA Prize – please contact Dr Brian Gerardot for more details.

The two projects are:

- **Broadband waveguide QED:** We will design, simulate, fabricate, and measure the coupling of either single quantum dots or NV defect centres in diamond to waveguides. The motivation here is to enhance the light-matter interaction efficiency for both 2 level systems (both defects in diamond and quantum dots) and 3- or 4- level systems (in quantum dots) to achieve optical non-linearity at the single photon level.

- **Telecom wavelength quantum dots:** We will develop a new class of quantum dots with emission near either 1.3 micron or 1.55 micron which would be more suitable for communication over fibres or in free space (compared to the more mature quantum dots emitting at < 1 micron). The main motivations here include: the generation of indistinguishable photons, the generation of 'on-demand' polarization entangled photons, and a characterization of spin coherence in these dots. This project would work closely with Robert Hadfield's group to give us access to the best superconducting single photon detectors.

These experimental projects allow a wide spectrum of experience with semiconductor device design, nano-fabrication, nano-optics, laser spectroscopy, cryogenics, and sophisticated electronics. The research is multi-disciplinary, involving: condensed-matter physics, quantum optics, materials science, and quantum information processing. We work closely with groups at Heriot-Watt (including Brendon Lovett and Patrik Ohberg on the theory side and Robert Hadfield and Gerald Buller on the experimental side) and abroad (at Eindhoven, Basel, Rochester, and Santa Barbara).

Wave Dynamics in Moving Media

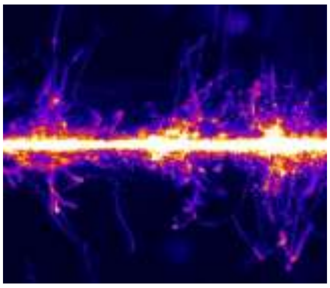
Dr. Daniele Faccio

Wave propagation in a moving medium may be described using the same space-time geometries usually found in general relativity. It is even possible to show that we may recreate, in the laboratory, analogues for black hole event horizons and study how waves interact with these horizons. Our group has recently demonstrated for the first time the analogue of Hawking radiation, i.e. black hole evaporation, using intense laser pulses focused into glass samples. The nest step, and goal of this project, is to continue these studies and investigate the details of Hawking radiation physics. The theory, supported also by simulations based on the Maxwell equations, predicts the possibility to obtain amplification of light pulses at the horizon boundary. A fascinating perspective is the creation of a “black-hole laser” in which light, trapped between two horizons, is continuously amplified in a laser-like fashion. Moreover, these ideas are relevant to other wave propagation regimes such as water-wave propagation, which shall also be considered. This is a highly ambitious project at the interface between wave dynamics, general relativity and quantum physics.

For further information, please contact Dr Daniele Faccio (email: d.faccio@hw.ac.uk).

Light-matter interaction at extreme intensities

Dr. Daniele Faccio



The most important application of lasers is energy deposition in micron or nanometre scale volumes: controlling the dynamics of the light-matter interaction is consequently of extreme importance. At extremely high intensities, the laser pulse electric field is predicted to severely distort the potential of the medium atoms so that the outer electrons may tunnel out. However, very little is known about tunnelling photo-ionisation in condensed media due to the impossibility to reach the required intensities: multiphoton-ionisation that occurs at lower energies, will clamp the laser pulse intensity to a maximum value, independently of how hard one tries to focus the laser pulse. The aim of this project is to overcome the intensity clamping by using novel laser-pulse focusing schemes that allow to readily reach into the tunnelling regime. This will open a completely new and unexplored light-matter interaction regime at extreme intensities. Applications will range from fundamental studies of the very nature of the tunnelling process to novel cavitation dynamics in liquids and laser-induced propulsion.

For further information, please contact Dr Daniele Faccio (email: d.faccio@hw.ac.uk).