Part IA: Dynamics: 2016-17

Prof Val Gibson

Prerequisites

This course assumes knowledge of the material in A-level Physics and Mathematics; however it is also accessible to students who have not taken A-level Physics but who have taken three Mechanics modules in A-level Mathematics and Further Mathematics.

Learning Outcomes and Assessment

In this course you will be introduced firstly to important concepts in the collection and analysis of experimental data and secondly to the application of rigorous mathematical models to describe familiar concepts in statics and dynamics. In addition you will be learning more sophisticated ways of tackling physics problems. We will work through numerous examples in the lectures which illustrate the physics and mathematics you are learning and show you how to think about and work through such questions.

At the start of the course you are given an introduction to university physics and will gain an understanding of the scientific method and the role and importance of both experiment and mathematical modelling in forwarding our understanding of the physical world. You are introduced to the use of dimensional analysis as an important tool in understanding the relationships between the different physical properties of a system. The differences between the prescriptive step-by-step approach taken to tackling Physics problems at A-level and the much less structured way of tackling physics problems at university are highlighted.

The two lectures on experimental physics are designed to fit in with what you are learning in the practical classes. You will understand the concept of a random error and be introduced to the Gaussian probability distribution - on which the analysis of the significance of errors is predicated. You will learn about the importance of making several measurements to improve the accuracy of your result and how to calculate the mean, standard deviation and error in the mean for your data. You will also learn about how to find the errors in functions of a single variable and also how to combine errors in two or more variables. You will understand the concept of a systematic error and learn about some techniques for dealing with systematic errors - with particular reference to the experiments carried out in the practical class.

In the sections on statics and dynamics you will be reacquainted with various concepts you have already met but cast in a more rigorous mathematical way. You learn about how to use calculus in physics in a simple way and will understand the basic application of differentiation and integration in analysing physical models; you will learn to set up differential equations (DEs) to describe the motion of physical systems - solving the equations directly in the case of first-order DEs but simply using substitution of a suggested solution in the case of second order DEs. Another useful mathematical tool you will learn is that of approximation i.e. looking at the behaviour of an equation or solution in the limiting case when the variable is either very small or very large.

You will understand the concept of a force: as something that has a tendency to produce motion and that is a vector which has components which can be resolved in different directions; you will understand the concept of equilibrium and the value of using free-body diagrams to analyse the forces acting on a system. The forces exerted by idealised springs, strings and pulleys, and the effects of friction on systems, will be considered. The concept of the work done by a force is introduced in 1-D and in 3-D using scalar (dot) products, and using integration in the case of a force which is a function of position; this leads on to the definition of potential energy, and its relationship to the internal forces in a system and to stable and unstable equilibrium.

The relationships between displacement, velocity and acceleration are described using calculus. You will look at Newton's 1st and 2nd laws of motion and use the 2nd law to derive the differential equations (the equations of motion) describing various physical systems. The rate of doing work on a system (the power) is described as the derivative of the work done. The kinetic energy of a system is defined through considering the work done accelerating it. You will learn about the principle of the conservation of energy - specifically that in an isolated system energy in all its forms is conserved. The concept of momentum is introduced and through considering Newton's 2nd law you will learn that the force applied equals the rate of change of momentum. From this and Newton's 3rd law it is shown that in an isolated system linear momentum is conserved. This law is used to analyse the motion of rockets and to look at elastic and inelastic collisions between two particles. The impulse of a force is defined as the integral of a force over the period for which it acts and is equal to the change in the momentum of the associated system.

You will understand the concept of a frame of reference, with particular reference to inertial frames of reference i.e. those which are travelling at a constant speed with respect to one another, and learn how to transform coordinates from one frame to another. In particular you will learn how to use a zero-momentum frame which can greatly simplify the analysis of collisions between bodies.

Synopsis

Introduction to university physics: role of experiment; mathematical models; dimensional analysis; tackling physics problems.

Experimental physics: random and systematic errors; Gaussian probability distribution; mean, standard deviation, error in the mean; errors in functions of a single variable, combining errors in two variables; examples of techniques for dealing with systematic errors; graphs.

Dynamics: *Concept of a force:* tendency to produce motion; forces as vectors; action and reaction; friction. *Calculus in physics*: use of integration. *Work*: potential energy; stable and unstable equilibrium. *Kinematics*: displacement, speed, velocity, acceleration. *Newton's laws of motion*: equations of motion. *Kinetic energy*: concept and definition; principle of the conservation of energy. *Linear momentum*: concept and definition; conservation of linear momentum; rockets; elastic and inelastic collisions; impulse of a force. *Frames of reference*: relative velocities, inertial frames of reference, zero-momentum frame, collisions.

Part IA: Gravitational and Electromagnetic Fields: 2016-17

Dr John Ellis

Synopsis

Gravitation: Newton's law, measurement of G. Action at a distance and concept of a local force field. Properties of conservative fields, including potential energy as a path integral. Superposition of fields. Gauss' law for gravity with simple quantitative applications.

Orbits: Kepler's laws. Derivation of elliptical orbits for planetary motion from Newton's law. Simple orbital calculations. Qualitative examples of gravity at work including tidal effects.

Electrostatic Fields: Static electricity, Coulomb's Law for point charges, the electric field **E** and the corresponding potential for point charges and electric dipoles. Gauss' law for electrostatic fields. Properties of ideal conductors. Capacitance including calculation for simple geometries. Mention effects of dielectric materials on capacitance and dipole moment of water molecule.

Magnetic Fields: Properties of bar magnets. Magnetic flux density **B**. Magnetic dipoles and currents as sources of **B**. Lorentz force and motion of charged particles in electric and magnetic fields; J.J. Thomson's experiment. Ampère and Biot-Savart laws, calculation of **B** field in simple cases. Faraday's law of induction; self and mutual inductance, energy stored in **B** field.

Maxwell's Equations: Displacement current term. Integral and differential statements. Example of plane wave solutions.

Part IA: Oscillating Systems: 2014-15

Dr John Biggins

Synopsis

Simple harmonic motion (SHM): equation of un-damped oscillation for a mass on a spring, its solution, relative phases of displacement, velocity and force. Approximations of oscillating systems to SHM: simple pendulum. Energy in SHM: vibration of two masses joined by a spring, quantum well.

Phasor diagrams: superposition of oscillations, beats, amplitude modulation.

SHM using complex numbers: Curves of time-dependence for an oscillator, amplitude, frequency, angular frequency and phase.

Damped oscillations: amplitude and energy decay, quality factor.

Forced oscillations: qualitative frequency response and resonance.

Revision of electrical circuits: voltage, current and charge in circuits, electrical resistance, Kirchhoff's laws, resistors in series and parallel. Inductors and capacitors. Circuits with exponential decays: discharge of a capacitor through a resistor, decay of current through an inductor.

Oscillations in electrical circuits and complex impedance: Oscillation in an LC circuit, relative phases of voltages, charge and currents. Complex current and voltage in resistors, capacitors and inductors. Complex impedance. Electrical resonance in an LCR circuit, simple filter, bandwidth, Q factor. Relationship of behaviours seen in electrical systems to those of mechanical systems. Mechanical impedance.

Part IA: Part IA Practicals: 2016-17

Dr Julia Riley, Dr Dave Green

Prerequisites

This course assumes knowledge of the material in A-level Physics and Mathematics; however it is also accessible to students who have not taken A-level Physics but who have taken three Mechanics modules in A-level Mathematics and Further Mathematics. It does not require any prior experience of carrying out Physics practical work.

Learning Outcomes and Assessment

The aim of the Part IA practical course is to teach basic experimental, data-analysis and record-keeping skills. The experiments have been chosen to develop particular skills, although the experiments in the Lent and Easter terms also reinforce material from the lectures.

In this course you will familiarise yourself with the tasks involved in performing an experiment and will understand how to make brief clear laboratory notes (including tabulating data and plotting graphs); you will also gain experience in writing formal reports on experiments. Through working in pairs (which will swap throughout the year) you will understand how to work well with other people and work together effectively as a team. You will also learn to pace yourself and balance the amount of detail and precision with the need to finish the task in the time available.

Through performing a variety of experiments you will acquire the following skills:

- taking readings and keeping records;
- using Excel spreadsheets to analyse data, carry out calculations, plot graphs and perform linear regression;
- assessing and understanding the nature of random errors, calculating the mean and standard deviation of a sample and the error in the mean;
- combining errors;
- assessing which parts of an experiment demand the more accurate measuring procedures;
- assessing, correcting for and eliminating (where possible) systematic errors;
- appreciating difficulties that can arise in data analysis and recognising unexpected phenomena.

You will learn how to use unfamiliar equipment proficiently and identify when it is not working. You will understand how to set up simple electrical circuits and how to use basic electrical apparatus, specifically multimeters, picoscopes and function generators.

Synopsis

Michaelmas Term

Four experiments are carried out. These are primarily intended to teach experimental skills – including how to keep a good laboratory notebook – and to introduce experimental errors and their treatment. The required theory, as well as a general overview of experimental skills, will be included in the “Dynamics” lecture course.

Marks for the first practical (E1) do not count towards the final total.

E1. **Attenuation of g-ray photons.** Through the statistics of radioactive decay, this aims to develop an understanding of random and systematic errors in count rates and to estimate the linear attenuation coefficient for photons in lead.

E2. **Galileo's rolling ball experiment.** This aims to introduce the basic methods of experimental measurement and errors through an investigation of the acceleration of a mass rolling down a ramp.

E3. **Thermal excitation in a semiconductor.** This experiment measures the variation of the electrical resistance of a semiconductor with temperature, testing the behaviour predicted by quantum physics.

E4. **Measurement of *g* using a rigid pendulum.** The aim of this experiment is to measure the value of *g* with a precision of about one part in a thousand using the oscillations of a rigid pendulum.

Lent Term

Four experiments are carried out, all of which illustrate material from the lecture courses. E5, E6 and E7 use concepts introduced in the "Oscillating systems" course. E5 is an investigation of damped oscillations and resonance in a mechanical system. E6 is an introduction to measuring electrical signals with a picoscope; the picoscope is then used in E7 to investigate electrical resonance. E8 investigates the geometric optical properties of simple lenses and mirrors, illustrating material from the section on optics in the "Waves and quantum waves" course.

E5. **Mechanical resonance*.** This experiment studies the free and forced rotational oscillations of a torsion pendulum, and investigates the phenomenon of resonance and the effect different levels of damping have on the motion.

E6. **Electrical measurement.** This experiment introduces the picoscope as a measuring instrument, through experiments looking at the output of a signal generator.

E7. **Electrical resonance and signal filtering*.** In this experiment the picoscope is used to study free and forced oscillations in *LCR* resonant circuits, and a practical application of an *LCR* network is investigated.

E8. **Geometric optics using lenses and mirrors*.** This practical involves a series of simple experiments demonstrating the properties of optical lenses and mirrors, and real and virtual images.

Easter Term

Two experiments are carried out, illustrating material from the lecture course "Waves and quantum waves". E9 is an investigation into diffraction by slits and gratings. E10 looks at the photoelectric effect – one of the experiments fundamental to the development of quantum physics. Half the class will carry out Experiment E9 in the first session of the Easter term, followed by E10 in the second session; the other half of the class will do E10 in the first session and E9 in the second.

E9. **Diffraction of laser light by slits and gratings.** This is a quantitative investigation into the diffraction patterns produced by double and multiple slits when illuminated by a laser.

E10. **The photoelectric effect.** This practical investigates the photoelectric effect; an estimate of Planck's constant is obtained, using the dependence of stopping voltage on the frequency of the incident light.

Formal Reports

Students are required to produce two formal reports which are assessed by a Head of Class; the marks awarded count towards the end-of-year assessment. The first report, to be handed in at the start of the Lent term, will be based on one of the experiments carried out in the Michaelmas term. The second one, to be handed in at the start of the Easter term, will be a full report on one of the three starred* Lent-term experiments (i.e. E5, E7 or E8).

BOOKS

Practical Physics, Squires G L (4th edn CUP 2001).

Experimental methods: *An Introduction to the Analysis and Presentation of Data*, Kirkup L (Wiley 1994).

Experimental Physics: *Modern Methods*, Dunlap R A (OUP 1989)

An Introduction to Experimental Physics, Cooke C (Routledge 1996)

Measurements and their Uncertainties: A Practical Guide to Modern Error Analysis, Hughes I G & Hase T P A (Oxford 2010)

Part IA: Rotational Mechanics and Special Relativity: 2017-18

Dr Lisa Jardine-Wright

Prerequisites

Pre-requisites for IA Physics are that students have studied maths for public examination at A level or equivalent and physics or the mechanics modules of further maths.

For this course it is assumed that students have completed the IA Physics courses in the Michaelmas and Lent terms i.e.

1) Dynamics

2) Oscillating Systems

3) Waves and Quantum Waves

Learning Outcomes and Assessment

At the end of this course students should be able able to:

(Rotational Mechanics):

1. Combine concepts from the first term course in mechanics be able **to solve problems for extended bodies** that are in equilibrium or accelerating using

    a) Newton's Laws of motion linearly and rotationally

    b) Conservation of momentum and angular momentum

    c) Conservation of energy linearly and rotationally

    d) The equations describing angular and circular motion

2. To understand and calculate the constant precession of a gyroscope.

(Special Relativity):

Primary objectives:

1. Describe and explain the **experimental evidence** for special relativity.

2. Derive and use the **Lorentz transformations** to relate, for example, displacement, time, velocity, momentum and energy in frames moving relative to one another at relativistic speeds.

3. Apply the **energy-momentum invariant** and **relativistic energy and momentum equations** to solve problems of particle collisions.

Secondary objective:

4. Draw **time-distance diagrams** to describe and understand relativistic problems in different frames of reference (e.g. the Earth and rocket frames)

Synopsis

Rotational Mechanics: *Turning moments*: lever balance; turning moment as a vector; moment of a couple; conditions for static equilibrium. *Centre of mass*: calculation for a solid body by integration. *Circular motion*: angle, angular speed, angular acceleration; as vectors; rotating frames; centripetal force. *Angular momentum*: concept and definition; angular impulse; conservation. *Moment of inertia*: calculation of moment of inertia; theorems of parallel and perpendicular axes. *Rotational kinetic energy*: simple collisions involving angular rotation. *Gyroscope*: how it works; precession.

Special Relativity: *Historical development*: problems with classical ideas; the Aether; Michelson-Morley experiment. *Inertial frames*: Galilean transformation. *Einstein's postulates*: statement; events, and intervals between them; consequences for time intervals and lengths; Lorentz transformation of intervals; simultaneity; proper time; twin paradox; causality; world lines and space–time diagrams. *Velocities*: addition; aberration of light; Doppler effect. *Relativistic mechanics*: momentum and energy; definitions; what is conserved; energy–momentum invariant. Nuclear binding energies, fission and fusion.

Part IA: Waves and Quantum Waves: 2013-14

Prof Jeremy Baumberg

Synopsis

Waves: The 1-D equation, application to waves on a string, sinusoidal solutions, amplitude, frequency wavelength, energy transport, transverse and longitudinal waves; boundary conditions at free or fixed end; superposition, interference; travelling and standing waves including complex form; plane waves in 2-D and 3-D, the wave vector and wave number.

Optics: Huygens' Principle, laws of reflection and refraction, lenses, lens formulae, real and virtual images, the simple telescope and microscope.

Diffraction: diffraction using complex amplitudes, Young's slits and the diffraction grating, finite slit using complex amplitude and via integration.

Quantum waves: reminder of wave-particle duality and de Broglie relation; introduction to the wavefunction and 1-D time independent Schrodinger equation; waves in wells and boxes and quantisation of wavelength; reflection at potential steps; penetration through a barrier and evanescent waves.

Part IB Physics B: Classical Dynamics: 2017-18

Dr Dave Green

Prerequisites

This course builds on the ideas introduced in NST Part IA “Physics”, using the tools of vector calculus taught in NST Part IA “Mathematics”.

Learning Outcomes and Assessment

The main areas covered are orbits, rigid body dynamics, normal modes and continuum mechanics (elasticity and fluids).

Synopsis

Newtonian mechanics, **frames of reference:** Review of Part IA mechanics: many-particle system, internal and external forces and energy. Central forces, motion in a plane. Non-inertial frames, rotating frames, centrifugal and Coriolis forces.

Orbits: Effective potential and radial motion, bound and unbound orbits. Inverse-square law orbits, circular and elliptic, Kepler's laws. Escape velocity, transfer orbits, gravitational slingshot. Hyperbolic orbits, angle of scattering, repulsive force. Two-body problem, reduced mass. General features of three-body problem. Brief treatment of tidal effects in gravitational systems.

Rigid body dynamics: Instantaneous motion of a rigid body, angular velocity and angular momentum, moment of inertia tensor, principal axes and moments. Rotational energy, inertia ellipsoid. Euler's equations, free precession of a symmetrical top, space and body frequencies. Forced precession, gyroscopes.

Introduction to Lagrangian mechanics: Generalised coordinates. Hamilton’s principle and Lagrange’s equations. Symmetries and conservation laws. Conservation of the Hamiltonian for time-independent systems.

Normal modes: Analysis of many-particle system in terms of normal modes. Degrees of freedom, matrix notation, zero-frequency and degenerate modes. Motion in three dimensions, modes of molecules.

Elasticity: Hooke's law, Young's modulus, Poisson's ratio. Bulk modulus, shear modulus, stress tensor, principal stresses, strain tensor. Elastic energy. Torsion of cylinder. Bending of beams, bending moment, boundary conditions. Euler strut. Brief treatment of elastic waves.

Fluid dynamics: Continuum fields, material derivatives, relation to particle paths and streamlines. Mass conservation, incompressibility. Convective derivative and equation of motion. Bernoulli's theorem, applications. Velocity potential, applications: sources and sinks; flow past a sphere and cylinder; vortices; Magnus effect. Viscosity, Couette and Poiseuille flow. Reynolds number, laminar and turbulent flow.

BOOKS

Classical Mechanics, Barger V D and Olsson M G (McGaw-Hill, 1995).

Fluid Dynamics for Physicists, Faber T E (Cambridge, 1995).

Lectures on Physics, Feynman R P, Leighton R B and Sands S L (Addison Wesley 1964).

Principles of Dynamics, Greenwood D T (Prentice & Hall 1988).

Classical Mechanics, Kibble T W B and Berkshire F H (Imperial College 2004).

Part IB Physics A: Condensed Matter Physics: 2014-15

Dr Andrew Jardine

Synopsis

Periodic Systems: Overview of crystal structures, the reciprocal lattice.

Phonons: Phonons as normal modes – classical and quantum picture. 1D monatomic chain, 1D diatomic chain, examples of phonons in 3D. Debye theory of heat capacity, thermal conductivity of insulators.

Electrons in solids:

Free electron model: Fermi-Dirac statistics, concept of Fermi level, electronic contribution to heat capacity. Bulk modulus of a nearly free electron metal. Electrical and thermal conductivity. Wiedemann-Franz law. Hall effect.

Nearly free electron model: Derivation of band structure by considering effect of periodic lattice on 1-D free electron model. Bloch's theorem. Concept of effective mass. The difference between conductors, semiconductors and insulators explained by considering the band gap in 2D. Hole and electron conduction.

Doping of semiconductors, *p* and *n* types, *pn* junctions – diodes, LEDs and solar cells.

BOOKS

In general the course follows the treatment in *Solid State Physics*, J.R. Hook and H.E. Hall (2nd edition, Wiley, 1991).

Introduction to Solid State Physics, Charles Kittel (8th edition, Wiley, 2005) is highly recommended. (need not be the latest edition)

Other books, generally available in College libraries and may usefully be consulted:

The Solid State, Rosenberg H M (3rd edn OUP 1988)

Solid State Physics, Ashcroft N W and Mermin N D (Holt-Saunders 1976).

Part IB Physics B: Electromagnetism: 2017-18

Prof Chris Ford

Prerequisites

It helps to have studied Electromagnetic Fields in Part IA Physics but it is not vital.

Learning Outcomes and Assessment

The electromagnetism course further develops the idea of electric and magnetic fields introduced in Part IA, with electrostatics and magnetostatics being treated as special cases of Maxwell's equations. The course introduces dielectric and magnetic media, and predicts and examines wave propagation in free space, as well as in insulating and conducting media and on transmission lines and waveguides.

Synopsis

Introduction: Electromagnetism in physics, and the role of Maxwell's equations.

Electrostatic fields: Electrostatic force, electric field, potential, grad, curl, line integrals, Stokes's theorem, conservative fields, electric monopoles, electric dipoles, field of a dipole, couple and force on a dipole, energy of a dipole, multipole expansions, electric flux, divergence, divergence theorem, charge conservation, Gauss's law, solutions for simple geometries, Laplace's and Poisson's equations, boundary conditions and uniqueness, conducting sphere in uniform $\boldsymbol{E}$ field, method of images, line charge near conducting cylinder, capacitance, capacitance of parallel cylinders, energy stored in electric field, force and virtual work, force on charged conductor.

Electrostatic fields in dielectric materials: Isotropic dielectrics, polarisation, polarisation charge density, Gauss's law for dielectric materials, permittivity and susceptibility, properties of $\boldsymbol{D}$ and $\boldsymbol{E}$, boundary conditions at dielectric surfaces, field lines at boundaries, relationship between $\boldsymbol{E}$ and $\boldsymbol{P}$, thin slab in field, dielectric sphere in field, energy density in dielectrics, general properties of dielectrics.

Magnetostatic fields: Force on and between current elements, magnetic flux, the ampere, $\nabla.\boldsymbol{B}=0$, magnetic dipoles, force and couple on a dipole, energy, magnetic scalar potential, solid angle of a loop, Ampère's law, magnetic vector potential. Ohm's law as $\boldsymbol{J}=\sigma\boldsymbol{E}$.

Magnetostatic fields in magnetic materials: magnetisation, existence of diamagnetism and paramagnetism, permeability and magnetic susceptibility, properties of $\boldsymbol{B}$ and $\boldsymbol{H}$, boundary conditions at surfaces, methods for calculating $\boldsymbol{B}$ and $\boldsymbol{H}$, magnetisable sphere in uniform field, electromagnets.

Time-varying electromagnetic fields: Faraday's law, emf, electromagnetic induction, Faraday's law for a circuit, interpretation of Faraday's emf, self-inductance, inductance of long solenoid, coaxial cylinders, parallel cylinders, mutual inductance, transformers, magnetic energy density.

Electromagnetic waves: equation of continuity, displacement current, Maxwell's equations, electromagnetic waves, velocity of light, plane waves in isotropic media, energy density, Poynting's theorem, radiation pressure and momentum, insulating materials. Characteristic impedance, reflection and transmission at an angle, total internal reflection; plasmas and the plasma frequency, evanescent waves; conducting media, skin effect. Guided waves, transmission lines, characteristic impedance; coaxial, parallel-wire, strip transmission lines; power flow; terminated lines, matching, reflection and transmission coefficients, impedance of short-circuited lines, impedance matching, introduction to waveguides, TE modes, waveguide equation, cut-off frequency, characteristic impedance.

Summary of Maxwell's equations: Restatement of equations, physical interpretation, classes of solutions, and applications.

Part IB Physics A: Experimental Methods: 2016-17

Prof Chris Haniff

Prerequisites

This course requires the material covered in the IA Physics and IA Maths for Natural Scientists courses, and exploits the ideas of Fourier theory that are more fully developed in the Mathematics options that run in parallel with this course in the Michaelmas term. Ideas of Fourier decomposition will be introduced, along with Fourier series, but they are covered more fully in the Mathematics option.

Learning Outcomes and Assessment

Physics is an empirical subject based on measuring physical phenomena. This course introduces techniques for putting together experiments and analysing their results. Many complex systems, ranging from telescopes to mobile phones, can often be understood in terms of a set of black boxes with simple interactions between them. This systems approach is particularly useful in experimental physics where the signal chain from the physical phenomenon under investigation to a measurement can involve many sequential and complex components such as transducers, amplifiers, filters and detectors.

The first part of this course explores this process – sometimes with reference to some of the experiments undertaken in the practical classes – while the second part introduces you to some of the essential material that a physicist needs to know so as to design experiments (including computational ones), to analyse data, and to evaluate other people's results.

Synopsis

Systems: Impedance and measurement. Operational amplifiers and filters. Positive and negative feedback with ideal and non-ideal amplifiers.

Random errors: examples, propagation, reduction with repeated sampling.

Systematic errors: examples, designs to reduce them (e.g. nulling), selection effects.

Basic data handling: taking and recording data. The right plot; error bars. Sampling, aliasing, Nyquist's criterion. Digitization errors.

Exclusion of unwanted influences: filtering, phase-sensitive detection and lock-in amplifiers. Vibrational, thermal and electrical shielding.

Probability distributions: binomial, Poisson and Gaussian; central limit theorem; shot noise and Johnson noise.

Getting the message across: writing a scientific report and presenting results.

Parameter estimation: likelihood, inference and Bayes' theorem, chi-squared, least-squares, hypothesis testing, non-parametric tests.

BOOKS

There are no books which cover the complete course syllabus, and so each lecture handout will be augmented with a set of supplementary notes. Reading these notes prior to the lectures will be helpful. The following books may be useful to refer to on certain aspects of the course:

The Art of Electronics, Horowitz P & Hill W (2nd edn CUP 1989)

Analogue and Digital Electronics for Engineers, Ahmed H & Spreadbury P J (CUP 1984)

An Introduction to Experimental Physics, Cooke C (CRC Press 1996)

Practical Physics, Squires G L (4th edn CUP 2001)

Experimental Physics: Modern Methods, Dunlap R A (OUP 1988)

Part IB Physics B: Introduction to Computing: 2014-15

Prerequisites

This course in computer programming will take place in Michaelmas. The course will teach the 'C' subset of C++. The course strongly takes the view that best way to learn how to write computer programs is to sit in front of a computer and to "have a go". Programming is a skill that (like learning to play a musical instrument) is best learned through direct experience, through practice, by learning from one's mistakes, by attempting to copy and understand examples etc. It is not a skill that can be absorbed simply by sitting in a lecture theatre and listening to a lecturer.

For this reason, the course will mostly be taught through self-guided study in practical classes in which students will work through examples in the course handout. The self-study part of the course will be preceded by two introductory lectures. The purpose of these lectures is to outline the basics tools required to follow the instructions in the course booklet, and to give a very brief introduction to the concept of computer programming. Students must understand that it is not the lecture course that will teach them how to program. Their most important resources for learning will be the handout, the student sitting next to them in the practical class, the practical class demonstrator, the other students on the course, and last but not least printed and on-line reference materials.

Anyone attempting to teach themselves to program will benefit strongly from having a C++ reference book beside them at all times (see some suggestions below) and an open web-browser in which to look up examples of code, etc.

Students are actively encouraged to discuss what they are doing with others doing the course, to work in pairs or small groups, and to and ask questions of the demonstrators and the people sitting near them in the examples classes.

The general structure of the course will be:

- Two introductory lectures, followed by practical classes in the MCS (formally PWF) in which the students will work through the self-study guide. Each practical session will have a specific programming task. The aim of the first half of the course is for every student to become familiar with linux, gnuplot, a text editor, elementary C++ programming, and a C++ debugger. In the second half of the course, students will each complete *two or three* mini-projects. Each mini-project will consist of a core task which all students will have to complete and optional parts introducing more interesting computational/physics ideas.

Learning Outcomes and Assessment

Assessment

The assessment will be weekly. After each practical session, each student will be required to upload work which shows how they solved the tasks described in the handout for that week. (Work may also be handed in early!) Each submission will lead to a simple pass/fail mark for that week. There are no bonus marks for fancy submissions -- the simpler the submission the better. For each project there will be two deadlines - (i) the recommended deadline, and (ii) the extended deadline. The latter will be one week after the former. All students should hand in work by deadline (i) in order to keep pace with the course, but applications for extension to deadline (ii) will be automatically granted when requested to cover problems caused by illness etc. Any work submitted later than the (already extended!) deadline (ii) will not be accepted therefore under any circumstances.

Synopsis

Week 1

Computing concepts What a C++ program looks like. Conditionals, loops. Monte Carlo methods.

Computing skills Using linux, bash, text editor, C++ compiler, execution.

Week 2

Computing concepts Representation of numbers in a computer. .

Computing skills Boolean expressions. Relational operators. Simple control structures. C++ debugger.

Week 3

Computing concepts Functions. Debugger.

Computing skills Defining, declaring, and calling functions. Passing values to and returning values from functions. Using gnuplot.

Weeks 4-6

Computing concepts Pointers. Memory allocation. Arrays. Passing arrays to functions. Code-testing.

BOOKS

Any web-search or visit to a book-shop or library will rapidly show that there are hundreds of C and C++ books on the market. Any of them is better than nothing, as all contain important reference material an example programs. Use whatever you have in your college library, or anything owned by "someone on your staircase", as any book is better than nothing. If you can really find no other sources, and want guidance, you could do worse than buy one of the following:

Recommended by the 2007 and 2008 lecturer:

C++: A Beginner's Guide, Second Edition (Beginner's Guides (McGraw-Hill)) (http://www.amazon.co.uk/Beginners-Guide-Second-Guides-McGraw-Hill/dp/0072232153/ref=sr_1_3?s=books&ie=UTF8&qid=1282145096&sr=1-3) by Herbert Schildt

The resource the current lecturer learned C++ from:

C++ Primer (http://www.amazon.co.uk/C-Primer-Stanley-B-Lippman/dp/0201721481/ref=sr_1_1?s=books&ie=UTF8&qid=1282145499&sr=1-1) by Stanley B. Lippman, Josée Lajoie, and Barbara E. Moo, (http://www.amazon.co.uk/Sams-Teach-Yourself-One-Hour/dp/0672329417/ref=sr_1_20?s=books&ie=UTF8&qid=1282145361&sr=1-20)

The first and most influential (but not necessarily the best written) book about C++:

The C++ Programming Language, Special Edition (http://www.amazon.co.uk/C-Programming-Language-Special/dp/0201700735/ref=sr_1_5?s=books&ie=UTF8&qid=1282145096&sr=1-5) by Bjarne Stroustrup

Everyone needs pocket reference, and it is only £4 on Amazon:

C++ Pocket Reference (Pocket Referemce) (http://www.amazon.co.uk/C-Pocket-Reference-Referemce/dp/0596004966/ref=sr_1_6?s=books&ie=UTF8&qid=1282145096&sr=1-6) by Kyle Loudon

Likely to be useful:

Accelerated C++: Practical Programming by Example (C++ in Depth Series) (http://www.amazon.co.uk

/Accelerated-Practical-Programming-Example-Depth/dp/020170353X/ref=sr_1_1?s=books&ie=UTF8&qid=1282145096&sr=1-1) by Andrew Koenig and Barbara E. Moo

Sams Teach Yourself C++ in One Hour a Day (http://www.amazon.co.uk/Sams-Teach-Yourself-One-Hour/dp/0672329417/ref=sr_1_20?s=books&ie=UTF8&qid=1282145361&sr=1-20) by Jesse Liberty, Siddhartha Rao, and Bradley L. Jones

Not about C++ per se, and far beyond what the course requires, but worth reading if the rest of the course is too easy and you want to do "real" object-oriented programming:

Design patterns : elements of reusable object-oriented software (http://www.amazon.co.uk/Design-patterns-elements-reusable-object-oriented/dp/0201633612/ref=sr_1_1?s=books&ie=UTF8&qid=1282145891&sr=1-1) by Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides

Website:

The course website for the last academic year may be found at:

http://www.hep.phy.cam.ac.uk/lester/c++2012/ (http://www.hep.phy.cam.ac.uk/lester/c++2012/)

Part IB Physics (A and B): Mathematical Methods: 2014-15

Prof Chris Haniff

Prerequisites

This course is offered to students taking either or both of Physics A and Physics B, but who are *not* taking "Mathematics" in NST IB.

This course requires the material covered in the NST IA Mathematics and Physics for Natural Scientists courses, and uses examples showing how the mathematical methods introduced can be utilised in a wide range of physical problems. Fluency with integration of the tools from NST IA Mathematics with the topics taught in NST IA Physics is required.

Learning Outcomes and Assessment

In conjunction with the material from "Mathematics" in NST IA, this course provides the mathematics required for Physics A and Physics B in NST IB, and the core and option lecture courses in Part II Physics. However, some of the topics required in Part II Physics TP1 and TP2 are *not* covered here.

Synopsis

Vector and Scalar fields in Cartesian coordinates: Basic definitions of scalar and vector fields. Line, surface, and volume integrals. Grad, Div and Curl. ∇ and Laplacian operators. Divergence Theorem, Stokes' Theorem, and Green's Theorem. Conservative fields. Maxwell's equations as example of vector differential operators.

Cylindrical, Spherical, and Curvilinear coordinate systems: Basic definitions of cylindrical and spherical coordinate systems. Application to scalar and vector fields. Curvilinear coordinate systems. Vector differential operators in cylindrical, spherical, and curvilinear coordinate systems.

Variational Principles: Lagrange multipliers. Euler–Lagrange equation.

Fourier Series: Fourier series of periodic functions using trigonometric functions. Discontinuities and Gibbs phenomenon. Even and odd functions. Fourier series in complex form. Solving one-dimensional differential equations using Fourier series. Notions of completeness and orthogonality.

Fourier Transforms: Definition. Symmetry considerations. Fourier transforms of differentials. The Dirac delta function. Convolution. Green's functions. Parseval's theorem.

Differential Equations: Laplace's equation, Poisson's equation, the diffusion equation, the wave equation, Helmholtz equation, Schrödinger's equation. Separation of variables in Cartesian, cylindrical polar, and spherical polar coordinate systems. Summary of common differential equations and orthogonal functions. Examples, including Bessel, Legendre, Hermite functions etc. Analogy between function expansions and geometrical vector expansions: orthogonality and completeness. Convergence of power series. Power series expansions and solution of ordinary differential equations. Legendre polynomials, Bessel functions, Hermite polynomials and Spherical Harmonics illustrated by examples. Brief summary of Sturm–Liouville theory.

Matrices and Tensors: Basic matrix algebra. Determinants. Special matrix types, including Hermitian matrices. Eigenvalues, eigenvectors and diagonalization. Basic concept of a tensor. Summation convention: Kronecker delta and Levi–Civita symbol**.**

BOOKS

Mathematical Methods in the Physical Sciences, Boas M L (3rd edn, Wiley 2006)

Mathematical Methods for Physics and Engineering, Riley K F, Hobson M P and Bence S J (3rd edn, CUP 2006)

Part IB Physics A: Oscillations, Waves & Optics: 2016-17

Dr Tijmen Euser

Prerequisites

The course assumes knowledge of the Part IA Physics and Part IA NST Mathematics courses. In addition, the mathematics of the Fourier Transform, which is taught in the Part IB NST Mathematics, or the Mathematical Methods course, is required.

Learning Outcomes and Assessment

At the end of this course, you should understand the motion of a harmonic oscillator, including both its free response from given starting conditions, and the response when driven at a single frequency. You will understand how to calculate the response to a general driving force using Fourier methods.

You will understand how to derive and solve the wave equation for a range of systems, and understand the general form of solution for non-dispersive waves in one, two and three dimensions. You will understand the concept of wave impedance, and be able to use it to calculate the reflection behaviour when waves encounter boundaries, and how media of different impedance can be matched. You will have an understanding of the properties of sound waves in gases, and on the possible acoustic waves that can propagate in solids. You will understand the effects on wave propagation caused by dispersion, and understand and define the concept of the group velocity for a wavepacket. You will understand the concept of guided waves, and be able to derive the dispersion relation for guided waves in simple cases.

The section on waves will enable you to understand how we can use Huygens' Principle to predict diffraction patterns caused when a wave encounters an obstacle. In particular, you will understand the nature of the diffraction pattern observed at large distances from an aperture and its relation to the Fourier transform, and how the pattern changes when it is observed close to the aperture. You will be able to calculate the far-field (Fraunhofer) diffraction patterns of simple one and two dimensional apertures, and the near-field (Fresnel) diffraction patterns caused by edges, slits and circular apertures. You will understand the imaging properties of a zone plate.

You will understand the processes which control the observed width and shape of spectral line emission, and how spectrometers can be used to measure lineshapes; in particular, you will be able to define and calculate the spectral resolving power of grating spectrometers. You will understand the effects of diffraction on imaging instruments such as microscopes and telescopes, and how they set the angular resolution obtained.

You will also understand the general conditions required for interference patterns to be observed, and be able to compute the interference patterns expected from thin films, and from cavities. You will be able to describe and understand the operation of a Michelson interferometer and a Fabry-Perot etalon, and how they can be used to measure the spectrum of light.

Synopsis

1. **Oscillations:** Driven damped oscillations, frequency response, bandwidth, Q-factor. Impulse response and transient response.
2. **Waves:** Revision of 1 dimensional wave equation. Waves on a stretched string. Polarisation. Wave impedance. Reflection and transmission. Impedance matching. Compression waves in a fluid. Waves in 2 and 3 dimensions. Standing waves in a box. Wave groups, group velocity, dispersion. Waveguides:

cut-off and dispersion relation.

3. **Fourier transforms**: Linear response and superposition in physics. Fourier series and Fourier transforms. Frequency response as Fourier transform of pulse response. Convolution. Applications to oscillating systems.
4. **Optics and diffraction:**
    1. Huygens' principle and solutions to the wave equation.
    2. Fraunhofer diffraction, Fraunhofer integral, relation to Fourier transform. Wide slit as example of extended source.
    3. The width of spectral lines.
    4. Gratings and spectroscopy.
    5. 2-D apertures, circular apertures, Babinet's principle.
    6. Fresnel diffraction: edges and slit diffraction patterns, use of the Cornu spiral. , zone plate.
5. **Interference:**
    1. General conditions for interference
    2. Thin-film interference.
    3. Fabry-Perot etalon.
    4. Michelson interferometer
    5. Fourier transform spectroscopy.

BOOKS

Vibrations and Waves in Physics, Main I G (3rd edn CUP 1993)

The Physics of Vibrations and Waves, Pain H J (5th edn Wiley 1999)

Vibrations and Waves, French A P (Chapman & Hall 1971)

Optics, Hecht E (4th edn Addison-Wesley 2001)

Part IB Physics (A and B): Part IB Practicals: 2014-15

Dr Tijmen Euser, Dr David Buscher

Learning Outcomes and Assessment

The Practical Classes for the IB Physics options (i.e. both the A & B courses) are organized around a set of fourteen experiments, six in the Michaelmas term and eight in the Lent term. Students taking the A, B or both A+B courses undertake different numbers and combinations of these experiments during the year.

Candidates taking a single Physics course will usually undertake a total of either 6 or 7 experiments during the year (3 in the Michaelmas term and either 3 or 4 in the Lent term) attending two 3¾ hour long afternoon sessions (over a fortnight) per experiment. One experiment must be written up as a Head of Class report. (Students taking only Physics A undertake 7 experiments, whereas students taking only Physics B undertake 6 experiments since they also take an assessed computing course.)

Candidates offering both Physics courses are expected to undertake 6 experiments in the Michaelmas term and 5 experiments in the Lent term, but will complete each of these over the course of a week (usually in one day). They also undertake a longer experimental investigation in groups of four, spread over the practical sessions in weeks 6 and 7 of the Lent term. One of the experiments undertaken in the Michaelmas term must be written up as a Head of Class report.

The **primary** aim of the classes is to provide students with an opportunity to develop the key skills associated with the design and execution of experiments, and with analysing experimental data, hypothesis testing, presenting results and, importantly (especially for theoreticians), assessing others' experimental results and analyses. Topics covered include a "systems approach" to experimental design, managing noise, offsets and systematic errors, and using experiments to tie down physical phenomena whose theoretical basis is uncertain or unknown – this is the standard situation for a research physicist. For those taking both the A and B courses, presentational skills and team-working also feature in the extended investigation carried out and assessed at the end of the Lent term.

A **secondary** aim of the classes is to demonstrate aspects of, and reinforce the content of, some of the Michaelmas and Lent term lectures.

The synopses for both Physics A and B practicals outline the full set of 14 experiments available during the year, although students will only ever be expected to undertake a subset of these. Students **must** refer to the table at the end of the Lent Term synopsis to determine which experiments they will be required to undertake.

Synopsis

MICHAELMAS TERM: SYSTEMS AND MEASUREMENT

These experiments demonstrate key aspects of "real world" physics, i.e. as an experimentally-driven subject where measurements both validate theories and provide the stimulus for new theoretical developments. Many of the experiments also demonstrate critical features of the physics introduced in the Physics A Experimental Methods, Oscillations, Waves and Optics, and Electromagnetism lecture courses. Students will usually be expected to work in pairs, with the classes running from week 2 to week 7 of the term.

There are six experiments in total, each lasting about six hours, as follows.

[1] Basic skills: Using a PicoScope; measuring input and output impedances, frequency response and phase shift; ensuring the measuring device does not affect the measurement; using an operational amplifier.

[2] Linear systems and feedback: An operational amplifier is used to explore various linear systems, including voltage amplifiers and integrators. The system concepts of negative and positive feedback are investigated.

[3] Non-linear systems: An analogue multiplier will be used to explore the properties of non-linear systems. Frequency doubling, mixing and de-modulation will be investigated.

[4] Hysteresis: Building a simple magnetometer and investigating hysteresis in three magnetic materials.

[5] Signals and noise in an optical link: An optical communication link is constructed. Phase-sensitive detection is used to extract the signal in the presence a very high level of contaminating noise.

[6] Twangs and clicks (data sampling and Fourier methods): An investigation of sampling, aliasing and Nyquist's theorem, followed by the design, construction and use of apparatus to test the validity of a model developed to explain the properties of a tuning fork.

Part IB Physics A: Quantum Physics: 2014-15

Prof Stafford Withington

Prerequisites

This Course assumes knowledge of the Part IA Physics and Part IA NST Mathematics courses, and certain additional topics taught in the IB Mathematics courses. Topics of primary importance include: Fourier Transforms, discrete and continuous probability theory, complex numbers and functions of complex variables, elementary notions of vector and operator methods including mappings, matrix algebra, inner products, eigenvectors and eigenvalues. A working knowledge of classical linear and angular dynamics is essential, and an appreciation of the mathematical description of elastic and electromagnetic waves in one, two and three dimensions is assumed. A general appreaciation of optics is beneficial. All of these subjects will be covered to the necessary levels in other IB courses.

Learning Outcomes and Assessment

The structure of the course is driven by the following learning outcomes: To appreaciate how classical physics breaks down at microscopic scales. To understand the conceptual foundations of quantum mechanics, and the notion of the state of a system. To gain a working understanding of Schrodinger's equation, and to become practised in using it to analyse the behaviour of a variety of one-dimensional systems having various potential functions: non-classical phenomena will emerge, such quantum-mechanical tunnelling. To appreciate the difference between time-dependent and time-independent quantum mechanics. To understand the meaning of non-commuting observables, and the origin and meaning of Heisenberg's uncertainty principle. To gain fluency in operator algebra, and a wokring knowledge of how it underpins quantum mechanics at a fundamental level. To appreciate the meaning of Dirac's bra-ket notation, to develop the mathematical skills associated with the algebra of linear operators, to understand the conceptual meaning of operator methods, and their use in solving problems. To understand the quantisation of angular momentum, the representation of angular momentum, and to see how it can be used to describe the internal behaviour of the hydrogen atom. To appreaciate the unique role of spin. To start to gain insight into the quantum mechanical description of multiple-particle systems, and to gain an appreciation of the rich physics that inevitably follows. To understand the difference between Fermions and Bosons, and to see how quantum mechanics necessarily leads to remarkable concepts such as entanglment.

Synopsis

The Quantum Revolution: Photoelectric effect. de Broglie Hypothesis. Bohr's atom and atomic structure. Electron diffraction, Davisson and Germer. Compton scattering. Blackbody radiation, u-v catastrophe. The central role of Planck's constant.

Wave-Particle Duality and the Uncertainty Principle: Young's double-slit experiment. Free particle in one dimension: wavefunctions and wave-packets. The Heisenberg Uncertainty Principle. Time evolution of wave-packets: dispersion and propagation.

The Schrödinger Equation: Time-independent and time-dependent Schrödinger Equation.

Wave Mechanics of Unbound Particles: Particle flux. One dimensional potentials and boundary conditions. The potential step: reflection and transmission. The potential barrier: tunnelling. Radioactivity.

Wave Mechanics of Bound Particles: The infinite square well potential and bound states. Normalization, parity and orthogonality. The Correspondence Principle. The finite square well potential. The harmonic oscillator: vibrational specific heat.

Operator Methods: Operators, observables, linear hermitian operators and operator algebra. Dirac notation: eigenstates and eigenvalues. Orthogonality, degeneracy and completeness of eigenstates. Compatible and incompatible observables: commuting operators and simultaneous eigenstates, non-commuting operators, generalized uncertainty relations, minimum-uncertainty states. Ladder operators: the harmonic oscillator, equipartition. Density matrix, pure and mixed states.

Time-Dependent Quantum Mechanics: Time-dependence: expectation values, Ehrenfest's theorem, stationary states, the time-evolution operator, time-energy uncertainty relation, conserved quantities.

Quantum Mechanics in Three Dimensions: General formulation. 3D potential box. Orbital angular momentum: eigenfunctions and parity. The 3D harmonic oscillator. The rigid rotator: rotational specific heats of gases. Central potentials: conservation of angular momentum, quantum numbers, separation of variables. The hydrogen atom. Non-central potentials and hybridization.

Spin: The Stern-Gerlach experiment. Spin angular momentum, spin operators, spin eigenstates. Combining spin and orbital angular momentum, combining spins. Matrix methods. Pauli spin matrix and spinors.

Identical Particles: Identical particle symmetry: multiparticle states, fermions and bosons, exchange operator, exclusion principle, symmetry and interacting particles, counting states. Entanglement. Two-electron system: helium ground and excited states.

BOOKS

Quantum Physics, Gasiorowicz S (Wiley 2003) A fine exposition of the subject, suitable for Part IB and Part II.

Quantum Mechanics, McMurry S M (Addison-Wesley 1994). Quite well suited to the course and includes a disc with interactive illustrative programs.

Quantum Mechanics, Rae A I M (Hilger 1992) A good alternative to Gasiorowicz or McMurry, much shorter and consequently less full in its treatment of difficult points.

Quantum Mechanics Mandl F (Wiley 1992). A good book, suitable for Part IB and Part II.

Introduction to Quantum Mechanics, Bransden and Joachin (Longman, 1989). A thick book, with very full coverage but perhaps less elegance and clarity than Gasiorowicz.

Problems in Quantum Mechanics, Squires (CUP, 1995). Worked solutions and summaries, extending beyond this course.

Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles, Eisberg R and Resnick R (Wiley 1985). Too elementary to recommend as a main textbook, but very good descriptive coverage of a wide range of quantum phenomena.

Part IB Physics B: Thermodynamics: 2014-15

Dr John Ellis

Learning Outcomes and Assessment

This course covers the foundations of classical thermodynamics and gives an introduction to the principles of statistical thermodynamics. In particular it aims to develop a good understanding of the concept of entropy. The kinetic theory of gases (including transport properties), phase transitions and thermal radiation are considered in the light of this foundation.

Synopsis

Fundamentals: Nature and scope of thermodynamics, thermodynamic variables; functions of state; zeroth law; concept of temperature; ideal gases; temperature scales; equations of state; work and heat; exact and inexact differentials; first law; heat capacities; reversible and irreversible changes; isothermal and adiabatic expansions of ideal gases.

Second Law and Entropy: Carnot cycle and Carnot's theorem; Clausius' theorem; entropy and its increase; Clausius and Kelvin formulations of second law; definition of thermodynamic temperature; heat engines, pumps and refrigerators; efficiency.

Analytical Thermodynamics: Thermodynamic potentials, relation to global entropy changes and uses; Maxwell relations and their applications.

Phase Changes: Phase diagram of real gases; van der Waals' equation; conditions for equilibrium; latent heat; Clausius-Clapeyron equation.

Third Law: Entropy at low temperatures; adiabatic demagnetisation; unattainability of absolute zero.

Thermodynamics of Radiation: Black body radiation; pressure and energy density; Kirchhoff's Law; Stefan-Boltzmann Law; Planck's Law.

Foundations of Statistical Thermodynamics: Concepts and definitions: basic postulates of statistical mechanics, macro-states and micro-states; statistical definitions of temperature and entropy; derivation of the Boltzmann distribution; equipartition theorem; the canonical ensemble; Gibbs Entropy; the partition function and its relation to other thermodymanic variables.

Kinetic Gas theory: Maxwell-Boltzmann distribution; flux; barometric height distribution; degrees of freedom and heat capacity; transport properties

BOOKS

The course will mainly follow the book "Concepts in Thermal Physics" S.J. Blundell & K.M. Blundell (Oxford University Press).

For further reading:

"Equilibrium Thermodynamics" Adkins C J (3rd edn CUP 1983).

"Thermodynamics and an Introduction to Thermostatistics" H. P. Callen (John Wiley & Sons 1985).

Part II: Advanced Quantum Physics: 2017-18

Dr Richard Batley

Prerequisites

The Part II Advanced Quantum Physics course assumes knowledge of the Part IB NST Physics A and Physics B courses, especially the Quantum Physics course, and, to a lesser extent, the Dynamics and Electromagnetism courses.

Learning Outcomes and Assessment

The use of approximate methods in the analysis of quantum systems will be introduced, especially variational approaches and perturbation theory. These methods will be used to understand important features of atomic and molecular structure, to estimate the influence of external electric or magnetic fields on atomic energy levels, and to compute atomic transition rates and scattering cross sections. The importance of symmetries, especially rotational symmetry and identical particle symmetry, in quantum systems will be emphasised. Quantum field theory will be briefly introduced, in the context of photons in a quantised electromagnetic field.

Synopsis

Review of Quantum Physics: Postulates of quantum mechanics, operator methods, time-dependence. Solutions to the Schrödinger equation in one and three dimensions. Angular momentum and spin; matrix representations. Addition of angular momenta, Clebsch-Gordan coefficients.

Approximate Methods: Time-independent perturbation theory, first and second order expansion; Degenerate perturbation theory. Variational method: ground state energy and eigenfunctions.

Motion of charged particle in electromagnetic field: gauge invariance; Aharonov-Bohm effect. Particle magnetic moments; Stern-Gerlach experiment. Landau levels; the Quantum Hall Effect.

Symmetries: Translations and rotations, parity. Conservation laws. The Wigner-Eckart theorem for scalar and vector operators. Selection rules. Land\'e projection formula.

Identical particles: Particle indistinguishability and quantum statistics; free particle systems; effects of interactions.

Atomic and molecular structure: Hydrogen atom; fine structure: relativistic corrections; spin-orbit coupling; hyperfine structure. Multi-electron atoms: LS coupling; Hund's rules; Stark effect, Zeeman effect. Born-Oppenheimer approximation; H2+ ion; molecular orbitals; H2 molecule; ionic and covalent bonding.

Time-dependent perturbation theory: Two-level system, Rabi oscillations, magnetic resonance. Perturbation series, Fermi's Golden rule. Scattering and the Born approximation.

Elements of quantum field theory: Quantization of the electromagnetic field, photons; number states. Radiative transitions, dipole approximation, selection rules, spontaneous emission and absorption, stimulated emission, Einstein's A and B coefficients; Cavity rate equations and lasers, coherent states, non-classical light.

BOOKS

Quantum Physics, Gasiorowicz S (2nd edition, Wiley, 1996; 3rd edition, Wiley, 2003)

Quantum Mechanics, Commins E D (CUP, 2014)

Quantum Mechanics, Bransden B H and Joachain C J (2nd edition, Pearson, 2000)

Physics of Atoms and Molecules, Bransden B H and Joachain C J (2nd edition, Pearson, 2003)

The Principles of Quantum Mechanics Shankar R (2nd edition, Springer, 1994)

Problems in Quantum Mechanics, Squires G L (CUP, 1995)

Part II: Astrophysical Fluids: 2016-17

Dr Debora Sijacki

Synopsis

Fluids are ubiquitous in the Universe on all scales. As well as obvious fluids (e.g. the gas that is in stars or clouds in the interstellar medium) a variety of other systems are amenable to a fluid dynamical description - including the dust that makes up the rings of Saturn and even the orbits of stars in the galactic potential. Although some of the techniques of conventional (terrestrial) fluid dynamics are relevant to astrophysical fluids, there are some important differences: astronomical objects are often self-gravitating or else may be accelerated by powerful gravitational fields to highly supersonic velocities. In the latter case, the flows are highly compressible and strong shock fronts are often observed (for example, the spiral shocks that are so prominent in the gas of galaxies like the Milky Way).

In this course, we consider a wide range of topical issues in astronomy, such as the propagation of supernova shock waves through the interstellar medium, the internal structure of stars and the variety of instabilities that affect interstellar/intergalactic gas. These include, perhaps most importantly, the Jeans instability whose action is responsible for the formation of every star and galaxy in the Universe. We also deal with exotic astronomical environments, such as white dwarfs and neutron stars (supported by electron and neutron degeneracy pressure respectively) as well as the orbiting discs of gas and dust which feed black holes.

On completion of the module students should:

- understand and learn to manipulate fluid dynamical equations in both Eulerian and Lagrangian form;
- be able to set up and solve simple hydrostatic equilibrium situations in spherical and disc geometries;
- be able to perform simple linear stability analyses and apply to wave propagation in hydrodynamical and magnetohydrodynamical systems;
- apply Bernoulli's theorem to astrophysical applications;
- understand the concept of shocks and their application to astrophysical blast waves;
- understand the role of viscosity in accretion discs.

Introduction. The concept of a fluid. Collisional and collisionless fluids. Kinematics. Conservation of mass. Pressure. (Inviscid) momentum equation for a fluid under gravity. Stress tensor and the concept of ram pressure. [2]

Basic concepts of gravity. Poisson's equation. Gravitational potential. The Virial Theorem. [2]

Equation of state. Barotropic relation between pressure and density. Energy equation. Hydrostatic equilibrium. Examples: hydrostatic atmosphere under uniform gravity; self-gravitating isothermal slab; self-gravitating polytropes as simple models of stars, mass-radius relation. [3]

Sound waves. Sound speed: adiabatic and isothermal case. Sound waves in a stratified atmosphere. [2]

Supersonic flows. Rankine-Hugoniot conditions for adiabatic and isothermal shocks. Application to blast waves and supernova remnants. [4]

Bernoulli's equation and its applicability. De Laval nozzle and its relevance to astrophysical jets. Bondi accretion, stellar winds and mass loss. [3]

Fluid instabilities. Convective instability, Schwarzschild criterion. Jeans instability. Rayleigh-Taylor and Kelvin-Helmholtz instability. Thermal instability, Field criterion. [3]

Viscous flows. Linear shear flow. Navier-Stokes equation. Vorticity and energy dissipation in viscous flows. Accretion discs. Steady thin discs. [4]

Magnetohydrodynamics. The ideal MHD equations. Alfven waves. [1]

RECOMMENDED BOOKS

Principles of Astrophysical Fluid Dynamics, Clarke, C.J. & Carswell, R.F. (Cambridge University Press 2014)
Fluid Mechanics, Landau & Lifshitz (Pergamon Press 1987)

FURTHER SUGGESTIONS

Elementary Fluid Dynamics, Acheson, D (Oxford University Press 1994)

An Introduction to Fluid Dynamics, Batchelor, G K (CUP 1991)

Hydrodynamics, Lamb, H (CUP 6th edn 1932, reprinted 1993)

An informal introduction to theoretical Fluid Mechanics Lighthill, M J (Oxford University Press 1993)

Part II: Computational Physics: 2017-18

Dr David Buscher

Prerequisites

This course builds on the IB course 'Introduction to Computing', and aims to develop further the computational physics skills acquired in that course. It also caters for those who have not done the IB course but do have a basic knowledge of Python or C++ programming.

Learning Outcomes and Assessment

The course consists of **eight lectures** in the first four weeks of Lent term, and **four 3-hour practical classes** in the MCS during weeks 4, 5, 6 and 7 of the Lent term.

The lectures will survey a range computational techniques used in physics and use this to illuminate the core concepts motivating the development of these techniques, such as numerical accuracy, stability and computational efficiency. The aim is to develop the skills needed to select and use appropriate algorithms from broad-ranging numerical libraries rather than to provide a detailed understanding of a small number of specific algorithms.

Students will be expected to be familiar with how to write and run programs, but advice will be given on techniques for developing high-quality software.

In the practical classes, students will solve a series of computational physics problems. Examples in the lectures will mostly use the Python language (which is easily learned by students who have used another programming language), but students can submit solutions in either Python or C++.

The focus is on self-learning, and learning by doing: the lectures are important, but it is only in the practical classes that real skills are developed. Demonstrators will be on hand in the MCS to assist with problems.

This course also covers the material required for students planning to offer an (optional) Computing Project (see separate synopsis for full description).

Assessment

The credit for this course is approximately equal to one fifth of a unit of further work. During each of the practical sessions, a computational physics problem is to be solved by writing, running and testing a piece of software. When complete and tested, students will upload their solutions for checking to a dedicated file space for marking. The expectation is that students will gain high marks if they complete the exercises satisfactorily.

Synopsis

The computational physics topics covered will include:

Representation of numbers; roundoff error.

Solution of Ordinary Differential Equations; accuracy and stability.

The Fast Fourier Transform;

Fitting models to data. Linear algebra and Deep Learning.

Pseudo Random Numbers; Monte-Carlo techniques.

Part II: Computing practical work (2): 2016-17

Dr David Buscher

Prerequisites

The course assumes attendance of the accompanying lectures on Computational Physics.

Learning Outcomes and Assessment

Students work through a series of 3 computational physics problems - see the lecture course and the class manual for more detail.

The deadline for hand-in is the last day of full term, **Friday 16th March 2018 at 16:00.**

Part II: Computing Project: 2016-17

Dr David Buscher

Synopsis

A Computational Physics Project constitutes one unit of further work and may be offered, optionally, by all Part II Physics students. There are no lectures or practical classes, but the compulsory course in Computational Physics provides the essential background for this work. Students chose one of a range of problems to investigate independently, using MCS (formally PWF) facilities or other equivalent facilities if they prefer. They will analyse the problem, write and test computer program to investigate and solve it, then write up their work in a report. It is required that the programs will be written in C++ or Python running under Linux. However, if a student wishes to use other supporting languages (e.g. Java, or a scripting language like Python), this may be acceptable given prior consent from the Head of Class.

Students may start their project work at any time in the Lent term. The deadline for submission of the project report is **4:00pm on the first Monday of Easter term (30th April 2018)**.

One copy of the report should be handed in to the **Undergraduate Office** (Room 212B, Bragg Building) in person before the submission deadline. In order to preserve anonymity when your report is looked at by the Part II examiners, **your name must not appear on the report itself, but only on the cover sheet which you will be given when you hand it in.** You should ensure that your candidate number appears on the first page of the report, **together with the title of the report.**

In addition, you should also upload, by the same deadline, your report **in PDF format** to the electronic course pigeon holes on the Physics MCS, along with the **source code, program executable (where relevant),** and possibly other relevant files you have created for the project (e.g. Makefiles, large graphic files, videos, etc).

The form of solution expected, and of the write up, will be described in more detail in the handout which contains the suggested projects. It will be marked by one of the Heads of Class, acting as Assessor for the Examiners. After the examination, you will receive a copy of the mark sheet, which will provide feedback on your performance. **The marks allocated by the Head of Class are subject to moderation and scaling by the examiners, so the mark you receive may not match the final mark for this piece of work in the College Markbook.**

Candidates may be selected for viva voce examination after submission, as a matter of routine, and therefore a summons to a viva should not be taken to indicate that there is anything amiss. You will be asked some straightforward questions on your project work, and may be asked to elaborate on the extent of discussions you may have had with other students. So long as you can demonstrate that your write-ups are indeed your own, your answers will not alter your project grades.

Part II: Concepts in Physics: 2016-17

Prof Malcolm Longair

Learning Outcomes and Assessment

This course is not examinable, but the material covered overlaps with and illustrates many aspects of the Part II syllabus. It aims to consolidate core physics and provide revision of a number of key topics from a somewhat different perspective to that presented in the core course. The aim is to provide additional background to a number of major themes of physics, to sketch the connections between them and to investigate unresolved questions. Attendance is strongly advised for all Part II students. The lectures are likely to cover at least some of the following:

Synopsis

Scaling Laws in Physics and Elsewhere: Dimensional analysis and the Buckingham P theorem, general pendulum, explosions, drag in fluids, flow past a sphere, Kolmogorov spectrum of turbulence, law of corresponding states.

Chaos: Discovery of chaotic behaviour. Necessary conditions for chaos. Damped driven non-linear pendulum, phase space diagrams, Poincare sections, bifurcation diagrams, Lorenz attractor. Logistic map, limit cycles, period doubling, Hyperion.

More on non-linear behaviour: Self-organised criticality, examples of scaling laws, fractals, sand piles.

Order, broken symmetry and phase transitions: the development of long-range order as a broken symmetry; why phase transitions are abrupt; scaling laws and critical phenomena.

The Galileo Case: Ptolemy, Copernicus, Tycho Brahe, Kepler and the Galilean revolution. The origins of experimental science, Galileo's physics, what Galileo got right and what he got wrong. The trial of Galileo. Physics as a hypothetical-deductive system. Galilean relativity, the Newtonian revolution.

Thermodynamics and Statistical Mechanics: The nature of heat, caloric theories, real steam engines and the genius of Carnot, caloric as entropy, the statistical nature of the Second Law, the origin of irreversibility.

Atoms get real - the kinetic theory:

Tracing the history of atoms from Boyle to the 19th century.

The Origin of Quantum Mechanics: The discovery of quanta. Classical derivation of the Stefan-Boltzmann law. Planck's (non)-statistical mechanics, how Einstein discovered photons.

The Origin of Maxwell's Equations: Origins of electromagnetism, Maxwell and analogy in physics, vortices and magnetic fields, a physical model for the aether, the origin of the displacement current, a paper which is 'great guns' - light as electromagnetic waves. Hertz and the properties of electromagnetic waves. The discovery of the photoelectric effect.

Relativity: The real story of the discovery of the Special Theory of Relativity, the difficult route to the General Theory, Mach's principle, tests of General Relativity, unresolved issues

Physics of the Cosmos: The technology of cosmology. Application of laboratory physics to the Universe on the largest scales: its successes, the origin of the Cosmic Microwave Background Radiation.

BOOKS

The following books may be useful as background reading to help your understanding:

Theoretical Concepts in Physics, Longair M S (2nd edn 2003)

The New Physics, Davies P C W (CUP 1989)

The Galileo Affair, Finocchiaro M A (U Calif Press 1989)

Inward Bound: Of Matter and Forces in the Physical World, Pais A (OUP 1986)

Subtle is the Lord. The Science and Life of Albert Einstein, Pais A (OUP 1982)

Scaling, Self-similarity, and Intermediate Asymptotics, Barenblatt G I (CUP 1996)

Does God Play Dice? Stewart I (2nd edn Penguin 1997)

Chaos: Making a New Science, Gleick J (Viking NY 1987)

Chaotic Dynamics - an Introduction, Baker G L and Gollub J P (CUP 1990)

Part II: Electrodynamics and Optics: 2015-16

Prof Henning Sirringhaus

Prerequisites

Note that the later parts of this course depends on material from the Part II “Relativity” course, which runs in parallel with this in the Michaelmas Term.

Learning Outcomes and Assessment

By the end of this course, you will be familiar with the theory of classical and relativistic electrodynamics and be able to apply it to understand a very broad range of phenomena in classical optics, radiation and antenna physics as well as modern relativistic electrodynamic phenomena occurring in high energy particle acceperators. You will understand how the electrodynamic theory described by Maxwell's equations is inherently consistent with the theory of special relativity. Electrodynamics is one of the most important theories in physics on which many of the more modern and advanced theories that you will encounter later in Part II and III, such as quantum electrodynamics and general quantum field theories, will build. Although the basic theory was formulated more than 100 years ago it is a surprisingly modern topic with many applications in modern physics research in fields ranging from nanophotonics to stellar interferometry.

Synopsis

Electromagnetic Waves and Optics: Revision of Maxwell’s equations. Light as an EM wave. Polarization and partial polarization. Light in media; anisotropic media; polarizers and waveplates; optical activity; Faraday rotation. Jones matrices. Metamaterials and photonic structures. Temporal and spatial coherence.

Electrodynamics: Vector potential ***A***. Calculation of ***A*** in simple cases; Aharonov-Bohm effect; Maxwell’s equations in terms of ***A*** and f; choice of gauge. Wave equations for ***A*** and f; and general solution; retarded potentials.

Radiation: Time-varying fields and radiation. Hertzian dipole; power radiated including angular distribution; magnetic dipoles. Properties of antennas: effective area; radiation resistance; power-pattern. Antenna arrays. Scattering: cross-section; Thomson and Rayleigh scattering; denser media and the structure factor.

Relativistic Electrodynamics: Charges and currents; 4-current; 4-potential; transformation of ***E*** and ***B***; covariance of Maxwell’s equations; invariants of the EM field; energy and momentum of the EM field; magnetism as a relativistic effect.

Radiation and relativistic electrodynamics: fields of a uniformly moving charge; Čerenkov radiation; accelerated charges; Larmor and Liénard formulæ; cyclotron and synchrotron radiation; Bremsstrahlung.

BOOKS

Optics, Hecht E (4th edn Addison Wesley 2002)

Optical Physics, Lipson S G, Lipson H & Tannhauser D S (3rd edn CUP1995)

Electromagnetic Fields and Waves, Lorrain P & Corson D R (3rd edn Freeman 1998)

Classical Electrodynamics, Jackson J D (3rd edn Wiley 1998)

Part II: Experimental Physics: 2017-18

Prof Pietro Cicuta

Synopsis

Waveguide – *Dr Richard Saunders*

Part II Laboratory, Room 170 (5 spaces)

Waveguide propagation of a cm wavelength radio wave is investigated

The aims of the experiment are:

i) to verify the waveguide propagation formula at frequencies both above and below cutoff;

ii) to use standing-wave measurements to determine the impedance of a reactive probe;

iii) to use the probe to match an arbitrary impedance (resistive sheet) at the end of the guide.

A solid-state Gunn oscillator provides a tunable signal in the range 8-11 GHz. Measurements of the standing-wave are made by means of a (high-impedance) probe in a slotted section of guide. For part (iii) a Smith chart is used to predict the variation of (normalised) impedance along the guide and to verify the correct conditions for matching. (The Smith chart is a convenient, conformally-transformed, plot of the variation of complex impedance with distance along a waveguide – or transmission line.)

Phase-Locked Loops - *Dr Andrew Irvine*

Part II Laboratory, Room 168 (5 spaces)

Operation and optimisation of phase-locked loops is investigated, for frequency locking and for recovery of signals buried in noise, and elements of programming-based computer control and data acquisition are introduced.

The experiment is based around the 4046 CMOS integrated circuit; this is designed for phase-locked loop applications and can be operated in two different modes, depending on the type of (integral) phase comparator which is used. The object of the experiment is to investigate the behaviour of the device in a variety of different applications, using each of the available comparators.

The project involves constructing automated control and measurement systems using the graphical LabVIEW programming environment. Control voltages are applied using an Arduino microcontroller (or otherwise) and experimental parameters are measured using a LabVIEW-linked PicoScope. Investigators will:

• Characterise the properties of the two comparator circuits and of the on-board oscillator using an Arduino as a phase-shifting pulse generator and voltage source.

• Measure the stability and locking/capture ranges of the closed-loop system, using the appropriate degree of automation.

• Assemble and investigate the behaviour of the phase-locked loop in some typical applications – as a frequency multiplier, a demodulator of frequency-modulated signals as a clock regenerator for an irregular train of pulses.

An ability to assemble working circuits and a basic understanding of electronics are helpful assets when doing the experiment. Very basic coding experience will help, though this is not a programming project and will be perfectly accessible to non-experts.

Optical Pumping of Rb - ***Prof. Mete Atature***

Part II Laboratory, Room 169 (3 spaces)

The Zeeman effect in the ground state of the rubidium atom is studied,

nuclear spins of 85Rb and 87Rb are obtained and multi-photon absorption

and power broadening are investigated

The objectives of the experiment are:

i) to study the Zeeman effect in the ground state of both isotopes of the rubidium atom

ii) to obtain the nuclear spins of 85Rb and 87Rb

iii) to make accurate measurements of the ground state Landé splitting factors, g

iv) to investigate (a) multiphoton absorption and (b) power broadening.

The Rb sample is contained in a small spherical cell and coils provide a B-field which both cancels the earth's field and produces the Zeeman splitting. Optical pumping by a separate Rb lamp is using to produce a non-equilibrium population of levels in the Rb atoms in the cell. Changes in the absorption of the Rb line can then be produced, and detected, resulting from the application of an exciting RF field at a frequency corresponding to the Zeeman splitting.

The experiment will certainly enhance your understanding of atomic physics!

Semiconductor Quantum Devices - ***Prof. David Ritchie***

Part II Laboratory, Room 170 (5 spaces)

The resonant tunnelling of electrons in semiconductors is investigated at both room temperature and 77K.

The experiment involves measurements of a Resonant Tunnelling Diode (RTD), samples of which are manufactured in the Cavendish. The device acts as a double quantum barrier, the properties of which are an extension of those of the single barrier (met in IB Quantum) and the Fabry-Perot interferometer (IB Optics).

The experiment is designed to be 'open-ended' based on measurements of the current/voltage characteristic of the device at both room temperature and 77 K (liquid N2). The results are compared with the relevant theory.

Mobility of Carriers in Semiconductors - ***Prof. Henning Sirringhaus***

Pt II Laboratory, Room 173 (5 spaces)

Propagation of carriers through a semiconductor is measured by a direct method

The purpose of the experiment is to investigate experimentally fundamental transport processes in semiconductors, including drift, diffusion, recombination as well as injection from metal contacts. A pulse of minority carriers is injected at one end of a bar of germanium. By measuring the arrival time and the shape of the current pulse at the other end of the bar direct information about the charge transport processes in the semiconductor is obtained.

The measurements required include:

i) Measurement of the mobility of Ge and its temperature dependence

ii) Estimate of the minority carrier lifetime in Ge

iii) Verification of the Einstein relation between mobility and diffusion coefficient

iii) Determination of the current/voltage characteristic of the rectifying injecting point contact.

Ferro-fluids – *Dr Lorenzo Di Michele*

Part II Laboratory, Room 173 (5 spaces)

An investigation is made of instabilities and pattern formations at Ferro-fluid interfaces

A ferrofluid consists of a colloidal suspension of very small ferromagnetic particles in a fluid medium. This behaves like a paramagnetic medium with very high paramagnetic susceptibility.

When a drop of the ferro-fluid is placed in an external magnetic field, its induced polaristion sets up a 'demagnetising' field. However the magnitude of this field depends on the shape of the drop and, since it can change its shape, the overall system is non-linear, exhibiting many of the characteristics of such systems. The behaviour of a drop of the ferro-fluid, placed between two closely-spaced glass plates, is studied for different applied fields using both a telescope and a video-camera which can capture digital images for computer analysis.

One or two specific sets of measurements are suggested, but the experiment is relatively 'open-ended' and many other tests could be done. The results are related to basic considerations of the magnetic energy, and hence stability, of the system.

[As with any non-linear system, a precise numerical analysis is quite complicated and not required!]

Dynamics in Complex Fluids - ***Prof*. *Pietro Cicuta***

Part II Laboratory, Room 173 (4 spaces)

This experiment has two aims (a) to understand the stochastic motion of passive and driven micron-sized objects, suspended in solution of both Newtonian and viscoelastic fluids; (b) use a fairly new and very powerful method of processing time-lapse video data, called Differential Dynamic Microscopy (DDM).

Brownian motion should be a familiar concept: thermal fluctuations drive the random motion of all molecules and particles in a fluid, and if a small tracer is suspended it will be seen to move diffusively. The mean square displacement grows linearly with time, and the coefficient is well known. This can be used to measure the properties of the suspended particles (e.g. particle size, if the fluid is characterised), or viceversa to learn about the fluid (viscosity) if the particles are well known. Very different is the situation of a driven particle: at low Reynolds number, a micron sized particle subject to a constant force quickly reaches a steady velocity, so its mean square displacement grows with the square of time. A different power law. A qualitative change can also be seen if particles are suspended in fluids that have some elastic character as well as viscous dissipation: in this case the motion is sub-diffusive, and the mean-square displacement versus time can often again be approximated by a power law, with exponent less than one. All these cases will be measured during the experiment. The first week will be quite prescriptive, on Newtonian fluids; week 2 will be open to personal investigations. Some theory can also be derived and deployed to match the data.

The experimental setup is made of very simple equipment (in our prototypes we used spare bits...), and the components of the experiment do not have stringent technical constraints, there is no alignment. High frame rate video is recorded on the computer. The DDM analysis consists of a series of spatial Fourier transforms, applied on every pair of image separated by a give time lag. The growth (as a function of the lag time) of the amplitudes of these Fourier modes contains all the dynamics in the movie, resolved (because of the spatial FT) by lengthscale. So from one movie, one can get characteristic dynamical times for every process at every lengthscale. This is incredibly powerful, and in contrast to many other image analysis methods does not require any user input (no filter parameters, etc).

Measurement of e/h using the Josephson Effect – *Dr Michael Sutherland*

Part II Laboratory, Room 186 (4 spaces)

The ratio of e/h is measured by studying the I-V characteristic of a Josephson junction immersed in liquid helium.

Measurements are made of the current/voltage characteristic of a Niobium Josephson junction in a liquid helium cryostat, both with and without an applied microwave voltage.

The junction is made using a sharpened oxidised niobium wire, which you have previously produced, contacting a niobium plate.

The experiment provides a good introduction to cryogenic techniques and involves a direct measurement of macroscopic quantum effects which can be compared with theory. It is the basis of a voltage standard used in many standards laboratories throughout the world.

Pulsed NMR at 15 MHz – *Dr Sian Dutton*

Part II Laboratory, Room 170 (8 spaces)

This experiment investigates and demonstrates the principles of Nuclear Magnetic Resonance (NMR). Spin-echo methods are employed to study the characteristic NMR properties of a number of samples.

Particle Tracks - *Dr Susan Haines*

Bragg Building, Room 178 (5 spaces)

Properties of short-lived hyperons are measured by analysing photographs from a liquid hydrogen bubble chamber

The experiment is based around measurements of film taken from bubble chamber experiments at the CERN particle physics laboratory near Geneva. While this technique is no longer current, it provides an immediate visual, introduction to the subject.

Measurements are made of:

(i) K+ decay modes;

(ii) K- + p interactions.

For (ii), measurements of the decay of product S+ and S hyperons are made using the projected length of the hyperon track and the curvature of the track of the recoil pion and, in the case of the S+ hyperon the decay mode (via proton or neutron) is noted. The decays of neutral (.o / S o) hyperons produced in (ii) are also studied.

Quantities which you are asked to measure include:

(i) the masses and mean lives of S+ and S hyperons

(ii) the branching ratios for the decays S+ . p po and S+ . n p+

(iii) the mass and mean life of the .o hyperon.

Scanning Tunnelling Microscopy - *Dr Andy Jardine*

Pt IB Laboratory, Room 166 (4 spaces)

The growth kinetics of graphite oxidation pits are investigated on atomic length scales

The Scanning Tunnelling Microscope (STM) is an important tool in current research as it is capable of mapping surfaces on an atomic scale. Its operation makes use of the tunnelling current of electrons between an atomically sharp tip and a surface placed a very short distance (~10 Å) away.

The instrument is interfaced to, and controlled by, a computer which also produces the images.

In this experiment, the STM is used to examine the surface of a graphite crystal. Measurements are made on different scales in order to become familiar with, and illustrate the potential of, the instrument. The STM is then used to investigate the nucleation and growth of oxidation pits on the surface of the graphite.

Coherence and information in a fibre interferometer - *Dr Tijmen Euser*

Part II Laboratory, Room 167 (4 spaces)

In this practical we consider a Mach Zehnder (MZ) interferometer and some quantum-mechanical implications. The pattern observed behind an MZ interferometer shows interference fringes, provided there is no way to determine which arm a photon has passed. Here we will place an optical amplifier along one of the MZ arms. The amplifier increases via stimulated emission the intensity of laser pulses. When coherent photon pulses from a laser pass the arm, they stimulate the emission of identical, coherent photons by the atoms of the amplifier medium.

What is the outcome of this experiment: Does the amplification localize the photons in one arm and is the interference therefore suppressed? Or does the process of stimulated emission not constrain the position of the incoming photons, so that the interference pattern is preserved and even amplified through the contribution of the stimulated emissions?

The aim of the practical is to perform the measurements and to explain the results. Some of the intermediate objectives are:

(i) To build a Mach-Zehnder interferometer and to characterize the interference patterns obtained for different light sources.
(ii) To study optical amplification and to understand how the gain and noise of an amplifier are determined by stimulated and spontaneous emission processes.
(iii) To place an optical amplifier in one arm of a Mach-Zehnder interferometer and to explain the results.

Experiments run in three sessions during Michaelmas (E1a/E1b/E1c) and three during Lent (E2a/E2b/E2c). Efforts are made to give students maximum choice and flexibility although it is not always feasible to run all the experiments.

Submission of your report

One copy of your report should be handed in to the **Undergraduate Office** (Room 212B, Bragg Building) in person before the submission deadline. In order to preserve anonymity when your report is looked at by the Part II examiners, **your name must not appear on the report itself, but only on the cover sheet which you will be given when you hand it in.** You should ensure that your candidate number, if known, appears on the first page of the report, **together with the name of the experiment and the name of your Head of Class.**

Late Submission of Coursework

The Department of Physics expects students to meet the advertised deadlines for the submission of all coursework, to ensure fairness to all students taking the course and allow prompt marking by the Department.

In accordance with the University's regulations, **work submitted after the advertised deadline will not count towards your final examination mark, unless the Department grants an extension of time on the grounds that there are significant mitigating circumstances.**

Any application for such an extension should be made by your college Tutor and Director of Studies to the Director of Undergraduate Teaching, c/o Undergraduate Office, (undergraduate-office@phy.cam.ac.uk). Students must complete the form available from the teaching webpages, including supporting cases from Tutor and Director of Studies.

In such circumstances, you should submit the work as soon as possible after the deadline.

Before the end of the relevant term, the report will be assessed by the Head of Class, who will then conduct a viva voce examination (typically 30 minutes long). The student will be asked to give a short verbal summary (typically 10 minutes), normally uninterrupted, of the report during the examination. Students should expect to be contacted by the Head of Class shortly after the submission of their report, to arrange the examination.

These Head of Class will write a report to the Part II Examiners and will recommend a mark. These marks are not necessarily final and may be amended by the examiners, who will also look at the report and the Head of Class’s written assessments. After the viva, you will receive a copy of the mark sheet, which will provide feedback on your performance. **The marks allocated by the Head of Class are subject to moderation and scaling by the examiners, so the mark you receive may not match the final mark for this piece of work in the College Markbook.**

The following guidelines for allocation of marks to Part II experimental reports will be given to the Head of Class.

- Understanding: (30%): of the physical system being measured, and of the experimental design.
- The experiment (40%): how well the work was done, quality of results, discussion of errors.
- Communications skills 1 - Report (20%): Was the report well written and clearly organised, with clear and well balanced arguments, appropriate use of figures, tables and references.
- Communications skills 2 - Viva (10%): Was the student able to summarise the work and respond coherently to questions?

After the viva, the Head of Class will send the report and recommended mark to the Undergraduate Office. After publication of the Part II Class List, students may, if they wish, retrieve their report from the Undergraduate Office.

If there are any queries concerning these arrangements, contact, Helen Marshall in the Undergraduate Office (undergraduate-office@phy.cam.ac.uk).

Part II: Particle and Nuclear Physics: 2016-17

Dr Tina Potter

Prerequisites

This course assumes familiarity with many of the topics in the "Advanced Quantum Physics" course.

Learning Outcomes and Assessment

At the end of the course, the students should be familiar with the following features of Particle Physics:

- how forces arise from virtual particle exchange (in outline only);
- the particle content and interactions of The Standard Model, together with an understanding of how to apply (spinless) Feynman Diagrams to make order-of-magnitude estimates for rates and signatures of allowed/disallowed Standard Model processes;
- the types of evidence upon which the three key parts of The Standard Model (i.e. electromagnetic, strong and weak), are founded;
- how to determine which hadron decays would or would not be consistent with the quark content of the Standard Model, with parity violation/conservation, with energy-momentum conservation, etc.

and with the following aspects of Nuclear Physics:

- the structure of nuclei, and simple nuclear models such as the liquid drop model and the shell model;
- techniques in scattering theory which are relevant in nuclear physics -- partial waves, Born approximation and compound nucleus formation;
- the main types of nuclear decays, and with models for calculating these and the associated selection rules;
- the key features of nuclear fission and fusion and their applications;

Synopsis

INTRODUCTION

Matter and Forces: Matter and generations. Leptons, quarks, hadrons and nuclei. Forces and gauge bosons.

Kinematics, Decays and Reactions: Natural units. Relativistic kinematics (Four-vectors, invariant mass, colliders and sqrt(s). Particle properties (mass, spin parity, decays, scattering). Particle decays and transition rates. Resonances and partial decay widths. Reactions and cross sections. Scattering.

PARTICLE PHYSICS

The Standard Model: Summary of the Standard Model of particle physics. Theoretical framework. Klein-Gordon and Dirac equations. Antimatter. Interaction via particle exchange. Yukawa potential. Virtual particles. Feynman diagrams. Colliders and detectors

Electromagnetic Interaction: QED. Gauge invariance. Electromagnetic interaction vertices. Scattering in QED. Discovery of quarks. Drell-Yan process. Experimental tests of QED. Higher orders and running of α.

Strong interaction: QCD. Strong interaction vertices. Gluons, colour and self-interactions, colour factors. QCD potential, confinement and jets. Jets. Running of the strong coupling. Scattering in QCD. Experimental evidence for gluons, colour, self-interactions and the running of alpha_s.

Quark Model of Hadrons: Hadron wavefunctions and parity. Light quark mesons and masses. Baryons, baryon masses and magnetic moments. Hadron decays. Discovery of the J/Psi. Charmonium. Charmed Hadrons. Discovery of the ϒ. Bottomonium and bottom hadrons.

Weak Interaction: Bosons and self-interactions. Weak charged current (W+- boson). Parity violation. Weak charged current lepton vertices. μ and τ decay. Lepton universality. Weak charged current interactions of quarks. Cabibbo suppression and the CKM matrix. Weak charged current quark vertices

Electroweak Unification: Neutral currents (Z0 boson). Electroweak Unification and the Glashow-Weinberg-Salam Model. Weak neutral current vertices and couplings. Summary of Standard Model vertices and drawing Feynman diagrams. Precision tests of the Standard Model at the Large Electron Positron collider (LEP). The top quark. The Higgs mechanism and the Higgs boson.

The Standard Model and Beyond: Incompleteness of the Standard Model. Neutrino oscillations. Beyond the Standard Model - supersymmetry.

NUCLEAR PHYSICS

Basic Nuclear Properties: Stable nuclei. Binding energy. Nuclear mass (Semi-Empirical Mass Formula). Spin and parity. Nuclear size. Nuclear moments.

The Nuclear Force: General features. The deuteron. Nucleon-nucleon scattering.

Nuclear Structure: Magic numbers, the Nuclear Shell Model and its predictions, excited states of nuclei (vibrations and rotations).

Nuclear Decay: Radioactivity and dating. α decay. β decay, Fermi theory of β decay. γ decay.

Nuclear Fission and Fusion: Nuclear fission. Reactors. Nuclear fusion. Nucleosynthesis. Solar Neutrinos.

BOOKS

Particle physics books *(Perkins is closest to the course; Thomson or Griffiths are good if you want to go beyond*):

Introduction to High Energy Physics, Perkins D H (4th edn CUP 2000).

Particle Physics, Martin B R & Shaw G (3rd edn Wiley 2008).

Introduction to Elementary Particles, Griffiths D J (2nd edn Wiley 2009).

Modern Particle Physics, Thomson, M A (CUP 2013)

Nuclear physics books *(Krane is closest to the course)*:

Introductory Nuclear Physics, Krane K S (Wiley 1988).

Basic Ideas and Concepts in Nuclear Physics, Heyde K (3rd edn CRC Press 2004).

Fundamentals of Nuclear Physics, Jelley N (CUP 1990).

Introductory books that cover the whole course, *(at a lower level generally):*

Nuclear and Particle Physics, Martin B R (2nd edn Wiley 2009).

The Physics of Nuclei and Particles, Dunlap P A (Thomson Brooks/Cole 2003).

Part II: Physics Education: 2016-17

Dr Lisa Jardine-Wright

Learning Outcomes and Assessment

Physics Education represents one unit of Further Work. It is aimed at those students considering a career in Physics Education, and offers experience of developing and presenting teaching material at the secondary-school level. This course aims to provide practical experience for the development of a wide range of transferable skills including: planning and organisation; time-management; communication and negotiation.

Synopsis

The course will typically be based on planning and preparing for, and successfully completing, a ½ day per week placement at a local school during the Lent Term, including developing and delivering a Special Project, under the supervision of a teacher. The student and their Supervising Teacher will collaborate to identify the basis of the Special Project. The Special Project must support physics education in the placement school and be approved by the Supervising Teacher.

All those interested in undertaking this course must attend a Preliminary Meeting, which will be held at the Cavendish Laboratory between **2-5pm on Friday 6th October 2017, in the Edwards Room, Bragg Building (room 236, near the Pippard LT)** and pass a background check conducted by the Criminal Records Bureau. Access to places on this course is limited and candidates will be selected by interview and reference from their Director of Studies. Interviews will take place on **13th October 2017 in Dr Jardine-Wright's office (room 243 in the Bragg Building near the Pippard LT)** and students will be asked to sign up for times at the preliminary meeting on the 10th. Interviews will be 15 minutes long and may require a short period to be missed from lectures on that day.

Placements will be identified for each student by the end of November 2017. It will be the responsibility of the student to contact their Supervising Teacher to arrange an appropriate date and time to begin their placement, and to make appropriate arrangements to complete a placement totalling 30 hours contact time. All placements must begin before the end of the first week of the Lent Term, and be completed before the end of Lent Term.

Students must write a written report about their work. The written report should be concise (**2000 words maximum**, excluding any appendices) on some area of Physics Education, approved in advance by the Head of Class. The student should discuss the general structure of the report with their Supervising Teacher, and the Head of Class, before writing is started, but the Head of Class should not read a full version of the text until it is submitted. During the preparation for the writing of the report, students will be asked to give a short talk presenting their preliminary work to the Head of Class and a group of students writing similar reports. It is expected that the Head of Class will organise the group session in the last two or three weeks of the Lent term. Students will receive feedback on the content and presentation of their reports from those present. This form of presentation is aimed at developing communication and presentational skills. You will be awarded 5% of the available marks for the written report upon giving the presentation (irrespective of its quality).

Assessment will be based on:

- The candidate’s class presentation (5 %);
- A written assessment of performance from the Supervisory Teacher (5%)
- The candidate’s project delivery, written report and viva-voce examination with the Head of Class and an Assessor (90 %).

The written assessment of performance by the Supervisory Teacher is considered confidential to the Head of Class, and will therefore be sent directly to the Head of Class by the Supervising Teacher: it will not be seen by the student.

The deadline for submission of the written report is **4:00pm on the first Monday of Easter Full Term (30th April 2018)**.

Two copies of the report should be handed in to the **Undergraduate Office** (Room 212B, Bragg Building) in person before the submission deadline. In order to preserve anonymity when your report is looked at by the Part II examiners, **your name must not appear on the report itself, but only on the cover sheet which you will be given when you hand it in.** You should ensure that your candidate number appears on the first page of the report, **together with the title of the report, the name of the Head of Class, and the name of your Supervising Teacher.**

As soon as possible after submission, the report will be assessed by two people, normally the Head of Class and another staff member, who will then conduct the viva voce examination (typically 30 minutes long) to be given by the student. The student will be asked to give a short verbal summary (typically 10 minutes), normally uninterrupted, of the report during the examination. The assessor, who will be appointed by the Teaching Committee, will generally not be a specialist in the field. Students should expect to be contacted by the Head of Class shortly after the submission of their report, to arrange the examination. These assessors will also be given a copy of the Supervising Teacher's written assessment.

These assessors will write a report to the Part II Examiners and will recommend a mark. These marks are not necessarily final and may be amended by the examiners, who will also look at the reports and the Supervising Teachers' written assessments. After the viva, you will receive a copy of the mark sheet, which will provide feedback on your performance. **The marks allocated by the assessors are subject to moderation and scaling by the examiners, so the mark you receive may not match the final mark for this piece of work in the College Markbook.**

The following guidelines for allocation of marks to Part II Physics Education reports will be given to assessors.

- *Quality of work (60%):* How carefully and accurately was the work planned and performed? Was an appropriate amount of relevant material included?
- *Communications skills 1 - Report (20%):* Was the report well written and clearly organised, with clear and well balanced arguments, appropriate use of figures, tables and references.
- *Communications skills 2 - Viva (10%):* Was the student able to summarise the work and respond coherently to questions?

After the formal presentation, the assessors will send their report and recommended mark to the Head of Class and will return the student's report to the Undergraduate Office. After publication of the Part II Class List, students may, if they wish, retrieve one copy of their report from the Undergraduate Office.

If there are any queries concerning these arrangements, contact, Dr L Jardine-Wright (Room 243, Bragg Building, telephone 37042, email ljw21@cam.ac.uk (mailto:ljw21@cam.ac.uk)).

Part II: Quantum Condensed Matter Physics: 2016-17

Prof David Ritchie

Synopsis

1. **Classical and Semi-classical models for electrons in solids (3L)**

Lorentz dipole oscillator, optical properties of insulators. Drude model and optical properties of metals, plasma oscillations. Semi-classical approach to electron transport in electric and magnetic fields, the Hall effect. Sommerfeld model, density of states, specific heat of; electrons in metals, liquid^3 He/^{4}He mixtures. Screening and the Thomas-Fermi approximation.

2. **Electrons and phonons in periodic solids (6L)**

Types of bonding; Van der Waals, ionic, covalent. Crystal structures. Reciprocal space, x-ray diffraction and Brillouin zones. Lattice dynamics and phonons; 1D monoatomic and diatomic chains, 3D crystals. Heat capacity due to lattice vibrations; Einstein and Debye models. Electrons in a periodic potential; Bloch's theorem, Bloch's theorem from translational symmetry. Nearly free electron approximation; plane waves and bandgaps. Tight binding approximation; linear combination of atomic orbitals, linear chain and three dimensions, two bands. Pseudopotentials. Band structure of real materials; properties of metals (aluminium and copper) and semiconductors.

Semi-classical model of electron dynamics in bands; Bloch oscillations, effective mass, density of states, electrons and holes in semiconductors

3. **Experimental probes of band structure (4L)**

Photon absorption; transition rates, experimental arrangement for absorption spectroscopy, direct and indirect semiconductors, excitons. Quantum oscillations; de Haas-Van Alphen effect in copper and strontium ruthenate. Photoemission; angle resolved photoemission spectroscopy (ARPES) in GaAs and strontium ruthenate. Tunnelling; scanning tunnelling microscopy. Cyclotron resonance. Scattering in metals; Wiedemann-Franz law, theory of electrical and thermal transport, Matthiessen's rule, emission and absorption of phonons. Experiments demonstrating electron-phonon and electron–electron scattering at low temperatures.

4. **Semiconductors and semiconductor devices (5L)**

Intrinsic semiconductors, law of mass action, doping in semiconductors, impurity ionisation, variation of carrier concentration and mobility with temperature - impurity and phonon scattering, Hall effect with two carrier types. Metal to semiconductor contact. p-n junction; charge redistribution, band bending and equilibrium, balance of currents, voltage bias. Light emitting diodes; GaN, organic. Photovoltaic solar cell; Shockley-Queisser limit, efficiencies. Field effect transistor; JFET, MOSFET. Microelectronics and the integrated circuit. Band structure engineering; electron beam lithography, molecular beam epitaxy. Two-dimensional electron gas, Shubnikov-de Haas oscillations, quantum Hall effect, conductance quantisation in 1D. Single electron pumping, single and entangled-photon emission, quantum cascade laser.

5. **Electronic instabilities (2L)**

The Peierls transition, charge density waves, magnetism, local magnetic moments, Curie Law. Types of magnetic interactions; direct exchange, Heisenberg hamiltonian, superexchange and insulating ferromagnets, band magnetism in metals, local moment magnetism in metals, indirect exchange, magnetic order and the Weiss exchange field.

6. **Fermi Liquids (2L)**

Fermi liquid theory; the problem with the Fermi gas. Liquid Helium; specific heat and viscosity. Collective excitations, adiabatic continuity, total energy expansion for Landau Fermi liquid, energy dependence of quasiparticle scattering rate. Quasiparticles and holes near the Fermi surface, quasiparticle spectral function, tuning of the quasiparticle interaction, heavy fermions, renormalised band picture for heavy fermions, quasiparticles detected by dHvA, tuning the quasiparticle interaction. $CePd_2Si_2$; heavy-fermion magnet to unconventional superconductor phase transitions.

BOOKS

Band Theory and Electronic Properties of Solids, J. Singleton (OUP 2008)

Optical properties of Solids, Fox M (2nd edn OUP 2010)

Solid State Physics, Ashcroft N W and Mermin N D, (Holt, Rinehart and Winston 1976)

Introduction to Solid State Physics, Kittel C (7th edn Wiley 1996)

Principles of the Theory of Solids, Ziman J M (CUP 1972)

Part II: Relativity: 2016-17

Prof Anthony Challinor

Synopsis

Foundations of special relativity: Inertial frames, spacetime geometry, Lorentz transformations, spacetime diagrams, length contraction and time dilation, Minkowski line element, particle worldlines and proper time, Doppler effect, addition of velocities, acceleration and event horizons in special relativity.

Manifolds, coordinates and tensors: Concept of a manifold, curves and surfaces, coordinate transformations, Riemannian geometry, instrinsic and extrinsic geometry, the metric tensor, lengths areas and volumes, local Cartesian coordinates, tangent spaces, pseudo-Riemannian geometry, scalar, vector and tensor fields, basis vectors, raised and lowered indices, tangent vectors, the affine connection, covariant differentiation, intrinsic derivative, parallel transport, geodesics.

Minkowski spacetime and particle dynamics: Cartesian inertial coordinates, Lorentz transformations, 4-tensors and inertial bases, 4-vectors and the lightcone, 4-velocity, 4-acceleration, 4-momentum of massive and massless particles, relativistic mechanics, accelerating observers, arbitrary coordinate systems.

Electromagnetism: the electromagnetic force, the 4-current density, the electromagnetic field equations, the electromagnetic field tensor, the Lorentz gauge, electric and magnetic fields, invariants, electromagnetism in arbitrary coordinates.

The equivalence principle and spacetime curvature: Newtonian gravity, the equivalence principle, gravity as spacetime curvature, local inertial coordinates, observers in a curved spacetime, weak gravitational fields, intrinsic curvature, the curvature tensor, the Ricci tensor, parallel transport, geodesic deviation, tidal forces, minimal coupling procedure.

Gravitational field equations: the energy-momentum tensor, perfect fluids, relativistic fluid dynamics, the Einstein equations, the weak field limit, the cosmological constant, particle motion from the field equations.

Schwarzschild spacetime: static isotropic metrics, solution of empty-space field equations, Birkhoff's theorem, gravitational redshift, trajectories of massive particles and photons. Singularities, radially infalling particles, event horizons, Eddington-Finkelstein coordinates, gravitational collapse, tidal forces, Hawking radiation.

Experimental tests of general relativity: precession of planetary orbits, the bending of light, radar echoes, accretion discs around compact objects, gyroscope precession.

Friedmann-Robertson-Walker spacetime: the cosmological principle, comoving coordinates, the maximally-symmetric 3-space, the FRW metric, geodesics, cosmological redshift, the cosmological field equations.

Kerr spacetime: *the general stationary axisymmetric metric, the dragging of inertial frames, stationary limit surfaces, event horizons, the Kerr metric, structure of a rotating black hole, trajectories of massive particles and photons, Penrose process.*

Linearised gravity and gravitational waves: *weak field metric, linearised field equations, Lorenz gauge, wave solutions of linearised field equations.*

Topics in italics are non-examinable, and might be omitted.

BOOKS

General relativity: an introduction for physicists, Hobson M P, Efstathiou G P & Lasenby A N (CUP 2005).

This covers all parts of the course.

Relativity: special, general and cosmological, Rindler W (OUP 2001). Good for the concepts and methods. Provides a lot of physical and geometrical insight.

Introducing Einstein's Relativity, d'Inverno R (OUP 1992). Provides a clear description covering most of the gravitation course material.

Gravity: an introduction to Einstein's general relativity, Hartle J B (Addison Wesley 2003). A clear introduction that does not rely too much on tensor methods.

Spacetime and geometry, Carroll S M (Addison Wesley 2004). A very thorough, yet highly readable, introduction to general relativity and the associated mathematics

General theory of relativity, Dirac P A M (yes, that Dirac…!) (Princeton University Press 1996). A short and well-argued account of the mathematical and physical basis of general relativity. Probably only useful once you already understand the subject.

Part II: Research Reviews: 2016-17

Dr Rachael Padman

Prerequisites

None

Learning Outcomes and Assessment

The Research Review is similar to the literature review which would be undertaken at the start of any major research project including a PhD. On completion of the review you should have:

- learnt to interrogate the primary literature via the web and other library/information resources, such as the Web of Science
- developed your critical faculties, so that you come to an informed view of the current state of knowledge in the field, with an ability to distinguish betvveen (on the one hand) widely known and accepted views, and (on the other hand), more speculative or less-developed theories and views;
- developed the ability to summarize, explain and present your research and conclusions in a cogent and coherent style;
- learnt to use at least one text-processing package effectively;
- practlsed presentlng your work in a style appropriate to the topic, both in writing (via the Report) and orally (via a presentatlon to peers).

Assessment

The following guidelines for allocation of marks to Part II Research Reviews will be given to assessors. Each heading carries equal weight.

- **Scientific content**: How much appropriate understanding of science (particularly physics) was shown?
- **Quality of work**: How carefully/accurately/successfully was the work planned and performed? Was an appropriate amount of relevant material included?
- **Communication skills**: Report: was the report well written and clearly organised, with clear and well-balanced arguments, appropriate use of figures and tables, etc? Viva: was the student able to summarise the work and to respond coherently to questions?

After the oral examination, the assessors will send the report and recommended mark to Dr Rachael Padman, (Room F21, Battcock Centre) and will return the review to the Undergraduate Office (Room 212B, Bragg Building). After publication of the Part II Class List, students may, if they wish, retrieve one copy of their review from the Undergraduate Office.

See below for details of the arrangements for assessment

Synopsis

A research review is aimed at producing a descriptive and critical review of an area of physics of particular interest to the student. Its precise form may vary, and is to be agreed with the supervisor. The topic could range from a review of the very latest research in a particular area to, for example, a classic discovery of the twentieth century. In some cases the supervisor may indicate one or two articles which serve as an introduction; in other cases the student may need to search in computeriseddatabases or citation indices to find relevant papers.

Choosing a review

The research review abstracts are available on the web, see www-teach.phy.cam.ac.uk/teaching/courses/research-reviews/101#abstracts (courses/research-reviews/101#abstracts)). Students may also suggest reviews of their own, but they must have a supervisor (who may be external) and the review must be approved in advance. Students interested in a particular review should discuss it as soon as possible with the relevant supervisor. The list of reviews on the web will be continuously updated as new ones are added.

By Friday 27th October 2017, students should select (via a form on the Web) the review topics they would like to do, in order of preference. A ballot will then be held in order to assign titles to students in a fair way, and students and supervisors informed of the outcome.

Doing the work

Reviews can be started during the Michaelmas term or they may be deferred until the lent term. It might be a good idea to start some reading over the Christmas vacation. It is important to remember that the review counts for the same as one Tripos paper, so students should bear this in mind when deciding how much time to devote to it. During the preparation for the writing of the report, students will be asked to give a short talk presenting their preliminary work to a group of students writing research reviews in similar areas. It is expected that supervisors will organise these group sessions, which will consist of, say, four to eight students, in the last two or three weeks of the lent term. Students will receive feedback on the content and presentation of their reviews from the supervisors present and from their fellow students. This form of presentation is aimed at developing communication and presentational skills. You will be awarded 5% of the available marks for the Research Review upon giving the presentation (irrespective of its quality).

The Web of Science database (http://wos.mimas.ac.uk (http://wos.mimas.ac.uk)) may be used to find relevant papers. You will need your Raven login.

Supervision

Review supervisors may claim payment for up to two hours of supervision from the student's College, via CamCORS in the usual way. If a Teaching Officer delegates the day-to-day supervision of the project to a Research Associate or other postdoc, then it would be appropriate for that person to be the one claiming payment.

It is not expected that review supervision will necessarily be limited to two hours. Colleges pay simply for the mentoring, monitoring and reporting aspects of supervision, and not for the subject teaching, which is the Department's responsibiliity and is a core part of a University Teaching Officer's duties.

Submission

The write-up of the review will typically be in the style of a paper published in a scientific journal. The style of the review should be agreed with the supervisor. The review should describe and explain the main features of the subject, suggesting in which direction the field is moving, and drawing some conclusions. The main text should be concise (**3000 words maximum**, excluding any appendices). In addition, there must be an abstract of not more than 250 words. The student and supervisor should discuss the general structure of the review before writing is started, but the supervisor should not read a full version of the text until it is submitted. A set of handy tips and information is given in the booklet entitled Keeping Laboratory Notes and Writing Formal Reports, which is handed out to students at the start of the year - make sure you get one.

The deadflne for submission of the research review is **4:00 pm on the first Monday of Easter Full** Term (30th April 2018). **Two copies** of the review should be handed in to the **Undergraduate Office** (Room 212B, Bragg Building) in person before the submission deadline. In order to preserve anonymity when your review is looked at by the Part II examiners, **your name must not appear on the review itself, but only on the cover sheet which you will be given when you hand it in**. You should ensure that your candidate number appears on the first page of the research review, **together with the title of the review and your supervisor's name**.

Viva

As soon as possible after submission, the review will be assessed by two people, normally the supervisor and another staff member, who will conduct an informal oral examination (typically 30 minutes long) of the student on the work. The student will be asked to give a short verbal summary, normally uninterrupted, of the review during the interview. The assessor, who will be appointed by the Teaching Committee, will generally not be a specialist in the field. Students should expect to be contacted by their supervisor shortly after handing their review in, to arrange the oral examination.

These assessors will write a report to the Part II Examiners and will recommend a mark. These marks are not necessarily final and may be amended by the examiners, who also look at the reviews. After the exams, you will be able to view the on-line mark sheet, which will provide feedback on your performance. **The marks allocated by the assessors are subject to moderation and scaling by the examiners, so the mark recorded on the marksheet may not match the final mark for this piece of work in the College Markbook.**

If there are any queries concerning these arrangements, please contact Dr Padman, (e-mail:rp11@cam.ac.uk (mailto:rp11@cam.ac.uk))

Part II: Soft Condensed Matter: 2015-16

Prof Ulrich Keyser, **Prof Tuomas Knowles**

Prerequisites

This course naturally follows from the Part II Thermal & Statistical Physics, and uses lots of concepts from 1B Electromagnetism and 1B Dynamics. Everyone attending this course would have done these courses, so should have no trouble following the new material.

Learning Outcomes and Assessment

This course is somewhat unusual (although there will be many more in this style later on). Its material is quite multidisciplinary and gathers many qualitative ideas from a large variety of classical physics subjects; to use a fashion word: a lot of "fusion" is taking place. At the same time (the other side of the same coin), it is often impossible to be mathematically rigorous in describing such a multi-parameter physical system, and large parts of this subject rely on qualitative estimates and what some may feel like "leaps of logic". In reality, Soft Matter is a mature subject and all such "leaps" can be (and most have been) well-justified - but that requires perhaps a higher level of theory than we shall reach this time.

As a result, the main outcome (or the measure of success in this course) is the ability to bring together several ideas (from dynamics, electromagnetism, statistical physics) to qualitatively capture the physical behaviour of a complex system driven simultaneously by mechanical, electromagnetic and entropic forces. Make an order of magnitude estimates predicting such a behaviour. Isolate the main factors and discard the less relevant influences that affect such a system.

Synopsis

Introduction: What is soft matter? Forces, energies and timescales.

Elements of fluid dynamics: Navier-Stokes equation; Reynolds number; Laminar and boundary layer flows; Stokes Law and drag; Viscosity of a hard sphere suspension; Hydrodynamic interaction between colloidal particles; Implications for living systems; How bacteria swim.

Viscoelasticity and Brownian motion: Non-Newtonian behaviour; Idea of complex viscosity; Linear viscoelasticity; Simple phenomenological models pf viscoelastic response. Stochastic force and Langevin equation; Free Brownian motion; Brownian motion in external potentials; Diffusion equation; Fokker-Planck and Smoluchowski equations; Kramers problem - escape over a potential barrier.

Surface energy and interactions: Surface energy and tension; Cahn-Hilliard model of a liquid interface; Wetting: Young's equation and contact angles; Hydrophobicity and hydrophilicity; Electrolyte solutions: Debye-Huckel theory; Interactions between colloidal particles, DLVO potential.

Self assembly: Chemical potential of systems that aggregate; Aggregation equilibria; Aggregation of amphiphilic molecules; Critical micelle concentration; Shape of micelles; Lipid bilayers; Nature of the cell membrane; Curvature elasticity; Fluctuations of membranes; Examples of self assembly: viruses and nanotechnology.

Polymers and biological macromolecules: Examples of polymers; Single-chain statistics, self-avoiding walks; Gaussian correlations in the chain; Entropic forces and excluded volume; Wormlike (semiflexible) chain and persistence length, DNA; Single chain in good and poor solvents: coil-globule transition and protein folding; Phase transitions: Flory Huggins free energy for solutions; Good, {theta} and poor solvent conditions; Osmotic pressure in dilute conditions; Scaling in semi-dilute solutions; Chain dynamics: Rouse model; Rubber elasticity.

KEY BOOKS (this is what students feel helps them the most in this course)

Soft Matter Physics, Doi M. (OUP 2013)

Soft Condensed Matter, Jones R.A.L. (OUP 2002)

USEFUL BOOKS (for several specific sections of this course)

Fluid Dynamics for Physicists, Faber T.E (CUP 1995)

Biological Physics, Nelson P. (Freeman 2003)

Molecular Driving Forces, Dill K.A. and Bromberg S., (Garland 2003)

MORE TEXTS THAT SOME PEOPLE FIND SOMETIMES USEFUL

Statistical Thermodynamics of Surfaces, Interfaces and Membranes, Safran S.A. (Addison Wesley 1994)

Applied Biophysics, Waigh, T.A. (Wiley 2007)

Physical Biology of the Cell, Phillips, R. Et al, (Garland 2009)

Molecular Biophysics, Daune M. (OUP 1999)

Part II: Theoretical Physics TP1: 2015-16

Dr Claudio Castelnovo

Prerequisites

The course covers theoretical aspects of the classical dynamics of particles and fields, with emphasis on topics relevant to the transition to quantum theory. This course is recommended only for students who have achieved a strong performance in Mathematics as well as Physics in Part IB, or an equivalent qualification. In particular, familiarity with variational principles, Euler-Lagrange equations, complex contour integration, Cauchy's Theorem and transform methods will be assumed. Students who have not taken the Part IB Physics B course 'Classical Dynamics' should familiarise themselves with the 'Introduction to Lagrangian Mechanics' material.

Synopsis

Lagrangian and Hamiltonian mechanics: Generalised coordinates and constraints; the Lagrangian and Lagrange's equations of motion; symmetry and conservation laws, canonical momenta, the Hamiltonian; principle of least action; velocity-dependent potential for electromagnetic forces, gauge invariance; Hamiltonian mechanics and Hamilton's equations; Liouville's theorem; Poisson brackets and the transition to quantum mechanics; relativistic dynamics of a charged particle**.**

Classical fields: Waves in one dimension, Lagrangian density, canonical momentum and Hamiltonian density; multidimensional space, relativistic scalar field, Klein-Gordon equation; natural units; relativistic phase space, Fourier analysis of fields; complex scalar field, multicomponent fields; the electromagnetic field, field-strength tensor, electromagnetic Lagrangian and Hamiltonian density, Maxwell's equations.

Symmetries and conservation laws: Noether's theorem, symmetries and conserved currents; global phase symmetry, conserved charge; gauge symmetry of electromagnetism; local phase and gauge symmetry; stress-energy tensor, angular momentum tensor; transition to quantum fields.

Broken symmetry: Self-interacting scalar field; spontaneously broken global phase symmetry, Goldstone's theorem; spontaneously broken local phase and gauge symmetry, Higgs mechanism.

Dirac field: [*not examinable*] Covariant form of Dirac equation and current; Dirac Lagrangian and Hamiltonian; global and local phase symmetry, electromagnetic interaction; stress-energy tensor, angular momentum and spin.

Phase transitions and critical phenomena: Landau theory, first order *vs.* continuous phase transitions, correlation functions, scaling laws and universality in simple continuous field theories.

Propagators and causality: Schrödinger propagator, Fourier representation, causality; Kramers-Kronig relations for propagators and linear response functions; propagator for the Klein-Gordon equation, antiparticle interpretation.

BOOKS

The Feynman Lectures, Feynman R P *et al*. (Addison-Wesley 1963) Vol. 2. Perhaps read some at the start of TP1 and re-read at the end.

Classical Mechanics, Kibble T W B and Berkshire F H (4th edn Longman 1996): A clear basic text with many examples and electromagnetism in SI units.

Classical Mechanics, Goldstein H (2nd edn Addison-Wesley 1980): A classic text that does far more than is required for this course, but is clearly written and good for the parts that you need.

Classical Theory of Gauge Fields, Rubakov V (Princeton 2002): The earlier parts are closest to this course, with much interesting more advanced material in later chapters.

Course of Theoretical Physics, Landau L D & Lifshitz E M: Vol.1 *Mechanics* (3rd edn Oxford 1976-94) is all classical Lagrangian dynamics, in a structured, consistent and very brief form;

Vol.2 *Classical Theory of Fields* (4th edn Oxford 1975) contains electromagnetic and gravitational theory, and relativity. Many interesting worked examples.

Quantum and Statistical Field Theory, Le Bellac M, (Clarendon Press 1992): An excellent book on quantum and statistical field theory, especially applications of QFT to phase transitions and critical phenomena. The first few chapters are particularly relevant to this course.

Part II: Theoretical Physics TP2: 2017-18

Prerequisites

This course is recommended only for students who have achieved a strong performance in Mathematics as well as Physics in Part IB, or an equivalent qualification. You should be VERY comfortable with the material from the Advanced Quantum Physics course. Some familiarity with Lagrangian mechanics (as discussed in TP1) is also useful but not essential.

Synopsis

The development of quantum theory during the 20th century leads to the introduction of completely new concepts to physics. At the same time, physicists were forced - sometimes unwillingly - to adopt myriad new techniques and mathematical ideas. In this course, we'll survey some of these more advanced topics.

Quantum Dynamics
The evolution operator and time ordering. Driven oscillator. Coherent states. A spin in a field. The adiabatic approximation. Berry's phase.

Introduction to path integrals
How does the Lagrangian appear in quantum mechanics? The method of stationary phase and the semiclassical limit.

Scattering Theory
Scattering in one dimension. Scattering amplitude and cross section. Optical theorem. Green's function and relation to propagator. Born series and Born approximation. Partial wave analysis. Bound states.

Density Matrices
Two kinds of probability. The density matrix and its properties. Time dependence of the density operator. Applications in statistical mechanics. Density operator for subsystems and quantum entanglement.

Identical Particles in Quantum Mechanics
Second quantisation for bosons and fermions. Density matrices for identical particles.

Lie Groups
Rotation group. SO(3) and SU(2).

Relativistic Quantum Physics
Klein–Gordon equation. Lorentz group. Spinors and the Dirac equation.

BOOKS

Principles of Quantum Mechanics, Shanker R (2nd edn Springer 1994)

Modern Quantum Mechanics, Sakurai J J (2nd edn Addison-Wesley 1994)

Lectures on Quantum Mechanics, Baym G (Benjamin WA 1969)

For mathematical background we'd heartily recommend Mike Stone and Paul Goldbart's *Mathematics for Physicists: A guided tour for graduate students* (SUP, 2009). This contains a lot of advanced material as well as much of what you covered in IB Mathematics.

A great resource for just about anything you may need to know about any of the functions we meet is the NIST *Digital Library of Mathematical Functions* at http://dlmf.nist.gov (http://dlmf.nist.gov).

Part II: Thermal and Statistical Physics: 2014-15

Dr Malte Grosche

Synopsis

Introduction and revision of Thermodynamics:

The ideal gas; the van der Waals gas; equations of state; phase diagrams. Thermodynamic variables and potentials. Thermodynamic equilibrium in closed systems, maximum entropy; open systems and availability – relation to thermodynamic potentials and to the probability of a state.

Fundamentals of statistical mechanics:

Principle of equal equilibrium probability; microcanonical, canonical and grand canonical ensembles; partition function and grand partition function – relation to thermodynamic potentials and variables; maximisation of partition function. Paramagnetic salt in an external field; ensemble of simple harmonic oscillators.

Classical ideal gas:

Counting of states in the phase space; equipartition theorem; indistinguishability; ideal gas in the canonical ensemble; additional degrees of freedom and external potentials; chemical reactions and chemical equilibrium. Grand partition function; density series expansion; p-T ensemble; m-p-T ensemble; ideal gas in the grand canonical ensemble.

Quantum statistical mechanics:

Quantum to classical crossover; Bose-Einstein and Fermi-Dirac statistics; quantum states of an ideal gas. The ideal Fermi gas; low-temperature limit; entropy and heat capacity of fermions of at low temperatures. The ideal Bose gas; Bose-Einstein condensation. Black-body radiation, phonons and spin waves.

Classical interacting systems:

Liquids; radial distribution function; internal energy and equation of state; pair interaction and virial expansion; van der Waals equation of state revisited. Mixtures and mixing entropy; phase separation; phase diagrams and critical points. Phase transformations; symmetry breaking and order parameters; the Ising model; the Landau theory of phase transitions; 1st and 2nd order transitions, critical points and triple points; transitions in external fields; critical behaviour and universality.

Fluctuations and stochastic processes:

Fluctuations in thermodynamic variables; probability distribution of fluctuations; fluctuations at critical points. Thermal noise; Brownian motion; stochastic variables and Langevin equation; fluctuation-dissipation theorem. Probability distribution and simple diffusion; diffusion in external potentials; the Kramers problem; generalised diffusion equations.

BOOKS

Equilibrium Thermodynamics, Adkins (3rd edn CUP 1983).

Concepts in Thermal Physics, Blundell and Blundell (Oxford 2006)

Introductory Statistical Mechanics, Bowley & Sanchez (Oxford 1996).

Statistical Physics (Course of Theoretical Physics, v.5), Landau & Lifshitz (Pergamon 1980)

Brownian Motion, Mazo (Oxford 2002)

Part II: Vacation Projects: 2017-18

Dr Rachael Padman

Prerequisites

If it is intended to use vacation work for credit, then approval must be requested before the end of **August** each year, by submitting an application form (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/LongVacApplicationForm.pdf) to the Teaching Office, Room 212B, Bragg Building, giving details of the project.

Every project will contain a substantial element of independent or original work in physics or a closely-allied subject. That may be theoretical development, equipment design and/or development, and practical or computational experimentation. There is scope for a very liberal interpretation of the guidelines as long as the project draws directly on skills gained as part of the physics course -- these may come from individual lecture courses, or may require the application of say quantitative analysis using physics methods to a problem from a different area of science or engineering.

Certain guidelines must be satisfied before approval is granted:

1. The project will normally be of at around two months' duration and must include a substantial element of independent or original work. It is important that the project includes a significant amount of physics and is not, to take two examples, simply a series of routine measurements or entirely devoted to computer programming.
2. An abstract of half to one page of A4 should be submitted describing the project.
3. Details of the work must not be restricted by commercial or other considerations (although precautions can be taken to safeguard patent applications)'
4. A suitably qualified supervisor who will be responsible for the project will need to fill in part of the application form outlining the proposed work before it can be approved as a suitable project. The supervisor should also be willing to write a brief report describing the work that has been done and giving an assessment of the quality of the work. These reports will normally be requested from supervisors shortly after the undergraduate has submitted his or her report on the project

Gaining approval for the project does not commit the student to using the project for examination credit: it is still possible (up until the due date for the report below) for the student to decide not to submit a report and gain credit instead from some other allowed item of further work. In this case the student should inform the Helen Marshall in the Teaching Office (hm328@cam.ac.uk) of the change in plans as soon as possible.

Learning Outcomes and Assessment

Outcomes will vary greatly depending on the nature of the project. Approval to submit the project for credit will not be granted unless the project provides at least some of:

- Transferable skills: team work, communication, project planning...
- Research skills: literature surveys, programming in relevant languages, database design, relevant experimental skills (clean room, cryogenics, data acquisition....)

Assessment

The deadline for submission is 4:00pm on the first FULL Monday in Michaelmas term. Two paper copies of the report on the project written by the student should be submitted to the Undergraduate Office (Room 212B, Bragg Building). A pdf of the report should also be uploaded to the TIS by the same deadline of 4:00pm. The report should be *concise*, 20-30 pages, 5000 words maximum. In order to preserve anonymity when your report is looked at by the examiners, your name must not appear on the report itself, but only on the cover sheet which you will be given when you hand it in.

The project will be awarded a mark based on the report and on a 30-minute oral examination carried out by two assessors, usually members of the Cavendish staff. The oral examinations take place during the Michaelmas Term.

Marks are split equally between three areas:

- Scientific content: How much appropriate understanding of science (particularly physics) was shown?
- Quality of work: How carefully/accurately/successfully was the work planned and performed? Was an appropriate amount of relevant material included?
- Communication skills: Report: was the report well written and clearly organised, with clear and well-balanced arguments, appropriate use of figures and tables, etc? Viva: was the student able to summarise the work and to respond coherently to questions?

Synopsis

Scientific work during the Long Vacation prior to your third or fourth year can count as project work worth one unit of Further Work in Part II, or one Minor Topic or unit of Further Work in Part III. Forms (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/LongVacApplicationForm.pdf) are available from the Teaching Office, the deadline for approval of the project is the beginning of September. You will be required to name in advance a suitably qualified on-site supervisor who is willing to write retrospectively to Dr Padman describing the work you have done and giving an assessment of your effectiveness. Normally the programme must be of at least two months duration and must include a substantial element of independent or original work. It is important that the project includes a significant amount of physics and is not, for example, simply a series of routine measurements or entirely devoted to computer programming.

Arranging Placements

It is up to individual students to arrange their own projects with research laboratories in industry and elsewhere. Students may be able to set up a suitable project with an industrial firm already sponsoring them, or by approaching other research laboratories. All arrangements for payment and other conditions of employment during the project period are the responsibility of the student.

Vacation projects within the University may be offered through the Undergraduate Research Opportunities Programme (UROP). See http://to.eng.cam.ac.uk/teaching/urops/ (http://to.eng.cam.ac.uk/teaching/urops/) for details. Some of these projects may be suitable as assessed Long-Vacation Work. The teaching web pages www-teach.phy.cam.ac.uk/teaching/vacWorkDB.php (http://www-teach.phy.cam.ac.uk/teaching/vacWorkDB.php) offers other useful suggestions.

Further Information

- Form to request approval of projects (.docx (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/long-vac-application-form.docx)) (.pdf (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/LongVacApplicationForm.pdf))
- Further guidelines (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/long-vac-guidelines.pdf/view)
- Physics vacation work database (http://www-teach.phy.cam.ac.uk/teaching/vacWorkDB.php)
- UROPs website (http://to.eng.cam.ac.uk/teaching/urops/)

Part III: Ethics in Physics: 2013-14

Dr Richard Jennings

Synopsis

This course of four workshops will address ethical issues that arise in doing physics. The format will be a moderated discussion of ethical problems that arise in four areas as follows:

Workshop 1 – military research

Workshop 2 – the politics of science and government funding policy

Workshop 3 – the use and abuse of data

Workshop 4 – intellectual property and allocation of credit

Broadly speaking the first two workshops are concerned with the responsible conduct of research and the second two with the applications of physics. My intention is to run a fairly open plan course, and I am willing to introduce topics of particular interest to participants. That said, the default topics are as follows:

Workshop 1

For this first ethics in physics workshop I will introduce some of the ethical questions that arise in doing military research and indicate alternatives to military research. My main resources are publications of Scientists for Global Responsibility. Three in particular are of interest and are available as handouts on the TIS:

Soldiers in the Laboratory

More Soldiers in the Laboratory

Behind Closed Doors

Workshop 2

This workshop will look at the politics of science and the origins of the government's funding policy. The discussion will focus on the question of how to balance the funding of pure basic research with the government's priority for wealth creation. This is a particularly sensitive issue for the most basic fields of research such as particle physics and astronomy.

The issues arise in a classic debate in the Journal *Minerva* Volume **1**, 1962:

Michael Polanyi, "The Republic of Science: Its Political and Economic Theory" pp. 54-73.

Alvin Weinberg, "Criteria for Scientific Choice" pp. 159-171.

Workshop 3

To compare Robert Millikan's dubious presentation of data in his 1913 paper, "On the elementary Electrical Charge and the Avogadro Constant," [The Physical Review Series II, Volume II, No. 2, (1913), pp. 109-143] and the more notorious presentation of data by Jan Hendrick Schön. The Millikan case is available at:

http://www.onlineethics.org/Education/precollege/scienceclass/sectone/cs2.aspx (http://www.onlineethics.org/Education/precollege/scienceclass/sectone/cs2.aspx)

Workshop 4

Problems of intellectual property range from straightforward plagiarism to industrial espionage. At a more subtle level, there are problems of how credit is shared out among members of a group working on a research project. We will discuss two cases: the case of Rosalind Franklin and her contribution to our knowledge of the chemical structure of DNA, and the case of Jocelyn Bell Burnell and the discovery of pulsars. In each case there is still a range of opinions concerning the distribution of credit, and these two cases provide good examples of the difficulties that can be encountered in fairly sharing the credit for discoveries. The case of Rosalind Franklin is available at:

http://www.onlineethics.org/Education/precollege/scienceclass/sectone/cs4.aspx (http://www.onlineethics.org/Education/precollege/scienceclass/sectone/cs4.aspx)

Part III: IDP3: Materials, Electronics & Renewable Energy: 2014-15

Dr F A Deschler, **Dr S E Dutton**

Prerequisites

Only IA-level physics is a prerequisite; those who have experience of solid-state physics will find some parts of the course more straightforward, but the material will be taught and examined in such a way that prior knowledge in this area is not required.

Learning Outcomes and Assessment

This interdisciplinary course looks at the physical issues concerning energy generation, storage and use. The course aims to develop skills in using simple physical estimates for a wide range of energy problems, while also looking in more detail at materials-based approaches to renewable energy.

Synopsis

Energy requirements and energy availability: Back-of-envelope models of energy consumption and production. Current and projected usage. Alternatives to fossil fuels: nuclear, wind, wave, tide, geothermal, solar.

Hydrogen and batteries: Hydrogen vs. electric vehicles. Generation and storage of hydrogen. Electrochemical principles. Batteries. Fuel cells.

Exergy: Heat engines, heat pumps. Exergy and exergy efficiency.

Heating and cooling: Practical heat pumps. Combined heat and power.

Engines: The Otto cycle. Stirling engines.

Solar energy: Sunlight, solar concentration, solar thermal. Scale of solar installations required. Theoretical limits to conversion of solar energy.

Electronic structure of molecules and solids: Tight-binding band structure. Interaction with light. Excitons. Electrons and holes. Doping.

Inorganic semiconductor solar cells: The p-n junction. Photovoltaic operation. Cell design, materials and performance.

Molecular semiconductors: Materials and optical properties. Excitons. Marcus theory. Photovoltaic devices: multilayers, bulk heterojunctions and dye-sensitised cells.

Advanced photovoltaics: Tandem cells. Multiple exciton generation.

Photosynthesis: Structure and optoelectronic operation. Charge separation and recombination. Efficiency. Biofuels.

BOOKS

Sustainable Energy - Without the Hot Air, Mackay D J C (UIT Cambridge 2009)

The Physics of Solar Cells, Nelson J (Imperial 2003)

Molecular Mechanisms of Photosynthesis, Blankenship R E (Blackwell 2002)

Part III: Major topic: Advanced Quantum Condensed Matter Physics: 2016-17

Prof Crispin Barnes

Prerequisites

It is expected that students will have taken the Part II option course Quantum Condensed Matter Physics. However, the course includes an introductory section that discusses and refreshes all solid state concepts needed. It is therefore possible to take the course without having taken Quantum Condensed Matter Physics.

Synopsis

•The independent-electron approximation

–Crystalline systems

–Independent electron theory.

•Electron-electron interactions

–Hartree-Fock theory, Jellium, phase diagram of the electron system.

–Density functional theory, Kohn-Sham, local density approximation, molecular simulation.

–Linear response theory, screening in an electron gas, correlation functions.

–Quasiparticles, Landau’s Fermi liquid theory, second quantisation for Fermions, Jellium.

•Magnetism:

–The Hubbard and Heisenberg models, exchange mechanisms and applications.

•Electron-photon interactions

–Weak electron-photon interactions, Kramers-Krönig relations, optical absorption in semiconductors.

–Strong electron-photon interactions, excitons in inorganic and organic semiconductors, Bose-Einstein condensation in excitonic systems.

•Electron-phonon interactions

–Phonons in crystals, electron phonon interactions, polarons.

–Boltzmann semiclassical transport theory.

–Effective electron-electron interactions through the exchange of phonons

•Quantum Transport

-Landauer formalism, electronic transport in 1D, 0D and 2D.

•Superconductivity

–Phenomenology, Cooper pairs, BCS theory of superconductivity, High-Tc superconductivity.

BOOKS

Basic general:

Solid State Physics, Ashcroft & Mermin (Holt, Rinehart and Winston, 1976)

Introduction to Solid State Physics, Kittel (Wiley, 7th edition 1996)

The Physics and Chemistry of Solids, Elliott (Wiley, 1998)

Advanced general:

Solid State Physics, Grosso, Parravicini, (Academic Press, 2000)

A quantum approach to Condensed Matter Physics, Taylor & Heinonen (Cambridge 2002)

Principles of condensed matter physics, Chaikin &Lubensky (Cambridge 1995)

Solid State Physics Phillips (Cambridge University Press 2012)

Specialized subjects:

Quantum Theory of the Electron Liquid, Vignale (Cambridge 2005)

Quantum Theory of Many-Particle Systems, Fetter & Walecka (Dover 2003)

Magnetism in Condensed Matter, Blundell (Oxford 2001)

Superconductivity, *Superfluids and Condensates*, Annett (Oxford 2004)

Fundamentals of Semiconductors, Yu & Cardona (Springer, 1996)

Optical Properties of Solids, Fox (Oxford 2005)

Part III: Major topic: Atomic and Optical Physics: 2014-15

Prof Zoran Hadzibabic

Prerequisites

There are no special requirements for taking this course, apart from a good knowledge of quantum physics (e.g. from the "Advanced Quantum Physics" Part II course). Supervisions will be done in groups of 6-8 students.

Learning Outcomes and Assessment

The ability to cool and control atoms by laser light has given a completely new twist to the traditional field of atomic physics in recent years. The Nobel prizes in physics of 1997, 2001, and 2005 document the fascinating recent advances in this field. Macroscopic quantum phenomena such as Bose-Einstein condensation have become experimentally accessible and the fundamental laws of quantum mechanics have been studied in new ways and with unprecedented precision. This course will serve as an introduction to this exciting field and give insight into the current state of research. It is intended to provide the basic understanding needed for the current research on a wide range of topics involving atoms, lasers, and quantum gases. Emphasis will be put on the connection between theory and experimental observation

Synopsis

Introduction and revision of basic concepts: Bohr’s theory, Einstein A&B coefficients, Stern-Gerlach experiment

Atomic structure: Hydrogen atom, fine structure, Lamb shift**,** hyperfine structure, electric dipole transitions, selection rules, Zeeman effect, magnetic dipole transitions, alkali atoms

Fundamentals of atom-laser interaction: Driven two-level system, Ramsey spectroscopy and atomic clocks, density matrix, optical Bloch equations, dissipation, cross-sections & line shapes, Doppler-free laser spectroscopy, ac Stark effect, two-photon and Raman transitions

Laser cooling & trapping: Scattering force, slowing of atomic beams, optical molasses, Doppler cooling limit, magneto-optical trap, optical dipole trap, Sisyphus cooling below the Doppler limit

Evaporative cooling and Bose-Einstein condensation of atomic gases: Requirements, magnetic trapping, evaporative cooling, critical temperature, condensate fraction, experimental observation of Bose-Einstein condensation

Properties of atomic Bose-Einstein condensates: Atomic interactions, macroscopic wave function, matter-wave interference of Bose-Einstein condensates, Gross-Pitaevskii equation, Thomas-Fermi approximation, Bogoliubov excitation spectrum, superfluidity.

BOOKS

Atomic Physics, Foot C J, (Oxford University Press)

Laser Cooling and Trapping, Metcalf H & van der Straten P (Springer - Verlag)

Bose-Einstein Condensation in Dilute Gases, Pethick C J & Smith H (CUP)

Part III: Major topic: Biological Physics: 2016-17

Prof Pietro Cicuta, **Dr Eileen Nugent**

Prerequisites

Required: Part II Thermal and Statistical Physics (or equivalent).

Recommended: Part II Soft Condensed Matter (or self-study of that material).

Learning Outcomes and Assessment

The interface between physical and life sciences has emerged as a key area in both academia and industry and is fundamentally changing how we investigate living matter. New technologies such DNA-sequencing, super-resolution microscopy and microfluidics are making it possible to probe the inner workings of cells and generate previously unimaginable data. The quantitative information emerging from these new techniques is enabling a new understanding of biological systems, grounded in quantitative models, with profound links to established areas of physics, such as statistical mechanics. In this course we will focus on model building based on physical concepts and laws. We will draw examples from different areas of modern biology including molecular and cell biology, microbiology, systems biology, developmental biology and neuroscience.

At the end of this course students should have gained an understanding of:

- The physical characteristics of living matter
- The role of thermal fluctuations and stochastic processes in biological systems
- The use of physical concepts and laws to model biological systems
- Quantitative analyses of the models produced
- The biological significance and key features of the systems introduced
- Modern experimental tools and techniques for quantitative studies with single-cell resolution

Synopsis

Introduction: an overview of different lengthscales and timescales for processes at the level of a biological cell; a focus on the "central dogma" of information processing in cell biology; consideration of important physical quantities at the cellular scale.

Linking with previous knowledge: how do statistical physics, soft matter, classical dynamics, condensed matter and other "modules" of physics help understand aspects of biological systems, particularly at the level of cell biology.

Elements of Networks: intro to basic concepts, random graphs, small motifs, percolation.

Statistical Physics of Living systems: A physical description of living systems; Chemical Forces; Macromolecules as two-state systems; Monod-Wyman-Changeux (MWC) Model of Cooperative binding; Applications of the MWC: Ligand-gated ion channels; Modeling Hemoglobin binding; Diffusion in the cell.

Molecular Motors: Free energy transductions in the cell; Single Molecule Techniques; Molecular Motors as Brownian Ratchets; Smolunchowski Equation; Models of motion; Polymerization ratchets; The Flagellar Rotary Motor in Bacteria; Models of Rotary Motion; Adaptation in Chemotaxis; ATP Synthase.

Neuro-physics: Neuronal Anatomy; Membrane Potential; Nernst Equation; Action Potentials; Cable Equation; Voltage gating Hypothesis; The cell Membrane as a bistable switch; Patch Clamp Experiments; Hodgkin-Huxley Model; Integrate and Fire Models; Opto-genetics.

Biological Pattern Formation: Morphogen Gradients; Reaction-Diffusion Systems; The Turing instability;

Modeling Protein Production with ODE: systems of differential equations to describe unregulated and autorepressed gene expression; dynamics and fluctuations.

Biochemical Noise: Small number stochasticity; Intrinsic and extrinsic noise; modelling noise in protein production; two-step model for protein production.

Regulation of Gene Expression: Statistical Physics description of RNA polymerase binding to promoters; cases of no regulation, activation and repression; behaviour of real promoters, example of the lac operon; the Gillespie approach to numerical modelling of stochastic dynamics.

General elements of dynamical systems: fixed points, phase space, control variables; description of dynamics from an effective potential; nullclines.

Genetic circuits: examples of synthetic and natural circuits exhibiting switching or oscillatory behaviour; application of dynamical systems concepts to model behaviour of genetic circuits; circuits and biological components designed to control gene expression noise.

The course includes guest lectures on biological pattern formation and genetic/proteomic networks and an outlook on the most active research areas of biological physics.

Recommended Reading:

"Physical Biology of the cell (2nd Edition)", *Phillips, Kondev, Theriot and Garcia*
"Biological Physics", Freeman Press, *Nelson*
"Physical Models of Living Systems", FreemanPress, *Nelson*
"Models of Life", CUP (available online through http://www.lib.cam.ac.uk/), *Sneppen*
"An Introduction to Systems Biology", Chapman and Hall, *Alon*
"Physics in Molecular Biology", CUP, *Sneppen and Zocchi*
"Molecular Biology of the Cell", Garland Science, *Alberts et al* (cell biology reference textbook)

Part III: Major topic: Particle Physics: 2014-15

Dr Christopher Lester

Prerequisites

The Part III Particle Physics Major option course aims to provide a description of the main topics in modern particle physics.

The course assumes students have some knowledge of Particle Physics from a previous introductory course of some kind. In the case of students who were in Cambridge for Part II, the relevant course would be the Particles part of Part II Nuclear and Particle Physics.

The Part II Particle and Nuclear Physics course is not officially a prerequisite, but students who have not attended that course (or a course with a similar Particle Physics content elsewhere) and who are not familiar with the overall structure of The Standard Model, the quark model of the hadrons, scattering processes, and wave equations at some level, have found the course hard in the past. Students who fit this background should strongly consider getting hold a book which follows the course most closely (e.g. Mark Thomson's) and reading up before starting the course.

contan to this course although familiarity with basic particle physics terminology is assumed. The course will concentrate on the Standard Model with the aim of providing both a detailed description of current experimental data, and the theoretical understanding to place these experimental results in context. The Minor Option course on "Gauge Field Theory" covers particle physics theory at a more advanced level.

Synopsis

Introduction, cross sections and decay rates: The structure of the Standard Model; revision of basic concepts; relativistic phase space and its role in two-body decays and two-body scattering.

Solutions to the Dirac equation: The Klein-Gordon equation; the Dirac equation and Dirac spinors; negative energy solutions and anti-particles; C and P symmetries; spin and helicity.

Interaction by particle exchange and QED: interaction by particle exchange; the QED vertex; Feynman rules for QED; scattering and e+e– annihilation in QED; the role of spin and helicity in QED and chirality; QED calculations using Dirac spinors.

Electron proton scattering: Rutherford scattering revisited; low energy electron proton scattering and form factors; deep inelastic scattering and structure functions; Bjorken scaling and the Callan-Gross relation; the quark-parton model; valance and sea quarks.

The quark model and QCD: symmetries and conservation laws; SU(3) flavour symmetry; mesons and baryon wave; SU(3) colour symmetry; confinement and gluons; Feynman rules for QCD; colour factors; the QCD potential; running couplings and asymptotic freedom; experimental evidence for QCD.

Particle Detectors: Particle interactions in matter, particle detection and large detectors at modern particle colliders.

Charged-current weak interactions: V-A Theory and parity violation; helicity structure of the weak interaction; lepton universality; neutrino scattering; neutrino structure functions and the anti-quark content of nucleon.

Neutrino physics and neutrino oscillations: Neutrino interactions; detecting neutrinos; solar and atmospheric neutrinos; neutrino oscillations and the PMNS matrix; CP and CPT in the weak interaction; recent neutrino experiments.

The CKM matrix and CP violation: The Cabibbo angle and the CKM matrix; CP violation in the early universe; the neutral kaon system and strangeness oscillations; CP violation in the kaon system; the CKM matrix and CP violation in the Standard Model.

Electroweak Unification and the Standard Model: W boson decay; the W and Z bosons and a unified electroweak theory; the Z resonance; precision tests of the electroweak theory at LEP; the Higgs mechanism; hunting the Higgs; problems with the Standard Model.

BOOKS

There are many books available on particle physics, at various levels. The following are suggested as useful for this course:

Particle Physics, Martin B R and Shaw G (2nd edn Wiley 1997). A good introductory text, more suited to Part II but covers most of the basic material.

Introduction to High Energy Physics, Perkins D H (4th edn CUP 2000).

Good coverage of experimental techniques and some aspects of theory. A slightly lower level than this course with a more historical approach.

Introduction to Elementary Particles, Griffiths D (Harper & Row 1987) out of print

Theoretical treatment, going slightly beyond the level of this course, but well written and clear. Good reference for those wishing to pursue some of the mathematical details.

Quarks and Leptons, Halzen F and Martin A D (Wiley 1984).

Goes beyond the level of this course, but provides a good description of the underlying theoretical concepts.

Part III: Major topic: Physics of the earth as a planet: 2017-18

Learning Outcomes and Assessment

Our aim in this course is to show how concepts from physics, especially from classical physics and continuum mechanics, can be used to understand the structure and evolution of the Earth, and to a lesser extent, the other terrestrial planets. Our approach is entirely different from that taken in Part IA Geology, and assumes no knowledge of that material. The course is intended for students who are theoretically inclined, and focuses on quantitative and mathematical parts of geophysics. Some of the lectures will be given by the other members of the Department of Earth Sciences whose research is related to topics discussed within the course.

Synopsis

Introduction to geophysics: Theories of planetary formation, composition of terrestrial planets and the bulk composition of the Earth, origin of the crust, mantle, and core, large scale static structure of the Earth.

Plate tectonics: Rotation vectors and poles of rotation, triple junctions, present-day plate motion, reconstructing past plate motions.

Continuum mechanics: Fundamentals of solid mechanics, variational principles, measures of deformation and stress, constitutive theory, material symmetries.

Seismology and elastic wave propagation: Linearised elasticity, plane wave propagation, elastodynamic Green function, seismic waves in stratified media, asymptotic ray theory, effects of self-gravitation and rotation, the free oscillations of the Earth and eigenfunction expansions.

Earth structure: Travel time observations, dispersion measurements from surface waves, spherically symmetric Earth structure, seismic tomography, constraints on density from free oscillations and the Adams-Williamson equation.

The earthquake source: Kinematic models for earthquakes, point source approximations and moment tensors, earthquake location, determination of source mechanisms.

Thermal and mechanical structure of plates: Structure of oceanic and continental plates, isostasy and gravity, thermal models, depth of the oceans, subduction, the elastic layer.

Dynamic processes: Heat sources, thermodynamics of convection, convective regime of the mantle, the cooling of the mantle, thermal history of the mantle.

Immediately after the Michaelmas term is over, Part II students in the Department of Earth Sciences take a week long tectonics field trip to Greece. This is an excellent way to see first hand the surface manifestation of earthquake faulting and other geophysical topics discussed from a more theoretical viewpoint in the Physics of the Earth as a Planet lectures. Students taking this Part III Physics course are welcome to come on the Greece field course but the field trip is not connected to the Physics of the Earth as a Planet lectures as such. The cost for the trip is around £85.

BOOKS

The solid Earth, Fowler C M R (2nd edn CUP 2004)

This is an excellent general book on geophysics. It covers about half of the course, but uses less mathematics than we do. Fowler's discussion of seismology is briefer than that of the present course, and she does not discuss mantle convection and dynamics at all.

Theoretical Global Seismology, Dahlen F A & Tromp J (Princeton 1998)

A comprehensive monograph on theoretical seismology. It covers the course material at a similar level, but includes additional topics and goes into more detail. Particularly good on the fundamentals of continuum mechanics.

The excitation and propagation of elastic waves, Hudson J A (Cambridge 1980)

A concise and elegant book dealing with the fundamentals of elastic wave propagation. Largely at the right level, though it does contain some more advanced material making use of complex variable techniques.

Geodynamics, Turcotte D L & Schubert G (Wiley 2002)

This covers much of the material of the course except seismology, at about the same mathematical level that we will use. It contains many problems with their solutions.

Part III: Major topic: Relativistic Astrophysics and Cosmology: 2016-17

Prof Andy Fabian, **Prof Anthony Lasenby**

Prerequisites

This course builds on material from the Part II Relativity course, although with a different emphasis and approach, and detailed tensor calculus manipulations, although referred to, will in general not be needed. It will also be helpful to have taken Astrophysical Fluid Dynamics in Part II, though again this is not essential.

Synopsis

Introduction: The main constituents of the Universe: solar system, stars, nebulae, star clusters, galaxies, clusters, radio sources, quasars etc. Sizes, velocities, masses, luminosities. The distance scale.

General Relativity: Review of foundations of general relativity: equivalence principle, strong and weak forms, curved spaces, the geodesic equation, the field equations, Schwarzschild solution.

Stars, white dwarfs, neutron stars: The physics of stars and stellar evolution, stellar structure, white dwarfs and the Chandrasekhar mass. General relativistic treatment of stellar structure, the Oppenheimer-Volkoff equations. Neutron star structure, mass-radius relation for cold matter, pair production and annihilation.

The end-points of stellar evolution: Supernovae, pulsars, supernova remnants, shock waves, accretion, accretion discs, the Eddington limit. X-ray binaries, the Crab Nebula, binary and millisecond pulsars, tests of general relativity.

Black holes: Formation, observational evidence, accretion discs, effects of spin.

Active Galactic Nuclei (AGN): Radiation processes, energy budget, Eddington limit and growth. Special relativistic effects in jetted sources. Gamma-ray bursts.

Gravitational waves: wave solutions to Einstein's equations in vacuum. Detection of gravitational waves. Astrophysical sources of radiation.

Galaxies and clusters of galaxies: Observational properties and structure. Black hole feedback. Evidence for dark matter. Gravitational lenses, rotation curves.

The Robertson-Walker metric: Basic observations. Hubble's law, isotropy and homogeneity of the Universe, comoving coordinates and spatial curvature, redshift. Distance measures, deceleration parameter, luminosity-redshift and angular diameter-redshift relations. Observed flux versus redshift relations. Number counts.

The standard Friedmann models: General solutions, cosmological constant, the redshift-cosmic time relation, horizons, the flatness and isotropy problems. Ages of stars and galaxies. Methods for determining the Hubble constant.

The Microwave Background Radiation: Evolution of blackbody spectrum. Energy densities, recombination and timescales. Imprints on the CMB and relation to the growth of structure.

The Early Universe: Nucleosynthesis, baryon asymmetry. Inflation and the problems it addresses. Origin of perturbations. Cosmological parameters and observations. Clues to the earliest times, links with fundamental theory.

BOOKS

At roughly the level of the course:

Essential Relativity, Rindler W (2nd edn Springer 1990). Good introduction to GR and cosmology.

Principles of Cosmology and Gravitation, Berry M V (2nd edn IoP 1989). Elementary but clear introduction to GR and cosmology, taking similar line to that used in course.

Black holes, White Dwarfs and Neutron Stars (The Physics of Compact Objects), Shapiro S L & Teukolsky S A (Wiley 1983). Good textbook for parts of course. Aimed at advanced physics students.

Accretion Power in Astrophysics, Frank J, King A & Raine D (2nd edn CUP 1992). Useful for high energy astrophysics aspects.

High Energy Astrophysics, Vols 1 and 2, Longair M S (2nd edn CUP 1992 1994). Useful chapters.

Exploring Black Holes: Introduction to General Relativity, Taylor E F & Wheeler J A (Addison- Wesley 2001).

Supplementary reading at an elementary level:

The Physical Universe, Shu F (University Science Books 1982). Excellent introduction to the whole field of astrophysics and cosmology.

The Big Bang, Silk J (2nd edn Freeman 1989).

Our Evolving Universe, Longair M S (CUP 1996)

Black Holes, Luminet J (CUP 1992). Excellent paperback account of black holes

Gravity's Fatal Attraction: Black Holes and the Universe, Begelman M C and Rees M (Freeman: Scientific American 1996)

More advanced books covering General Relativity in greater detail:

Introducing Einstein's Relativity, d'Inverno R (OUP 1995)

Introduction to Cosmology, Narlikar J V (2nd edn CUP 1993)

General Relativity: An Introduction for Physicists, Hobson M P, Efstathiou G P & Lasenby A N (CUP 2006)

Part III: Major Topic: Theories of Quantum Matter: 2016-17

Dr Austen Lamacraft

Prerequisites

You should have taken a quantum mechanics course at the level of the advanced quantum course in Part II. You don't need to have taken TP2. One of the main methods we use -- second quantization -- is covered in TP2 but will be introduced again from scratch.

Learning Outcomes and Assessment

The purpose of this course is to introduce **simple models** of phenomena in condensed matter physics, and to equip you with the tools needed to analyse their behaviour. This involves the application of quantum mechanics to **many body systems**. There is a strong overlap with the subject of **quantum field theory**, which deals with the quantum mechanics of continua (i.e. fields).

Synopsis

Many Body Wavefunctions (http://tqm.courses.phy.cam.ac.uk/docs/lectures/ManyBodyWavefunctions/)

Product States. Fermi gas. Density, density matrix, and pair distribution. Quantum hall effect.

The Lieb-Liniger Model (http://tqm.courses.phy.cam.ac.uk/docs/lectures/LiebLinigerModel/)

Bethe's wave function. The Bethe equations. Excited states.

The Elastic Chain (http://tqm.courses.phy.cam.ac.uk/docs/lectures/ElasticChain/)

Quantizing a chain. Ground state displacement fluctuations.

Spin Models (http://tqm.courses.phy.cam.ac.uk/docs/lectures/SpinModels/)

Heisenberg model. Heisenberg chain. Magnons. Antiferromagnets. Symmetry breaking. Spin wave theory.

A is for Annihilation (http://tqm.courses.phy.cam.ac.uk/docs/lectures/SecondQuantization/)

Fock states and occupation numbers. Creation and annihilation operators. The case of fermions. Representation of operators.

More Second Quantization (http://tqm.courses.phy.cam.ac.uk/docs/lectures/MoreSecondQuantization/)

Density matrix and density correlations. Second quantized Hamiltonians. Hartree--Fock theory. Hanbury Brown and Twiss effect.

Lattice Models and Strong Correlation (http://tqm.courses.phy.cam.ac.uk/docs/lectures/Lattice/)

Tight binding models. Hubbard models and the Mott transition. Superexchange.

Bose Gas (http://tqm.courses.phy.cam.ac.uk/docs/lectures/BoseGas/)

Gross--Pitaevskii approximation. Bogoliubov theory. Superfluidity.

Fermi Gas (http://tqm.courses.phy.cam.ac.uk/docs/lectures/FermiGas/)

Interactions described by perturbation theory. Quasiparticles. Landau Fermi liquid.

Superconductivity (http://tqm.courses.phy.cam.ac.uk/docs/lectures/Superconductivity/)

Cooper's problem. BCS theory. The BCS-BEC crossover.

Response and Correlation (http://tqm.courses.phy.cam.ac.uk/docs/lectures/ResponseAndCorrelation/)

Response functions. Structure factor. Dielectric function. Sum rules.

Jellium (http://tqm.courses.phy.cam.ac.uk/docs/lectures/Jellium/)

Ground state energy. Hubbard--Stratonovich transformation

The Kondo Effect (http://tqm.courses.phy.cam.ac.uk/docs/lectures/KondoEffect/)

The Kondo model. Divergences at second order. Scaling theory.

Quantum Dissipation (http://tqm.courses.phy.cam.ac.uk/docs/lectures/DissipationQM/)

Modelling dissipation by a bath. Orthogonality catastrophe.

The Jordan-Wigner Transformation (http://tqm.courses.phy.cam.ac.uk/docs/lectures/JordanWigner/)

Spin-1/2 XY model as a system of free fermions. Bosonization

The Ising Model and Quantum Phase Transitions (http://tqm.courses.phy.cam.ac.uk/docs/lectures/IsingModel/)

Quantum phase transition in the transverse field Ising model. Relation to 2d classical model. Majorana edge modes.

Part III: Minor topic: Colloid Physics: 2016-17

Dr Erika Eiser

Synopsis

Draft 15-08-16

Simulations of light scattering experiments. The experimental techniques of static and dynamic light scattering will be introduced and discussed. We will test intensity correlation functions, the Siegert relation and other parameters that are not directly accessible in experiments. This will be done using *Brownian Dynamics simulations*.

Computing Flow in a Slit. Using *stochastic rotation-dynamics* or *Dissipative Particle Dynamics* (DPD): SRD and DPD are mesoscopic solvent models that are very powerful for the simulation of systems with a separation of length scales. First we will simulate a fluid in a slit with stationary hard boundaries. By then applying a homogenous force to all fluid particles in the slit we will see how a classical Poisseuille flow develops. From that we can compute the fluids' viscosity. Different boundary conditions and the concept of slip length along a wall will be discussed. Finally, we will measure the viscosity as function of the fluid density.

Simulating Micro-Rheology. Measuring the diffusion coefficient of a colloid in a viscous and viscoelastic medium. In particular we will compute the mean-square displacements of a colloid in a fluid using stochastic rotation dynamics to obtain the viscosity of the solvent.

Coupling of Colloid Motion to the Surrounding Fluid. Simulating a fluid performing Couette-flow, where one surface is stationary while the other is moving. What happens to the fluid flow when colloids that are much larger than the fluid particles are added?

Simulating Depletion Forces. In a mixture of small and large colloids one typically observes an attractive force between the large spheres, which is purely entropic in origin. This so-called depletion interaction will be simulated as function of the colloidal size ratios concentrations. (This is a static problem, which we will address with Monte Carlo Simulations.)

Simulating Polymers. Using *off-lattice Monte Carlo* simulations we will describe a polymer in terms of a random walk (fixed distances with random rotation).

We will briefly discuss why **C**, **Fortran** or other languages more suitable for large calculations. Interpreted languages such as *Python* or *Matlab* are perhaps more intuitive and easy to handle but are much slower.

Literature

1. Frenkel & B. Smit , Understanding Molecular Simulation , Book, 2nd edition Academic Press, ISBN 0-12-267351-4
2. P. Allen & D. J. Tildesly, *Computer Simulation of Liquids*, Oxford Science Publications, ISBN 0-19-855645-4

Handbooks for programming in Fortran, C, and Python

http://www.mrao.cam.ac.uk/~rachael/compphys/SelfStudyF95.pdf (http://www.mrao.cam.ac.uk/~rachael/compphys/SelfStudyF95.pdf)

http://www-pnp.physics.ox.ac.uk/~tseng/teaching/lab/handbook_C.pdf

http://www.physics.nyu.edu/pine/Teaching.html (http://www.physics.nyu.edu/pine/Teaching.html)

Part III: Minor topic: Exoplanets and Planetary Systems: 2016-17

Prof Didier Queloz

Prerequisites

general knowledge of mechanics and hydrodynamics.

Learning Outcomes and Assessment

The course aims at providing to the student a solid introductory knowledge to understand the most recent results of the field.

Synopsis

Centuries ago, scientists studying the Solar System assumed that it was representative of other existing systems. Formation and evolution theories were developed to describe planetary systems in general, not surprisingly, predicting that other planetary systems would be similar to our own. The completely unexpected characteristics of this first planet captured the imagination of the scientific community, and stimulated the development of a new “paradigm”

The course will address and discuss the following chapters:

- How do we detect and characterize planets orbiting others stars?
- What are the properties of these exoplanets and their systems?
- What is the most common configuration of planetary systems in the Universe?
- What do we know about planetary formation and evolution?

Part III: Minor topic: Formation of Structure in the Universe: 2014-15

Prof Roberto Maiolino

Prerequisites

It is assumed that students are familiar with the basics of the Part II course
Astrophysical Fluids and with the basics of the Part III Cosmology course (Michealmas term).

Learning Outcomes and Assessment

The course will discuss how structure forms in the Universe on all scales from stars, through galaxies, to the largest structures we know about in the Universe. At the end of the course students will be familiar with the main models of star formation and of galaxy evolution throughout the cosmic epoch, as well as with the several observational results that have been obtained so far, validating or testing these models. The topics covered are at the forefront of active research in astrophysics. Failings of our current understanding and models will be discussed along with likely developments in the near future, which will be achieved thanks to the advent of new major observing facilities and new advanced numerical simulations.

Synopsis

Introduction: overview of the evolution of structure in the universe; main properties of galaxies in the local universe; star-forming regions; a first-look at the high-redshift universe.

Physical processes in the baryonic gas: heating processes; cooling processes; emission mechanisms; thermal stability and instability; multi-phase medium in galaxies; baryonic gas in the early universe.

Gravitational stability and instability: the isothermal sphere as a simple model; virial equilibrium; Jeans analysis in an infinite medium; role of magnetic fields, turbulence and angular momentum.

Formation of stars: inside-out collapse; formation of the first core and second core; deuterium burning; hydrogen burning; angular-momentum, discs and stellar jets.

Star-formation on galactic scales: properties and structure of star-forming galaxies; initial mass functions; factors controlling star formation; Schmidt-Kennicutt star-formation law; starburst galaxies; a first look at star formation histories.

Cosmological origins of structure: Origin and early growth of density perturbations and the matter power spectrum.

Galaxy formation: collapse of a spherical over density; evolution of the baryonic gas; numerical simulations; hierarchical structure formation; galaxy dynanmics.

Supermassive Black Holes: observational evidence; measurement of black holes masses; black hole scaling relations; black hole accretion; Active Galactic Nuclei (AGNs).

Feedback in galaxies: the need for negative feedback; supernova feedback; AGN feedback; improved models for galaxy evolution; positive feedback.

The high-redshift universe and galaxy evolution: observational properties of galaxies at high redshift; evolution of the galaxy population; dominant galaxy evolutionary mechanisms; evolution of the AGN population and evolution of black holes; confronting predictions and observations; formation of the first stars and of the first black holes in the primordial Universe.

Large-scale structure: clusters and superclusters; correlation functions; remnants of primordial structure; the cosmic web.

Challenges: problems with our current models of galaxy formation; the end of the dark ages – the epoch of re-ionisation; the equation of state of dark energy; testing our predictions.

BOOKS

The physics of the interstellar medium, Dyson J E and Williams D A (2nd edition IoP)

Accretion processes in star formation, Hartmann L (Cambridge)

An introduction to modern cosmology, Liddle A (2nd edition Wiley) – a good and relatively simple text to put material in context

The Structure & Evolution of Galaxies, Philips S (Wiley)

Galaxy formation, Longair M S (2nd edition Springer)

Cosmology – the origin and evolution of cosmic structure, Coles P and Lucchin F (2nd edition Wiley) – a more advanced text

Observational Cosmology, Sarjeant S. (Cambridge)

Part III: Minor topic: Gauge Field Theory: 2014-15

Prof Ben Gripaios

Prerequisites

There are no formal prerequisites for the course though it would be helpful to have attended the Part III Particle Physics or Quantum Field Theory Major Options; for those who have not, the lectures cover the essential material, including the necessary relativistic quantum field theory.

Learning Outcomes and Assessment

This course is an introduction to the gauge field theories of modern Particle Physics, focusing on the gauge-invariant Lagrangian of the Standard Model of electroweak and strong interactions, with particle masses introduced via spontaneous symmetry breaking (the Higgs mechanism).

Synopsis

Relativistic quantum mechanics: Covariant notation; transition rates; phase space; two-body decay and scattering; interaction and scattering via particle exchange; Feynman graphs; Klein-Gordon equation; Dirac equation; free-particle spinors; helicity and chirality; electromagnetic interactions, photons; charge conjugation; gamma matrix algebra; Compton scattering.

Relativistic quantum fields: Classical field theory, Lagrangian densities; Klein-Gordon field; Fourier analysis; second quantization; single-particle and two-particle states; quantising the electromagnetic field; vacuum energy and normal ordering; complex fields; symmetries and conservation laws; Noether's theorem; Dirac field; spin-statistics theorem; Majorana fields.

Gauge field theories: Gauge symmetry in QED; non-Abelian gauge symmetry; strong interactions, QCD; weak interactions; electroweak interactions; spontaneous symmetry breaking; gauge boson masses; the unitary gauge; Yukawa interactions, quark and lepton masses; Higgs mechanism; parameters of the Standard Model; properties of the Higgs boson.

Renormalisation: Ultraviolet divergences; renormalisability; dimensions of fields and couplings; non-renormalisable interactions and effective theories.

Beyond the Standard Model: neutrino masses, the seesaw mechanism; grand unification, SU(5).

BOOKS

Quantum Field Theory, Mandl F and Shaw G (2nd edn Wiley 2009)

A Modern Introduction to Quantum Field Theory, Maggiore M (OUP 2005)

Gauge Theories in Particle Physics, Aitchison I J R and Hey A J G (3rd edn 2 vols IoP 2003)

An Introduction to Quantum Field Theory, Peskin M E and Schroeder D V (Addison-Wesley 1995)

Part III: Minor topic: Medical Physics: 2014-15

Dr Sarah Bohndiek

Prerequisites

The material should be accessible to all Part III students. The course is divided into two parts: the first 6 lectures concentrate on the basic physics of biomedical imaging, while the second 6 lectures (given by Addenbrookes hospital staff and other imaging researchers) provide a broad insight into the applications of physics in medicine. The latter half of the course should be accessible to all those with an interest in medical physics.

Learning Outcomes and Assessment

After attending this lecture series and completing supervision problems, students should be able to:

- Describe the importance of physics in medicine
- Understand the general principles of medical image reconstruction and registration
- Compare and contrast the medical imaging techniques that are available in a hospital setting and explain their relative merits
- Explain the difference between imaging with ionising and non-ionising radiation in the context of radiation dosimetry and risk
- Describe sensing and therapeutic applications of physics in medicine

Synopsis

Introduction: Historical background; radiation interactions; general imaging concepts; and contrast mechanisms.

Medical Imaging Methodology: For all clinically applicable imaging techniques, a detailed description of contrast mechanisms, data acquisition hardware and image reconstruction will be provided. This will cover: imaging with ionising radiation, including X-ray, CT, nuclear medicine, SPECT and PET; imaging with non-ionising radiation, including MRI and ultrasound; and general principles of image reconstruction and registration of images over time and between modalities.

Clinical Applications of Physics: Clinical examples of the utility of medical imaging in diagnosis and treatment of disease. Sensing applications of physics in hospitals, including patient monitoring. Therapeutic applications of physics, particularly radiotherapy in cancer patients.

Part III: Minor topic: Non-linear optics and Quantum States of Light: 2014-15

Prof Mete Atature

Prerequisites

A good grasp of electromagnetism and quantum mechanics is desirable. Atomic and Optical Physics major option is not required as a prerequisite, but it can be beneficial for some parts of the course.

Learning Outcomes and Assessment

These minor option lectures will provide a basic overview on the field of nonlinear optics from classical to quantum-mechanical descriptions of light. A survey of key nonlinear optical processes will be covered and recent advances of the field leading to the generation of nonclassical states of light displaying squeezing and entanglement will be discussed.

Synopsis

Introduction: Historical development of nonlinear optics, physical origins of nonlinear response, anharmonic oscillators, coupled wave equations, classical and quantum mechanical derivation of nonlinear optical susceptibility, symmetry properties of nonlinear susceptibilities.

Second-Order Nonlinear Interactions: second harmonic generation, depleted pump effects, Gaussian beams, pulse propagation in nonlinear medium.

General Parametric Processes: up-conversion, amplification, optical gain, sum- and difference-frequency generation, phase matching, quasi-phase matching.

Ultrafast Pulse Phenomena: amplitude and phase measurement of optical pulses using nonlinear optics, frequency-resolved optical gating and other techniques.

Nonlinearities in Refractive Index: Third-order nonlinearity, Kerr medium, intensity dependence and self-phase modulation, self-focusing, optical filamentation, soliton formation.

Nonclassical light: quantization of electromagnetic waves, parametric fluorescence, squeezed light, quantum correlations and photon statistics, Fock, thermal and coherent states of light, superposition and entanglement, vacuum field and spontaneous emission.

Supervisions: The course will include 3 supervisions to cover example problems and supplementary concepts.

BOOKS

Primary: Nonlinear Optics, R. W. Boyd, Academic Press, 2003

Principles of Nonlinear Optics, Y. R. Shen, Wiley-Interscience, 1984.

Introductory Quantum Optics, C. Gerry and P. L. Knight, 2004.

Auxiliary: Quantum Theory of Light, R. Loudon, OUP, 2000.

Optical Coherence & Quantum Optics, L. Mandel & E. Wolf, CUP, 1995. Quantum Electronics, A. Yariv, John Wiley & Sons, 1989.

Part III: Minor topic: Phase Transitions: 2016-17

Dr Michal Kwasigroch

Prerequisites

As a theoretical option, this course will prove challenging to students without a mathematical background. Although the course will develop methods of statistical field theory from scratch, students will benefit from having attended either the Theories of Quantum Matter or Quantum Field Theory course in Part III.

Learning Outcomes and Assessment

This course aims to develop a framework in which to describe critical properties associated with classical and quantum phase transitions, emphasising the importance and role played by symmetry and topology. The majority of the course will be involved in developing the important concept of universality in statistical mechanics. Connections will be made with quantum field theories of the standard model, and in particular, the Gauge Field Theory course.

Synopsis

Introduction to Critical Phenomena: Concept of Phase Transitions; Order Parameters; Response Functions; Universality.

Ginzburg-Landau Theory: Mean-Field Theory; Critical Exponents; Symmetry Breaking, Goldstone Modes, and the Lower Critical Dimension; Fluctuations and the Upper Critical Dimension; Importance of Correlation Functions; Ginzburg Criterion.

Scaling: Self-Similarity; The Scaling Hypothesis; Kadanoff's Heuristic Renormalisation Group (RG); Gaussian Model; Fixed Points and Critical Exponent Identities; Wilson's Momentum Space RG; Relevant, Irrelevant and Marginal Parameters; ε-expansions.

Topological Phase Transitions: Continuous Spins and the Non-linear σ-model; Running Coupling; XY-model; Algebraic Order; Topological Defects, Confinement, the Kosterlitz-Thouless Transition; Lattice Gauge Theory.

Quantum Phase Transitions: Classical/Quantum Mapping; the Dynamical Exponent; Quantum Rotors; Haldane Gap; Asymptotic Freedom; Quantum Criticality.

BOOKS

Statistical Physics of Fields, Kardar M (CUP 2007)
Principles of Condensed Matter Physics, Chaikin P M & Lubensky T C (CUP 2007)
Scaling and Renormalisation in Statistical Physics, Cardy J (CUP 1996)

Part III: Minor topic: Quantum Information: 2016-17

Prof Crispin Barnes, **Prof Crispin Barnes**

Prerequisites

There are no prerequisites for this course. It is a set of new concepts that people who have taken the IB quantum mechanics course could easily step into. You should expect your understanding of quantum mechanics to be challenged.

Synopsis

Introduction: The postulates of quantum mechanics - the Copenhagen Interpretation. Quantum entanglement. Density matrices.

Measurement 1: What constitutes a measurement? Schrödinger's cat and Wigner's friend. The Einstein-Podolsky -Rosen paradox.

Some alternative interpretations of quantum mechanics: Many worlds. Bohm's guiding waves. Transaction interpretation. Histories. Quantum-state diffusion.

Hidden variables theories: Bell's theorem; experimental tests.

Quantum Entanglement: Bipartite systems: Schmidt decomposition, reduced density matrix, entanglement measures. Tripartite systems.

Measurement 2: Positive Operator Value Measure (POVM); Weak measurements.

Decoherence: Decoherence time.

Quantum cryptography: The BB84 protocol. The no-cloning theorem. Eavesdropping strategies. Privacy amplification. Other protocols. Experimental realisations.

Quantum teleportation: Theoretical strategy and experimental realisations.

Quantum computing: Qubits. Logical operations. Algorithms for quantum computers: factorisation, database searches. Error correction. Possible systems for implementing quantum computing: ion traps; nuclear magnetic resonance; semiconductor quantum dots.

BOOKS

An easy to understand introduction to the subject can be found in the March 1998 edition of Physics World and articles on quantum information often appear in the news media.

The following books provide detailed coverage of parts of the course:

Quantum Computation & Quantum Information, Nielson MA & Chuang IL (CUP 2000)

The Physics of Quantum Information, Bouwmeester R, Ekart A, Zeilinger A (Spring 2000)

Introduction to Quantum Computation and Information, H.-K. Lo, S. Popescu and T. Spiller (World Scientific 1998). Note that this book may not be routinely stocked in bookshops and may have to be ordered.

Quantum Mechanics, Rae A I M (3rd edn IOP 1992).

The Interpretation of Quantum Mechanics, Onnes R (Princeton 1994).

Quantum Theory: Concepts and Methods, A. Peres (Kluwer 1993).

There are some very good resources on the World Wide Web such as at:

http://www.theory.caltech.edu/~preskill/ph229 (http://www.theory.caltech.edu/~preskill/ph229) - Lecture notes and examples for a course on Quantum Information taught by John Preskill at Caltech. Note however that this treatment is much more mathematical than the present course.

http://www.qubit.org (http://www.qubit.org) - The Quantum Information Research Group in Oxford.

http://www.cam.qubit.org (http://www.cam.qubit.org) - The Quantum Information Research Group in Cambridge.

Part III: Minor topic: Quantum Simulation: 2017-18

Dr U W Schneider

Prerequisites

While all concepts will be briefly reviewed, basic knowledge of Bose and Fermi statistics and the formalism of second quantization from Part II Advanced Quantum Physics is required. Familiarity with the Bloch wave formalism from Part II Quantum Condensed Matter and the content of the Part III Atomic and Optical Physics course is helpful but not required.

Learning Outcomes and Assessment

Quantum simulators utilize tailored quantum systems to experimentally investigate fundamental models and thereby understand the behavior of relevant real systems in a fashion broadly similar to the use of wind tunnels to study aerodynamics.

This course will mostly focus on many-body systems, which, due to their exponentially large Hilbert spaces, are not amenable to exact classical simulations. Prime examples are emergent phenomena in condensed matter systems (Magnetism, (High-Tc) Superconductors, …) or high energy physics (Quark-Gluon plasmas).

Synopsis

Introduction - The challenge of many-body physics
• Exponential scaling of Hilbert space, Limits for exact solutions
• Examples of emergent phenomena: Mott insulators, Superfluidity & Superconductivity, Magnetism, Strongly correlated systems, Quantum Hall effect, Topology, Spin liquids

Synthetic many-body systems
• Cold atoms including Optical Lattices and Microtraps
• Ion traps
• Others: Superconducting qubits, Rydberg atoms, NV centers.

Phase Transitions and Quantum Fluids
• Superfluidity, Landau criterion, vorticity
• Degenerate Fermi gases, Cooper instability, BCS state, Feshbach resonances and BEC-BCS crossover
• Influence of dimensionality

Simulating lattice effects
• Bosonic Mott insulators
• Fermionic Mott insulators and Heisenberg Antiferromagnet
• t-J models, d-wave superfluids
• Simulating classical magnetism, Ising and XY model

Beyond ground states
• Closed system quantum thermodynamics
• Critical temperatures / critical entropy scales
• Eigenstate thermalization hypothesis / Measuring entanglement
• Alternatives to thermalization: Integrable systems, Many-body localization

Out-of-Equilibrium dynamics
• Transport properties / diffusion

- Light-cone effects and correlation measurements
- Relativistic theories, Dirac equation and Klein tunneling
- Structure Formation, Kibble-Zurek Mechanism
- Driven-dissipative systems, reservoir engineering

Topological effects

- Artificial gauge fields
- Periodic modulations and Floquet theory
- Hall conductance and topological insulators
- Thouless charge and spin pumps
- Non-Abelian gauge fields

Part III: Minor topic: Superconductivity and Quantum Coherence: 2014-15

Prof Gil Lonzarich

Prerequisites

It is assumed that students taking this course will have also done Advanced Quantum Condensed Matter Physics.

Learning Outcomes and Assessment

The course presents a unified treatment of superconductivity, superfluidity and Bose-Einstein condensation as an introduction to the general problem of quantum coherence.

Synopsis

Introduction to Superconductivity: Historical overview; superconducting materials; macroscopic properties; Meissner effect and levitation; type-I and type-II states; Landau theory; critical field Bc.

Ginzburg-Landau Theory: The Ginzburg-Landau free energy and Ginzburg-Landau equations; London equations; penetration depth and coherence length; gauge transformations and gauge symmetry breaking (broken symmetry in internal space).

Vortex Matter: Flux quantization; vortex lines and vortex lattice; the critical fields Bc1 and Bc2, type-I and type-II superconductivity; vortex pinning and critical currents; vortex liquid state.

Josephson Effect and SQUIDs: DC and AC Josephson effects; gauge invariant phase; quantum interference for weak links; the DC SQUID; applications.

Superfluidity: Phenomenology; superfluid wavefunction; two-fluid model and the fountain effect; flow quantization and vortices; first and second sound; rotons; Landau's critical velocity.

Bose-Einstein Condensation (BEC): Ultra-cold atomic gases; BEC with weak interactions; coherent states and second quantization; the Bogoliubov Theory and connection to the phenomenological Ginzurg-Landau Theory.

The Bardeen-Cooper-Schrieffer (BCS) Theory: BEC to BCS cross-over; Cooper pairs; the BCS wavefunction; the Bogoliubov quasiparticles and the energy gap; experimental evidence for the validity of the BCS theory; order parameter and the Ginzburg-Landau coherence length.

Current Problems in Superfluidity and Superconductivity: Unconventional forms of quantum order; p-wave spin-triplet superfluidity in 3He; spin-triplet superconductivity in Sr2RuO4 and UGe2; d-wave superconductivity in the high Tc cuprates; phase-sensitive measurements of the gap anisotropy; the pseudo-gap state; unconventional mechanisms for superconductivity; collective modes in superfluids and superconductors; the Anderson-Higgs mechanism and superconductivity.

BOOKS

Superconductivity, Superfluids and Condensates, Annett J F (Oxford University Press, 2004)

Superconductivity of Metals and Cuprates, Waldram J R (Institute of Physics Publishing, 1996)

Also:

Bose-Einstein Condensation in Dilute Gases, Pethick C J and Smith H (Cambridge University Press, 2002)

Introduction to Superconductivity, Tinkham M (McGraw-Hill, 1996)

Part III: Minor topic: The Physics of Nanoelectronic Systems: 2016-17

Prof Chris Ford, **Prof Charles Smith**

Prerequisites

The Part II Quantum Condensed Matter Physics course would be useful but is not vital.

Learning Outcomes and Assessment

This course aims to introduce students to the transport and optical physics of a range of systems where electrons are confined within less than about 100 nm in one or more dimensions. Familiarity with some solid-state physics in assumed (the Part II Quantum Condensed Matter Physics course would be useful but is not vital). On completion of the course, students should be able to appreciate the physics of low-dimensional systems, to describe experiments to measure such systems, and to calculate straightforward problems related to the field.

Synopsis

Introduction to low dimensional systems: length and energy scales, overview of fabrication techniques and possibilities, applications of low-dimensional physics, *examples, top-down vs bottom-up*.

Electronic properties in low-dimensional systems: band engineering; heterostructures, 2D electron gas.

Ballistic motion, collimation, experiments.

Quantum transport in 1D wires: eigenstates, conductance, saddle-point potential, d.c. bias.

Electrons in high magnetic fields: Hall effects, Landau levels, oscillation of the Fermi energy. Landauer-Büttiker formalism, integer quantum Hall effect, edge states.

Electron-electron interactions, quasiparticles. Fractional quantum Hall effect, composite fermions.

Transport through 0D quantum dots, Coulomb blockade, resonant tunnelling, charge detection, single-electron dots, artificial atoms, antidots. Surface-acoustic-wave current source.

Optical properties. Optical transitions, excitons. Semiconductor lasers as example of effects of confinement. S-K growth, self-assembled quantum dots, microcavities, coupled modes. Single and entangled photon sources for quantum cryptography.

Spintronics: Giant magnetoresistance (briefly), tunnelling magnetoresistance (spin-valve) in layered structures. Spin injection from a ferromagnet to a semiconductor.

Quantum computation (briefly). Spin in a quantum dot as a qubit for quantum computation. Detection and manipulation of single spins – charge-to-spin conversion, electron spin resonance.

Molecular systems. Self-assembly. Conjugated polymers – electronic structure and devices. Transport in carbon nanotubes and graphene. Single-molecule transport. Nanocrystals, nanorods.

BOOKS

A comprehensive set of notes will be given out. No book covers the whole course. Background material may be found in semiconductor text books such as Kittel, and Ashcroft and Mermin.

Low-dimensional Semiconductors: Materials, Physics, Technology, Devices, Kelly M J (Clarendon Press 1996).

The physics of low-dimensional semiconductors: an introduction, Davies J H (CUP 1997).

Nanophysics and Nanotechnology, E. L. Wolf (Wiley-VCH 2007).

Part III: Philosophy of Physics: 2014-15

Dr Jeremy Butterfield

Synopsis

This course of four lectures offers an introduction to the philosophy of modern physics. This is a technical area, although an interdisciplinary one. Its closest cousin is the branch of physics called 'foundations of physics'. Thus in both areas, we examine the mathematical structures of physical theories. This course will emphasise two specific theories: relativity and quantum theory.

The first and second lectures will survey the philosophy of relativity theory. I will emphasise Einstein's famous 'hole argument', as a lesson about the foundations of general relativity. Einstein devised this argument in late 1913, as an argument *against* general covariance: namely, that any generally covariant theory would be radically indeterministic. Late in 1915, after he had found the field equations of general relativity, which *are* generally covariant, he re-assessed the argument as showing only that we should not think of spacetime points as objects, on pain of a radical indeterminism. Broadly speaking, there the matter rested, until about twenty years ago, when the assessment of the argument became again a live topic, because of its connection with other issues in the interpretation of general relativity. The controversy continues today.

The third and fourth lectures are devoted to the measurement problem of quantum theory: in short, Schroedinger's cat. There are many aspects, technical and philosophical (and even historical), one could discuss about this. I will in part be guided by the interests of the class. But here are two:

(i) The nature and role of decoherence. In short, decoherence gives a dynamical basis to the selection of a preferred quantity, but does nothing to 'select' an individual, definite measurement-outcome, or more generally a definite macroscopic reality.

(ii) The current prospects for the Everett interpretation (also known as: the relative-state, or many worlds, interpretation). In short, the interpretation is very strange, but its current prospects are surprisingly good!

BOOKS NB: Most of the books cited will surely be in your College library.

All four Lectures: The Stanford Encyclopedia of Philosophy (SEP), and the Pittsburgh philosophy of science e-arXive, both available online, have many good philosophy of physics articles.

First and second Lectures:

Theoretical Concepts in Physics, Longair M, (2nd edn CUP 2003); Chapter 17.1-2.

SEP article on Einstein's philosophy of science: http://www.seop.leeds.ac.uk/entries/einstein-philscience/ (http://www.seop.leeds.ac.uk/entries/einstein-philscience/)

SEP article on Einstein's Hole Argument

http://www.seop.leeds.ac.uk/entries/spacetime-holearg/ (http://www.seop.leeds.ac.uk/entries/spacetime-holearg/)

Third and fourth Lectures:

Speakable and Unspeakable in Quantum Mechanics, Bell J S (2nd edn CUP 2004); Chapters 20 and 23

Philosophical Concepts in Physics, Cushing J T (2nd edn CUP 1998); Chapters 20-22.

SEP article on Bell's theorem:

http://www.seop.leeds.ac.uk/entries/bell-theorem/

SEP article on decoherence in quantum mechanics:

http://www.seop.leeds.ac.uk/entries/qm-decoherence/ (http://www.seop.leeds.ac.uk/entries/qm-decoherence/)

Pittsburgh e-arXive articles on the Everett interpretation include the following two:

philsci-archive.pitt.edu/archive/00000208/ (http://philsci-archive.pitt.edu/archive/00000208/)

and

philsci-archive.pitt.edu/archive/00000681/ (http://philsci-archive.pitt.edu/archive/00000681/)

Part III: Projects: 2017-18

Prof Charles Smith

Synopsis

Each Part III and MASt Physics student is required to undertake a project worth about one-third of the final tripos mark. A project is aimed at investigating a topic of current interest in physics, giving an opportunity to perform original work and develop new ideas. The precise form of the project may vary from topic to topic and will be specified by the supervisor.

The various types of project work available are as follows:

Experimental Project: generally this is an extended investigation, which is open-ended and gives considerable freedom of approach.

Theoretical Project: this is a small-scale theoretical research project, requiring an element of original theoretical development and/or computation.

Computing Project: this generally requires the writing or use of computer programs to investigate some aspect of physics. Some theoretical work is usually required as a basis for the program.

The project abstracts, provided by members of staff and Senior Research workers, are available on the web: see (http://www-teach.phy.cam.ac.uk/students/courses/projects/100). Students may also suggest projects of their own, but they must have a supervisor (who may be external) and the project must be approved in advance by Professor Smith. Students interested in a particular project should discuss it as soon as possible with the relevant supervisor. The list of projects on the web will be continuously updated to show which ones have already been taken. On Wednesday the 4th of October there will be a project fair with a number of projects displayed outside the Pippard lecture theatre. For many projects, supervisors will be on hand to explain the project in more detail.

Students must choose their projects by the middle of the third week of Michaelmas term (Wednesday 25th October). Supervisors will decide, by that same deadline, which students may undertake their projects. Supervisors may allocate projects earlier than this date, but they are asked not to make a decision until Friday, October 13th 2017, at the earliest. The purpose of this delay is to allow students time to talk to several supervisors and to allow supervisors to find the most suitable students for their projects. In response to student concerns, a code of practice for projects allocations has been agreed by both the Teaching Committee and the Staff Student Consultative Committee – see below for the full version.

Supervisors will offer the project to a student using the web interface, where they will also indicate the safety risks associated with the project, and students will be asked to indicate their acceptance of the offer, via email. In the interests of fairness both to the supervisor and to fellow students, students will not normally be allowed to change their project once they have accepted an offer.

Safety

In all research there are possible risks associated with performing the work. Each supervisor will indicate what the risks are associated with their experiment on the sign up form. Before the project starts the student and supervisor will sign a project card which will confirm that the student will be trained appropriately to cover the risks associated with the project. No project will start until this card is received in the Undergraduate Office. The card will also list the name of the “day to day” supervisor and the laboratories in which the student will be working. If there is a safety hazard associated with the project then supervisors will suggest appropriate safety courses for the student to go on. The laboratory will provide these safety courses, which will be held in the Michaelmas term. Attendance records will be taken at these lectures and no student will be allowed to start their project unless they have attended the appropriate courses. Supervisors and Students will now complete and sign a risk assessment form showing they understand the risks associated with their project experiments. These forms will be prepared with the help of the supervisor and these will be handed in to the Safety Officer before the start of experiments or before Friday, November 3rd 2017, whichever is the sooner. Changes of experimental procedure during the project will require an updating of the risk assessment forms. A set of safety lectures will be held on Thursday, 26th October 2017 at 3:30pm in the Small Lecture Theatre, which all must attend. At the end of the lecture, students will pick up their laboratory note books from the Undergraduate office.

Where work is performed in Laboratories outside the Cavendish Laboratory, the Undergraduate Office will write to the department concerned drawing attention to the fact that one of our students will be working there to get their agreement on the project going ahead. If for any reason a project needs to move between departments the Undergraduate Office must be informed and the new department made aware of the arrangements.

Expected time students should spend on the project

The project workload is expected to take up one third of your time for the year:

Michaelmas Term: approximately one sixth of your project time spread through the term.

Lent Term: approximately four sixths of your time with concentrated effort at the beginning and end of the term.

Easter Term: one sixth of your project work, at the beginning of Full Term.

Students should not devote too much time to the project to the detriment of their preparation for the examinations. Students should schedule their time carefully, and start as early as possible, so as not to conflict with preparation for exams during the vacations.

Laboratory Note Book

Students will be required to keep a laboratory note book during the project. This will act as a day to day record of the project work and will be handed in with the project write up. Although the note book will not be marked, the information in it will be used in assessment of the project and will help indicate how the day to day issues that come up in the research were dealt with. During the safety course there will be a short presentation on what is expected in the Laboratory note book.

Progress reports

Students will be asked to complete two progress reports. At the end of the Michaelmas Term you must submit an Initial Report (one copy; between 4 and 6 A4 pages in length). This Initial Report should describe the project in your own words, putting the physics into context (including references to the relevant literature) and describing the goals of the project; it must also include a project plan. This report should be signed by your supervisor to indicate his or her agreement with the plan and should be handed in by Friday, December 1st 2017. The signed copy of the Initial Report will be retained by the Undergraduate office and forwarded to the assessor in Easter Term – failure to submit an Initial Report will result in the loss of 5% of the available project marks. The second report is a simple “tick box” form, which will be issued during week 3 of the Lent term. This will invite you to report any problems with your project, and to confirm that a presentation has been scheduled. This report card must be returned to the Undergraduate office by Wednesday, February 7th 2018. The second report will not form part of any assessment, but will allow any problems to be identified by Professor Smith well before the time the project has to be handed in.

It is very important that students bring any unforeseen delays or other problems with their projects to Professor Smith’s attention at the earliest possible opportunity. The earlier such problems are addressed, the more chance there is of taking suitable remedial action.

Supervisions and presentation

Supervisors should be academic staff members or have a position that allows them to supervise PhD or Masters Students. They may delegate some of the day to day supervision to members of their group, but supervisors will be available to mark projects and attend project vivas between the dates of project submission and the project assessors meeting in early June. Supervisors should offer up to six supervisions on the project. One of these should be in the form of a presentation of preliminary project results; either to the supervisor’s research group (strongly encouraged) or to a small group of say 4 — 6 project students and supervisors. It is expected that supervisors will organise these presentations in about the seventh week of the Lent term, (or later, perhaps even at the very start of the Easter term, if mutually acceptable). Students will receive feedback on the content and presentation of their projects from the supervisors and others present, which should help them with their oral exam. This form of presentation is aimed at developing communication and presentational skills. Failure to give this presentation will result in the loss of 5% of the available marks for the project.

The project write-up

The project should usually be presented in the style of a paper published in a scientific journal. The main text (excluding appendices and abstract) should be concise (20–30 pages, 5000 words maximum (excluding references)). The text should describe and explain the main features of the project, the methods used, results, discussion and conclusions, and should be properly referenced. Detailed measurement records, calculations, programs, etc. should be included as appendices. (Programs of more than a few hundred lines can be submitted – one copy only – on a memory stick, please ensure it is labelled with your Examination number.) In addition, there must be an abstract of at most 500 words.

This final write-up is an important part of the project and must be the student's own work. A lecture on Project report writing will be given on Friday 19th January 2018 at 3:00pm in the Small Lecture Theatre. Once the majority of the research work has been completed, the student and supervisor should discuss the general structure and content of the report before writing is started. Thereafter, the student must write the final report without advice on the report from the supervisor, although discussion of the scientific results is allowed during this period. A set of handy tips and information is given in the booklet entitled Keeping Laboratory Notes and Writing Formal Reports, which is handed out to students at the start of the year and is also available on the web - make sure you get one.

Submission of the project

The deadline for submission of the project is:

4:00pm on the third Monday of Easter Full Term (14th May 2018)

A request for a delay in the hand-in date of your project report due to illness must go through your Director of Studies and then be agreed by the Applications Committee. Treat this deadline like you would an exam date.

Two copies of the project plus your laboratory note book should be handed in to the Undergraduate Office (Room 212B, Bragg Building) in person before the submission deadline. In order to preserve anonymity when your project is looked at by the Part III examiners, your name must not appear on the project itself. Two cover sheets, available from the Undergraduate Office, should be attached to the front of each project. The blue cover sheet, which has a space for both your name and candidate number, goes on the outside. The green cover sheet, which has only your candidate number, goes immediately behind it. (The blue sheet will be removed before the Part III Examiners receive your report). You should ensure that your candidate number appears on the first page of your project, together with the title of the project and your supervisor’s name.

The blue cover sheet contains the following declaration, which you should sign: Except where specific reference is made to the work of others, this work is original and has not been already submitted either wholly or in part to satisfy any degree requirement at this or any other university.

Plagiarism

As a result of a case of plagiarism in a Part III project a few years ago, you are now asked to submit an electronic version of your project which can be checked for plagiarism using the Turnitin system. This system will only be used if the assessor or supervisor has identified what looks like plagiarism in part of the project write up. The project coordinator may then submit that project to the Turnitin system. The department's statement on plagiarism can be found at www.phy.cam.ac.uk/students/teaching/resources-links/plagiarism.

The lecture on how to write up your report given in the Lent term will also cover advice on how to properly cite the work of others.

Project Assessment

As soon as possible after submission, the project will be assessed by two people, normally the supervisor and another staff member (the assessor), who will conduct an informal oral examination of the student on the work. The assessor, who will be appointed by the Teaching Committee, will not usually be a specialist in the field. The student will be asked to present a short verbal summary, normally uninterrupted, of the project during the interview. A projector will be made available if requested in advance. Students should expect to be contacted by their supervisor shortly after handing their project in, to arrange the oral examination. Students should be available to attend their project viva from the submission date to the end of May.

The supervisor and assessor will write separate reports plus a joint report to the Part III Examiners and will recommend a mark. These marks are not necessarily final and may be amended by the examiners, who also look at the projects. The marks and reports will be handed in by the end of May at the latest.

The following guidelines for allocation of marks to Part III Projects will be given to assessors. Each heading carries equal weight.

Scientific content: How much appropriate understanding of science (particularly physics) was shown?

Quality of work: How carefully/accurately/successfully was the work planned and performed (the laboratory note book will be used to help assess this). Was an appropriate amount of relevant material included?

Communication skills: Report: was the report well written and clearly organised, with clear and well-balanced arguments, appropriate use of figures and tables, etc? Viva: was the student able to summarise the work and to respond coherently to questions?

After the oral examination, the assessors will return their report and recommended marks, along with both (signed) copies of the projects and the Laboratory note books, to the Undergraduate Office (Room 212B, Bragg Building). After publication of the Part III Class List, students may, if they wish, retrieve one copy of their project from the Undergraduate Office.

If there are any questions about these arrangements come and see Professor Charles G. Smith, in the Mott Building, Room 358, telephone 37483, e-mail cgs4@cam.ac.uk.

Further information:

Allocation of Projects

In response to concerns about the transparency of the project allocation process, the following text has been approved by the Teaching Committee and the Staff Student Consultative Committee. Project supervisors are enjoined to act within the spirit of the following code.

Code of Practice for allocation of Part III Projects

Part III Projects cover the full range of research in Physics, involving analytical, experimental and computational work in various proportions. They may involve working in research groups either in the Department of Physics or elsewhere in the University. Part III projects are often closely linked to the supervisor's own research, and may result in single or joint publication. Unlike Part II Research Reviews, the successful conclusion of a project requires a reasonable match between the skills and interests of the student and those required by the project. It is reasonable that the project supervisor should be the judge of these: it is not therefore appropriate to assign projects by a general lottery, for example.

Supervisors are, however, asked to ensure fair play in the allocation process. This requires that the requisite skills be fully advertised in the project abstract, and that the supervisor should be prepared to discuss the project with all students who make serious inquiries. He or she should also keep an open mind until the end of the consultation period, and should then make and announce a decision as quickly as possible, to avoid keeping students "on a string". If more than one student indicates serious interest, the supervisor should make clear how he or she intends to make the allocation – in some cases this might be as simple as drawing names from a hat, while for an analytical project closely tied to the supervisor's research project, it might be on the basis of performance in TP1 and/or TP2 in the previous year. The essential point is that whatever method is used should be seen to be appropriate and fair, should be clear to the students, and should be settled expeditiously once the system opens to allocations. Students can then make a reasonable guess at their chances, and can pursue such other projects as they wish.

Supervisors may create projects expressly for a particular student, and are encouraged to do so (either in response to the student's initiative in proposing the project, or in response to strong demand). However, such projects should not be advertised to the class via the web, but should be flagged as "hidden" or "inactive" until allocated. As well as not raising false hopes, this will also avoid having to answer unwanted inquiries.

Out of fairness to supervisors, students are not normally allowed to change projects once they have been allocated one and have accepted it. This places an additional responsibility on supervisors to ensure a fair, transparent and efficient allocation.

Further Health and Safety considerations

Supervisors should always discuss safety aspects of their projects with the students concerned, mentioning potential hazards and procedures with which students may not be familiar. Supervisors should ensure that the student has read and understood the relevant risk assessments for the activities to be carried out. For new activities, risk assessments should be carried out by the supervisor in consultation with the student. For safety reasons, students must at all times remain within shouting distance of help, and, if performing an experiment, sign in a book provided by the supervisor, on each occasion when they start and when they finish work. They are only allowed to work on experiments in the Department outside normal lab hours in exceptional circumstances, by prior arrangement with the supervisor, and with the approval of the Departmental Safety Officer and the Head of Department. Supervisors must ensure that students are aware of general and experiment-related emergency procedures. By accepting the project, students are indicating their agreement to abide by these and other safety rules.

Use of bibliographic databases

The Web of Science database (http://wok.mimas.ac.uk) may be used to find relevant papers. Students must first sign a form (available from the Rayleigh Library) unless they signed one last year

Part II: Vacation Projects: 2017-18

Dr Rachael Padman

Prerequisites

If it is intended to use vacation work for credit, then approval must be requested before the end of **August** each year, by submitting an application form (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/LongVacApplicationForm.pdf) to the Teaching Office, Room 212B, Bragg Building, giving details of the project.

Every project will contain a substantial element of independent or original work in physics or a closely-allied subject. That may be theoretical development, equipment design and/or development, and practical or computational experimentation. There is scope for a very liberal interpretation of the guidelines as long as the project draws directly on skills gained as part of the physics course -- these may come from individual lecture courses, or may require the application of say quantitative analysis using physics methods to a problem from a different area of science or engineering.

Certain guidelines must be satisfied before approval is granted:

1. The project will normally be of at around two months' duration and must include a substantial element of independent or original work. It is important that the project includes a significant amount of physics and is not, to take two examples, simply a series of routine measurements or entirely devoted to computer programming.
2. An abstract of half to one page of A4 should be submitted describing the project.
3. Details of the work must not be restricted by commercial or other considerations (although precautions can be taken to safeguard patent applications)'
4. A suitably qualified supervisor who will be responsible for the project will need to fill in part of the application form outlining the proposed work before it can be approved as a suitable project. The supervisor should also be willing to write a brief report describing the work that has been done and giving an assessment of the quality of the work. These reports will normally be requested from supervisors shortly after the undergraduate has submitted his or her report on the project

Gaining approval for the project does not commit the student to using the project for examination credit: it is still possible (up until the due date for the report below) for the student to decide not to submit a report and gain credit instead from some other allowed item of further work. In this case the student should inform the Helen Marshall in the Teaching Office (hm328@cam.ac.uk) of the change in plans as soon as possible.

Learning Outcomes and Assessment

Outcomes will vary greatly depending on the nature of the project. Approval to submit the project for credit will not be granted unless the project provides at least some of:

- Transferable skills: team work, communication, project planning...
- Research skills: literature surveys, programming in relevant languages, database design, relevant experimental skills (clean room, cryogenics, data acquisition....)

Assessment

The deadline for submission is 4:00pm on the first FULL Monday in Michaelmas term. Two paper copies of the report on the project written by the student should be submitted to the Undergraduate Office (Room 212B, Bragg Building). A pdf of the report should also be uploaded to the TIS by the same deadline of 4:00pm. The report should be *concise*, 20-30 pages, 5000 words maximum. In order to preserve anonymity when your report is looked at by the examiners, your name must not appear on the report itself, but only on the cover sheet which you will be given when you hand it in.

The project will be awarded a mark based on the report and on a 30-minute oral examination carried out by two assessors, usually members of the Cavendish staff. The oral examinations take place during the Michaelmas Term.

Marks are split equally between three areas:

- Scientific content: How much appropriate understanding of science (particularly physics) was shown?
- Quality of work: How carefully/accurately/successfully was the work planned and performed? Was an appropriate

amount of relevant material included?

- Communication skills: Report: was the report well written and clearly organised, with clear and well-balanced arguments, appropriate use of figures and tables, etc? Viva: was the student able to summarise the work and to respond coherently to questions?

Synopsis

Scientific work during the Long Vacation prior to your third or fourth year can count as project work worth one unit of Further Work in Part II, or one Minor Topic or unit of Further Work in Part III. Forms (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/LongVacApplicationForm.pdf) are available from the Teaching Office, the deadline for approval of the project is the beginning of September. You will be required to name in advance a suitably qualified on-site supervisor who is willing to write retrospectively to Dr Padman describing the work you have done and giving an assessment of your effectiveness. Normally the programme must be of at least two months duration and must include a substantial element of independent or original work. It is important that the project includes a significant amount of physics and is not, for example, simply a series of routine measurements or entirely devoted to computer programming.

Arranging Placements

It is up to individual students to arrange their own projects with research laboratories in industry and elsewhere. Students may be able to set up a suitable project with an industrial firm already sponsoring them, or by approaching other research laboratories. All arrangements for payment and other conditions of employment during the project period are the responsibility of the student.

Vacation projects within the University may be offered through the Undergraduate Research Opportunities Programme (UROP). See http://to.eng.cam.ac.uk/teaching/urops/ (http://to.eng.cam.ac.uk/teaching/urops/) for details. Some of these projects may be suitable as assessed Long-Vacation Work. The teaching web pages www-teach.phy.cam.ac.uk/teaching/vacWorkDB.php (http://www-teach.phy.cam.ac.uk/teaching/vacWorkDB.php) offers other useful suggestions.

Further Information

- Form to request approval of projects (.docx (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/long-vac-application-form.docx)) (.pdf (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/LongVacApplicationForm.pdf))
- Further guidelines (http://www.phy.cam.ac.uk/students/teaching/teachingfiles/long-vac-guidelines.pdf/view)
- Physics vacation work database (http://www-teach.phy.cam.ac.uk/teaching/vacWorkDB.php)
- UROPs website (http://to.eng.cam.ac.uk/teaching/urops/)