University of London

MSci Intercollegiate Planning Board

Physics MSci

STUDENT HANDBOOK

Intercollegiate taught courses for 2018-2019 session

This version is correct as at 16 January 2019

Contents

1 Courses and Teachers

Each course has a code number used by the Intercollegiate MSci board, shown at the left hand side. Colleges use local codes for the courses they teach. The *number* is usually the same as the MSci code, but some are different; beware!

All courses are a half course unit (15 credits). In QMUL language, they are a full course unit.

The list shows the course code and title, the term in which it is taught, the course lecturer, the home College and the local course. On the adjacent page are the email addresses of the course leaders and any websites connected to the course.

Students will undertake one or more project-related courses in accordance with practice at their own colleges.

eve Course taught at QMUL in the *evening* this session.
Course unavailable to UCL students for syllabus reasons
~ Course unavailable/potentially unavailable to RHUL students for syllabus reasons
+ Course taught by the *Mathematics* department at KCL
€ Course content is mathematically demanding

In the interest of balance and/or for syllabus reasons

- **Students should take no more than three KCL maths courses**
- **Students should take no more than one of the following:**
    - **4541** Supersymmetry
    - **4545** Supersymmetric Methods in Theoretical Physics
- **Students should take no more than two of the following:**
    - **4431** Molecular Physics
    - **4473** Theoretical Treatments of Nano-systems
    - **4476** Electronic Structure Methods

No	Course Title	Term	Teacher	Taught by	Local no	Lecturer email address	Webpage
4201	Math Methods for Theoretical Physics ~	1	Dr Jean Alexandre	KCL	7CCP4201	jean.alexandre@kcl.ac.uk	
4205	Lie Groups and Lie Algebras €	1	Prof Jurgen Berndt	KCL+	7CCMMS01U/T	jurgen.berndt@kcl.ac.uk	http://www.mth.kcl.ac.uk/courses
4211	Statistical Mechanics	2	Prof B P Cowan	RHUL	PH4211	b.cowan@rhul.ac.uk	http://personal.rhul.ac.uk/UHAP/027/PH4211/
4215	Phase Transitions	1	Prof M Dove	QMUL	SPA7013U/P	martin.dove@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=3316
4226	Advanced Quantum Theory	1	Dr A Olaya-Castro	UCL	PHAS0069	a.olaya@ucl.ac.uk	
4228	Advanced Topics in Statistical Mechanics	2	Prof I J Ford	UCL	PHAS0061	i.ford@ucl.ac.uk	
4242	Relativistic Waves & Quantum Fields	1	Prof G Travaglini	QMUL	SPA7018U/P	g.travaglini@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=3307
4245	Advanced Quantum Field Theory	2	Dr S Ramgoolam	QMUL	SPA7001U/P	s.ramgoolam@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=3309
4246	Functional Methods in Quantum Field Theory	2	Dr R Russo	QMUL	SPA7024U/P	r.russo@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=4584
4247	Differential Geometry in Theoretical Physics	1	Dr C Papageorgakis	QMUL	SPA7027U/P	c.papageorgakis@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=6575
4319	Galaxy Dynamics, Formation and Evolution	1	Dr I Ferreras	UCL	PHAS0065	ipf@mssl.ucl.ac.uk	
4336	Advanced Physical Cosmology	2	Dr A Pontzen	UCL	PHAS0067	a.pontzen@ucl.ac.uk	
4421	Atom and Photon Physics	1	Dr A Emmanouilidou	UCL	PHAS0105	a.emmanouilidou@ucl.ac.uk	
4425	Photonics & Metamaterials (Advanced Photonics)	2	Dr F Rodriguez-Fortuno	KCL	7CCP4126	francisco.rodriguez_fortuno@kcl.ac.uk	
4427	Quantum Computation and Communication	2	Dr A Serafini/ Dr S Bose	UCL	PHAS0070	a.serafini@ucl.ac.uk/s.bose@ucl.ac.uk	
4428	Quantum Electronics of Nanostructures	2	Prof O Astafiev	RHUL	PH4428	oleg.astafiev@rhul.ac.uk	
4431	Molecular Physics	2	Dr J Blumberger	UCL	PHAS0099	j.blumberger@ucl.ac.uk	

No	Course Title	Term	Teacher	Taught by	Local no	Lecturer email address	Webpage
4442	Particle Physics	1	Prof R Saakyan	UCL	PHAS0072	r.saakyan@ucl.ac.uk	http://www.hep.ucl.ac.uk /~markl/teaching/4442
4450	Particle Accelerator Physics	1	Dr P Karataev	RHUL	PH4450	pavel.karataev@rhul.ac.uk	http://moodle.rhul.ac.uk/ course/view.php?id=250
4455	Collider Physics	2	Dr C White	QMUL	SPA7029U/P	christopher.white@qmul.ac.uk	
4471	Modelling Quantum Many-Body Systems	1	Dr J Bhaseen	KCL	7CCPNE05	joe.bhaseen@kcl.ac.uk	
4472	Order and Excitations in Condensed Matter	2	Prof N Skipper	UCL	PHAS0075	n.skipper@ucl.ac.uk	
4473	Theoretical Treatments of Nano-systems	2	Prof. M Van Schilfgaarde/ Prof L Kantorovitch	KCL	7CCP4473	lev.kantorovitch@kcl.ac.uk	
4475	Physics at the Nanoscale	1	Dr V Antonov	RHUL	PH4475	v.antonov@rhul.ac.uk	http://moodle.rhul.ac.uk/ course/view.php?id=249
4476	Electronic Structure Methods	2	Dr A Misquitta	QMUL	SPA7008U/P	a.j.misquitta@qmul.ac.uk	http://qmplus.qmul.ac.uk/ course/view.php?id=3317
4477	Computer Simulation in Condensed Matter	2	Prof K Refson	RHUL	PH4477	keith.refson@rhul.ac.uk	
4479	Advanced Condensed Matter	1	Dr Cedric Weber	KCL	7CCP4931	cedric.weber@kcl.ac.uk	
4501	Standard Model Physics and Beyond	2	Prof N Mavromatos	KCL	7CCP4501	nikolaos.mavromatos@kcl.ac.uk	http://keats.kcl.ac.uk/cou rse/view.php?id=22727
4512	Nuclear Magnetic Resonance	2	Dr C P Lusher	RHUL	PH4512	c.lusher@rhul.ac.uk	http://moodle.rhul.ac.uk/ course/view.php?id=247
4515	Statistical Data Analysis	1	Prof G D Cowan	RHUL	PH4515	g.cowan@rhul.ac.uk	http://www.pp.rhul.ac.uk/ ~cowan/stat_course.html
4534	String Theory and Branes €	2	Prof N Lambert	KCL+	7CCMMS34U/T	neil.lambert@kcl.ac.uk	http://www.mth.kcl.ac.uk/ courses
4541	Supersymmetry €€	2	Prof C Herzog	KCL+	7CCMMS40U/T	christopher.herzog@kcl.ac.uk	http://www.mth.kcl.ac.uk/ courses
4545	Supersymmetric Methods in Theoretical Physics	2	Dr M Buican	QMUL	SPA7031U/P	m.buican@qmul.ac.uk	
4600	Stellar Structure and Evolution ~	1eve	Prof R. P. Nelson	QMUL	SPA7023U/P	r.p.nelson@qmul.ac.uk	http://qmplus.qmul.ac.uk/ course/view.php?id=2268

No	Course Title	Term	Teacher	Taught by	Local no	Lecturer email address	Webpage
4601	Cosmology ~	1	Dr D Mulryne	QMUL	SPA7005U/P	d.mulryne@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=3371
4602	Relativity and Gravitation #	1	Dr T Clifton	QMUL	SPA7019U/P	t.clifton@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=3299
4605	Astroparticle Cosmology	2	Prof M Sakellariadou	KCL	7CCP4600	Mairi.sakellariadou@kcl.ac.uk	
4606	Advanced Cosmology	2	Dr K Malik	QMUL	SPA7028U/P	k.malik@qmul.ac.uk	
4616	Electromagnetic Radiation in Astrophysics	2eve	Dr G Anglada-Escudé	QMUL	SPA7006U/P	g.anglada@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=2457
4620	Dark Matter and Dark Energy	1	Prof M Fairbairn	KCL	7CCP4935	malcolm.fairbairn@kcl.ac.uk	
4630	Planetary Atmospheres	2	Dr G Jones	UCL	PHAS0063	ghj@mssl.ucl.ac.uk	http://www.mssl.ucl.ac.uk/teaching/UnderGrad/4312.html
4640	Solar Physics	2	Prof L van Driel-Gesztelyi/ Prof L Green/ Dr D Long	UCL	PHAS0064	Lidia.vanDriel@obspm.fr/ lucie.green@ucl.ac.uk/ david.long@ucl.ac.uk	http://www.mssl.ucl.ac.uk/~lvdg/
4650	Solar System	1eve	Prof C Murray	QMUL	SPA7022U/P	c.d.murray@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=2167
4660	The Galaxy	2eve	Dr N Cooper	QMUL	SPA7010U/P	n.cooper@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=2643
4680	Space Plasma and Magnetospheric Physics	2	"Dr J Rae/ Prof C Owen	UCL	PHAS0074	jonathan.rae@ucl.ac.uk/ c.owen@ucl.ac.uk	http://www.mssl.ucl.ac.uk/teaching/UnderGrad/4665.html
4690	Extrasolar Planets & Astrophysical Discs	2	Dr S Paardekooper	QMUL	SPA7009U/P	s.j.paardekooper@qmul.ac.uk	http://qmplus.qmul.ac.uk/course/view.php?id=2640
4800	Molecular Biophysics	1	Dr S Banerjee	UCL	PHAS0103	shiladitya.banerjee@ucl.ac.uk	
4805	Cellular Biophysics	1	Dr Dylan Owen	KCL	7CCP4933	dylan.owen@kcl.ac.uk	
4807	Physical Models of Life	2		UCL	PHAS0078		
4810	Theory of Complex Networks	1	Dr Izaak Neri	KCL+	7CCMCS02U/T	izaak.neri@kcl.ac.uk	http://www.mth.kcl.ac.uk/courses

No	Course Title	Term	Teacher	Taught by	Local no	Lecturer email address	Webpage
4820	Equilibrium Analysis of Complex Systems	2	Prof R Kuehn	KCL+	7CCMCS03U/T	reimer.kuehn@kcl.ac.uk	http://www.mth.kcl.ac.uk/courses
4830	Dynamical Analysis of Complex Systems	1	Dr A Annibale	KCL+	7CCMCS04U/T	alessia.annibale@kcl.ac.uk	http://www.mth.kcl.ac.uk/courses
4840	Mathematical Biology	2	Prof ACC Coolen	KCL+	7CCMCS05U/T	ton.coolen@kcl.ac.uk	http://www.mth.kcl.ac.uk/courses
4850	Elements of Statistical Learning #	1	Prof S Gilmour	KCL+	7CCMCS06U/T	steven.gilmour@kcl.ac.uk	http://www.mth.kcl.ac.uk/courses

2 Programme Strands

The table below gives a coherent base of courses for your registered programme and specialisation interests. It is strongly recommended that you choose one of these programme strands, and then select other courses to make up your full complement.

You should also note that some courses, particularly the more mathematical ones may require a high degree of mathematical ability – certainly more than would be contained in a standard single-honours Physics programme. Such courses would be appropriate for some joint degrees.

	Recommended Courses	
Strand	Autumn Term	Spring Term
Particle Physics	4205: Lie Groups and Lie Algebras 4226: Advanced Quantum Theory 4242: Relativistic Waves and Quantum Fields 4442: Particle Physics 4450: Particle Accelerator Physics 4471: Modelling Quantum Many-Body Systems 4515: Statistical Data Analysis 4602: Relativity and Gravitation 4620: Dark Matter & Dark Energy	4211: Statistical Mechanics 4245: Advanced Quantum Field Theory 4246: Functional Methods in QFT 4455: Collider Physics 4501: Standard Model Physics and Beyond 4534: String Theory and Branes 4541: Supersymmetry
Condensed Matter	4201: Math Methods for Theoretical Physics 4215: Phase Transitions 4226: Advanced Quantum Theory 4421: Atom and Photon Physics 4471: Modelling Quantum Many-Body Systems 4475: Physics at the Nanoscale 4478: Superfluids, Condensates and Superconductors 4479: Advanced Condensed Matter 4515: Statistical Data Analysis 4800: Molecular Biophysics 4810: Theory of Complex Networks 4830: Dynamical Analysis of Complex Systems	4211: Statistical Mechanics 4228: Advanced Topics in Statistical Mechanics 4427: Quantum Computation and Communication 4428: Quantum Electronics of Nanostructures 4431: Molecular Physics 4472: Order and Excitations in Condensed Matter 4473: Theoretical Treatments of Nano-systems 4476: Electronic Structure Methods 4477: Computer Simulation in Condensed Matter 4512: Nuclear Magnetic Resonance 4820: Equilibrium Analysis of Complex Systems

Astrophysics	4201: Math Methods for Theoretical Physics 4242: Relativistic Waves and Quantum Fields 4319: Galaxy Dynamics, Formation and Evolution 4515: Statistical Data Analysis 4600: Stellar Structure and Evolution 4601: Cosmology 4602: Relativity and Gravitation 4620: Dark Matter and Dark Energy 4650: Solar System	4336: Advanced Physical Cosmology 4605: Astroparticle Cosmology 4606: Advanced Cosmology 4616: Electromagnetic Radiation in Astrophysics 4630: Planetary Atmospheres 4640: Solar Physics 4660: The Galaxy 4670: Astrophysical Plasmas 4680: Space Plasma and Magnetospheric Physics 4690: Extrasolar Planets and Astrophysical Discs
General / Applied Physics	4215: Phase Transitions 4421: Atom and Photon Physics 4442: Particle Physics 4475: Physics at the Nanoscale 4515: Statistical Data Analysis 4800: Molecular Biophysics 4805: Cellular Biophysics 4850: Elements of Statistical Learning	4211: Statistical Mechanics 4425: Photonics & Metamaterials 4427: Quantum Computation and Communication 4428: Quantum Electronics of Nanostructures 4431: Molecular Physics 4472: Order and Excitations in Condensed Matter 4512: Nuclear Magnetic Resonance 4840: Mathematical Biology
Theoretical Physics	4201: Math Methods for Theoretical Physics 4205: Lie Groups and Lie Algebras 4226: Advanced Quantum Theory 4242: Relativistic Waves and Quantum Fields → 4247: Differential Geometry in Theoretical Physics 4442: Particle Physics 4471: Modelling Quantum Many-Body Systems	4211: Statistical Mechanics 4228: Advanced Topics in Statistical Mechanics 4245: Advanced Quantum Field Theory 4246: Functional Methods in Quantum Field Theory 4534: String Theory and Branes 4541: Supersymmetry 4545: Supersymmetric Methods in Theoretical Physics

3 Teaching and Examination Arrangements

Teaching Term Dates:

Courses are taught in eleven-week terms.
For the session 2018-2019 the teaching dates are:

First term
Monday 1 October – Friday 14 December 2018
Apart from KCL Mathematics courses which will start on Monday 24 September 2018

Second term
Monday 14 January – Friday 29 March 2019
Apart from UCL courses which will start on Monday 7 January 2019

Note: these teaching dates may not be the same as your College terms!

Although some Colleges have reading weeks, there will be no reading weeks for MSci courses.

MSci Administrative contact points at each College

KCL:	Leslee Frost	pgt-physics@kcl.ac.uk	tel 0207 848 1207
QMUL:	Leonie dos Santos	l.y.dossantos@qmul.ac.uk	tel 0207 882 6959
RHUL:	Gill Green	gill.green@rhul.ac.uk	tel 01784 443506
UCL:	Selina Lovell	selina.lovell@ucl.ac.uk	tel 0207 679 7246

Registration

Note: If you are taking courses at another College, it is very important that you fill out a course registration form from that College.
(*i.e*. you must fill out a UCL form for UCL taught courses, a KCL form for KCL taught courses and so on). If you do not fill out these types of form for all of your courses at other colleges you will not have a place in the examination hall. It is not enough to inform your home College of your selection.
You must complete the registration forms and submit them through your own College administrator as soon as possible and definitely by Friday 12 October 2018.

Any changes to autumn term courses can be made up until Friday 12 October 2018 and changes to spring term courses can be made up until Friday 25 January 2019.

Remember – the sooner you register on a course, the sooner you will have access to e-learning resources.

If you drop a course at another College you should inform both your own College and the administrative contact point at the College that runs the course.

Class locations

The timetable gives details of room locations; this is published separately from the Handbook and it is also available on the Intercollegiate MSci web pages

https://www.royalholloway.ac.uk/physics/informationforcurrentstudents/msci4thyear/msci-4th-year.aspx

All KCL courses are taught at KCL, all QMUL courses are taught at QMUL and all UCL courses are taught at UCL. RHUL courses are either taught at Senate House, UCL or at RHUL, some with a video conference link to QMUL. Students are welcome to attend the lectures in person at RHUL at the Egham campus or via the link at QMUL.

Some of the QMUL courses will be taught in the evening; check pages 4 - 7 and the timetable for details.

Attendance

Registers will be taken at lectures and there may be an attendance requirement for certain courses.

Coursework policy

Some courses have coursework associated with them and others do not. The details are given in the Course Descriptions below.

Computer and Library facilities at UCL

Registration on any UCL course will get you automatic library access, a UCL computer account and a UCL security card. This takes about a week from UCL receiving your signed form and submitting it to their Exam section. The Exam section then set all this up and will email you with details about how to obtain your UCL student card/user id/password.

Once a student is registered with another College you should receive by email details of your user id/password and email address for that College.

You should make sure you link your email addresses so you do not miss any communications from another College. Detailed instructions on **how to forward mail** can be accessed by visiting http://help.outlook.com/ and **Options** and **Connected Accounts Tab** (you may need to use IE browser to access this as the link does not work on some browsers). This process is very easy, but you do have to maintain your College account. When you delete a forwarded message from, say, Hotmail, it will not be deleted from the Royal Holloway account. **It is your responsibility** to log on to your College account occasionally and conduct some account maintenance or your account may become full and therefore will not forward messages.

Senate House Library (Malet Street, London, WC1E 7HU. Tel: 020 7862 8461; http://www.ull.ac.uk).

This is the central library of the University of London, where you can borrow up to twelve books with a library ticket http://www.senatehouselibrary.ac.uk/membership which you can obtain using your College ID card.

Examination arrangements

Note: Remember you must register with the College who is teaching the course unit you are studying before their deadline.

Note: The examination period for MSci courses may not coincide exactly with your home College examination period.

The main examination period is in April/May/June.

The policy concerning resit examinations may vary depending on the College. If your College allows resits after the fourth year, then it will be possible to resit any exams regardless of which College teaches the course in question.

UCL students: You will sit UCL and RHUL examinations at UCL. You will sit KCL examinations at KCL and QMUL examinations at QMUL.

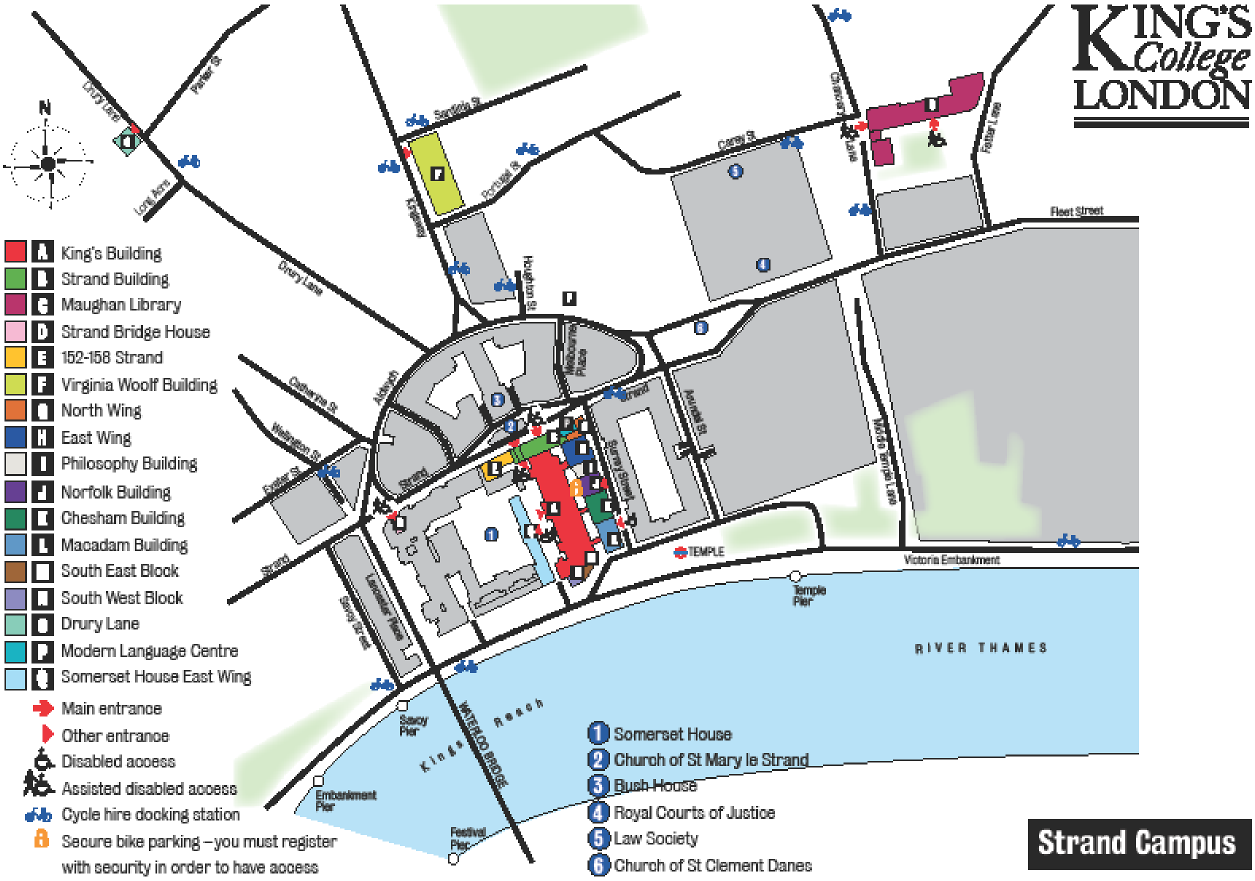
KCL students: You will sit KCL and RHUL examinations at KCL. You will sit UCL examinations at UCL and QMUL examinations at QMUL.

QMUL students: You will sit QMUL and RHUL examinations at QMUL. You will sit UCL examinations at UCL and KCL examinations at KCL.

RHUL students: You will sit all your examinations at RHUL.

4 College and Class Locations

King's College, Strand, London WC2



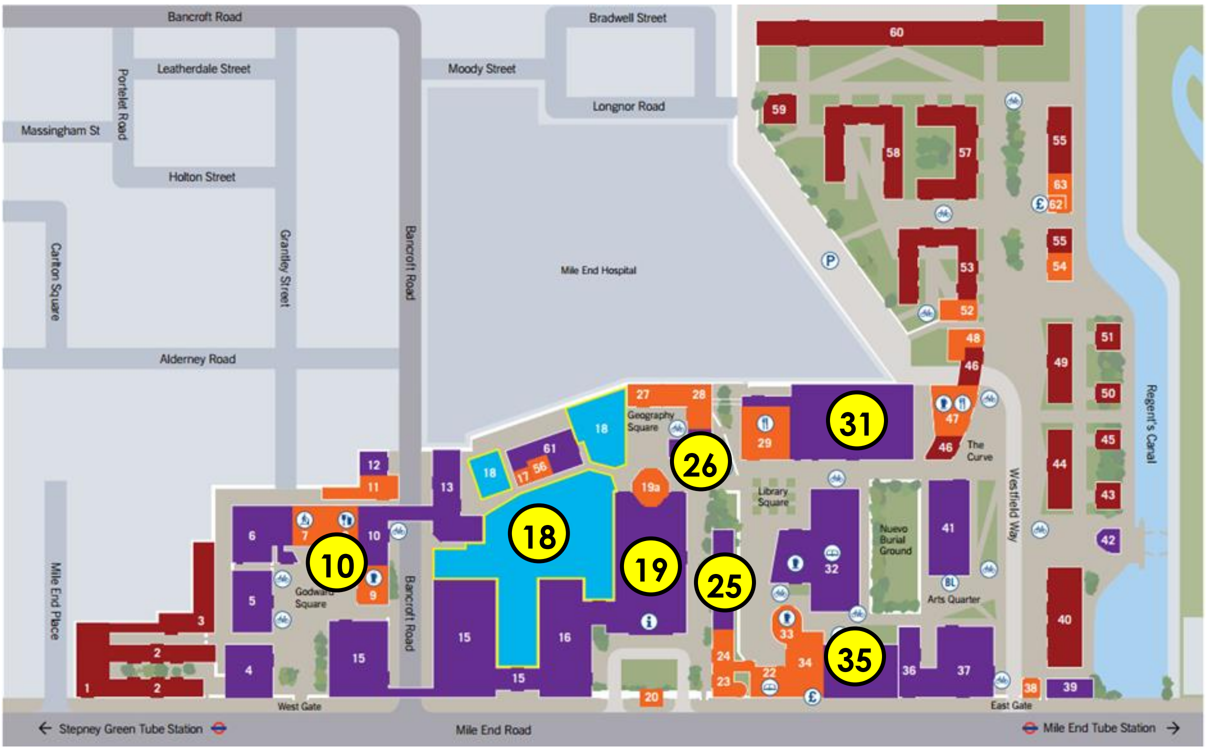
Travel by tube: Temple (District and Circle lines): 2 minute walk. Charing Cross (Bakerloo and Northern lines): 10 minute walk, Embankment (District, Circle and Bakerloo lines): 10 minute walk, Waterloo (Jubilee, Northern, Bakerloo, Waterloo & City lines): 12 minute walk, Holborn (Central and Piccadilly lines): 12 minute walk, Chancery Lane (Central line): use exit 4 - 15 minute walk.

Travel by train: Charing Cross: 9 minute walk. Waterloo: 12 minute walk. Waterloo East: 10 minute walk. Blackfriars: 12 minute walk.

Travel by bus: Buses stopping outside the university: 1, 4, 26, 59, 68, 76, X68, 168, 171, 172, 176 (24 hour), 188, 243 (24 hour), 341 (24 hour), 521, RV1.

Directions to classrooms from the main Strand reception can be found here: https://internal.kcl.ac.uk/timetabling/room-info/strand/index.aspx

Queen Mary University of London, Mile End Road, London E1



Arts Two (35)
G.O. Jones Building (25)
Graduate Centre (18)
The Bancroft Building (David Sizer LT) (31)
Bancroft Road Teaching Rooms (10)
Geography (26)
Queens' Building (19)

The main building is Queens' Building (19). Here, you can collect your QM ID card from the Student Enquiry Centre on the Ground Floor.
The Physics and Astronomy School office is on the 1st floor of G.O. Jones (25).

Travel by tube: Stepney Green tube station is on the District and Hammersmith & City line. To get to campus, turn left out of the station and walk along Mile End road for approximately 5 minutes. Mile End tube station is on the Central, District and Hammersmith & City line. To get to campus, turn left out of the station, walk under the bridge and along Mile End road for approximately 5 minutes. Whichever way you come from, you will see the main entrances to campus on either side of the Clock Tower (opposite Sainsbury's).

Travel by bus: A number of buses including the 25, 205 and 339 stop just outside the main entrance.

Royal Holloway, University of London, central London base

Senate House

DIRECTIONS TO UNIVERSITY OF LONDON, SENATE HOUSE

Public Transport

By bus: numbers 73, 29, 134, 10, 24, 68, 168, 7, 188, 91, 59 stop in the surrounding streets of Tottenham Court Road, Gower Street or Russell Square.

By rail: Euston, Kings Cross, St Pancras are local mainline stations

By London Underground: Russell Square (Piccadilly line), Tottenham Court Road (Central line), Goodge Street (Northern line), Warren Street (Victoria line), Euston Square (Circle, Hammersmith & City and Metropolitan lines).

Contact Details

Address: Malet Street London WC1E 7HU

Main switchboard telephone: 020 7862 8000

Main Reception: 020 7862 8133

Royal Holloway, University of London, Egham Campus TW20 0EX

T125 – located in the Department of Physics on the ground floor of the Tolansky Laboratory

By Rail: There are frequent services from London Waterloo to Egham station (40 mins).

From Egham station by Bus: There is a College bus service that carries students and visitors directly from Egham station to the bus stop on Campus.

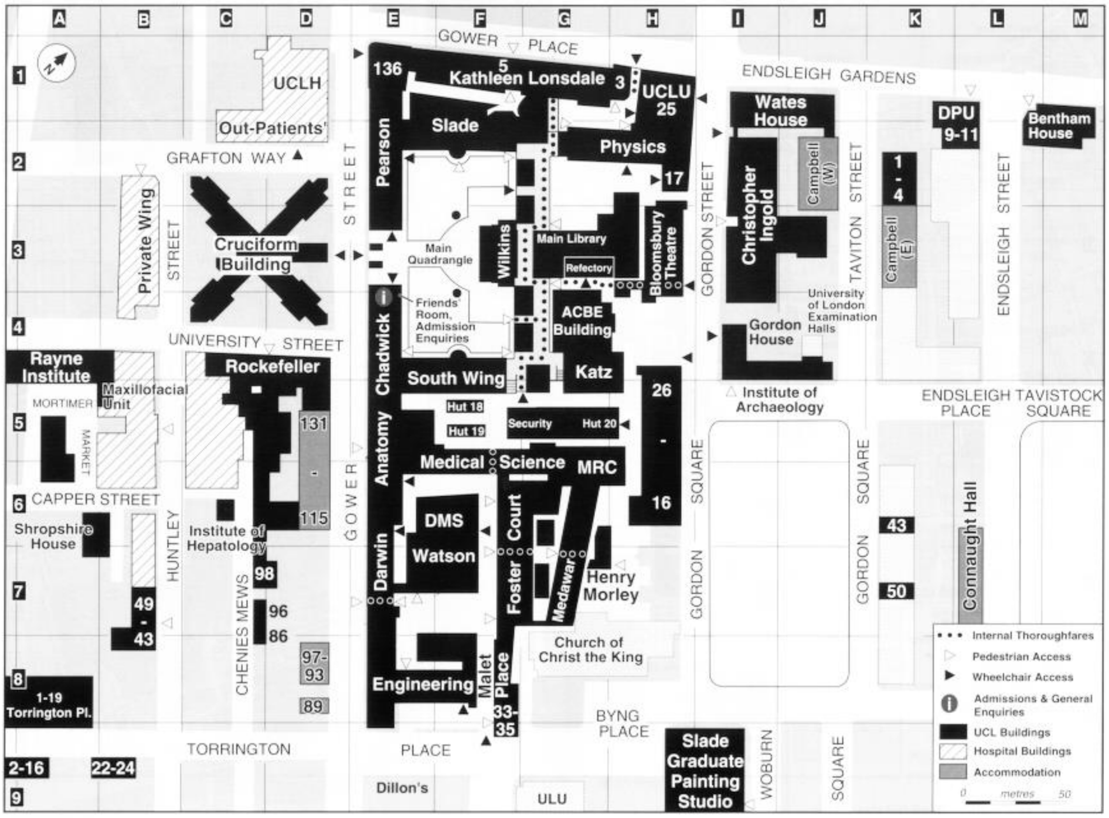
From Egham station by Foot: The College is just over a mile from Egham Station, about 20 minutes' walk. Turn right out of the station along Station Road and walk about 100 yards to the T-Junction and the traffic lights. Turn left at the junction and follow the road up to the large roundabout; go left up Egham Hill (south-west direction). It is easiest to enter by the gate before the foot bridge over the road and follow the path to the Department of Physics – Tolansky and Wilson Laboratories.

By Road: The College is on the A30, 19 miles from central London and about a mile south-west of the town of Egham. It is 2 miles from junction 13 of the M25. After leaving the motorway follow the A30 west (signposted Bagshot and Camberley)-this is the Egham by-pass. At the end of the by-pass, continue on the A30 up Egham Hill. The entrance to the College is on the left immediately after the second footbridge.

Car parking on campus is restricted to permit holders.

Further details can be found at
https://intranet.royalholloway.ac.uk/students/campus-life/travel/home.aspx

University College, Gower Street, London WC1



Entrance to the UCL campus is from Gower Street into the Main Quadrangle and then into the appropriate building. UCL-based lectures can take place in lecture theatres across UCL's Bloomsbury Campus. Detailed downloadable maps and a routefinder - which can give you detailed walking directions to any lecture theatre - can be found at http://www.ucl.ac.uk/maps

5 Course Details

4201 Mathematical Methods for Theoretical Physics

Aims of the Course

- develop the theory of complex functions in order to facilitate the applications of special functions and conformal invariance in two dimensions (widely used in theoretical physics)
- develop the equations of the calculus of variations and, via the variational principle, derive and solve the equations governing some fundamental theories

Objectives

On completion of this course, students should understand:

- applications of the powerful methods of complex analysis for the solution of problems in both applied and fundamental physics;
- the all pervasive role of the calculus of variations in the formulations of classical mechanics, quantum mechanics, field theories, strings and membranes.

Syllabus

(The approximate allocation of lectures to topics is shown in brackets below.)

- Functions of a complex variable (1)
- Mappings of the complex plane (2)
- Cauchy-Riemann equations for an analytic function (2)
- Physical significance of analytic functions (2)
- Properties of power series, definition of elementary functions using power series (1)
- Complex integral calculus, contour integrals, upper bound theorem for contour integrals (1)
- Cauchy-Goursat theorem (1)
- Cauchy integral representation, Taylor and Laurent series, singularities and residues (1)
- Residue theorem and its applications (1)
- Properties of the gamma function G(z) (1)
- Conformal invariance and irrotational flow (2)
- Classical mechanics (1)
- Constraints and generalised co-ordinates D'Alembert's principle 1)
- Lagrange equations of motion (1)
- Hamilton's equation of motion (1)
- Conservation laws and Poisson brackets (1)
- Calculus of variation (1)
- Functionals (1)
- Euler-Lagrange equation (1)
- Invariance principles and Noether's theorem (1)
- Minimum surface energy of revolution (1)
- Properties of soap films, strings and membranes (2)
- Hamilton's principle in classical mechanics (1)
- Multiple integral problems and field equations (1)
- Applications to scalar and gauge field theories (1)

Prerequisites
Knowledge of mathematics of multi-dimensional calculus, vector calculus, solution of ordinary and partial differential equations at the level of 5CCP2265 and knowledge of tensor calculus used in special relativity are required.

Textbooks
(a) Complex analysis
- *Mathematical Methods for Physicists*, Sixth Edition: A Comprehensive Guide [Hardcover] by G B Arfken, H J Weber and F E Harris, (Publisher : Elsevier)
- *Mathematical Methods in the Physical Sciences*, by M L Boas, (Publisher: Wiley)
- *Visual Complex Analysis*, by T Needham (Publisher: Oxford)
- *Schaum's Outline of Complex Variables*, by M Spiegel (Publisher: McGraw-Hill)
- *Fluid Mechanics*, by P K Kundu (Publisher: Elsevier)

(b) Calculus of Variations
- *Mathematical Methods for Physicists*, Sixth Edition: A Comprehensive Guide [Hardcover] by G B Arfken, H J Weber and F E Harris, (Publisher : Elsevier)
- *Mathematical Methods in the Physical Sciences* by M L Boas,(Publisher: Wiley)
- *A First Course in String Theory* by B Zwiebach (Publisher:Cambridge)
- *Calculus of Variations*, by R Weinstock (Publisher: Dover)

Methodology and Assessment
30 lectures and 3 problem class/discussion periods. Lecturing supplemented by homework problem sets. Written solutions provided for the homework after students have attempted the questions.

Assessment is based on the results obtained in the final 3 hour written examination (90%) and two tests (10%)

4205 Lie Groups and Lie Algebras

Aims and objectives
This course gives an introduction to the theory of Lie groups, Lie algebras and their representations, structures which arise frequently in mathematics and physics.

Lie groups are, roughly speaking, groups with continuous parameters, the rotation group being a typical example. Lie algebras can be introduced as vector spaces (with extra structure) generated by group elements that are infinitesimally close to the identity. The properties of Lie algebras, which determine those of the Lie group to a large extent, can be studied with methods from linear algebra, and one can even address the question of a complete classification.

Syllabus
Basic definitions and examples of Lie groups and Lie algebras. Matrix Lie groups, their Lie algebras; the exponential map, Baker-Campbell-Hausdorff formula. Representations of Lie algebras, sub-representations, Schur's Lemma, tensor products. Root systems, Cartan-Weyl basis, classification of simple Lie algebras (perhaps with some of the proofs being left out.)

Web page: See http://www.mth.kcl.ac.uk/course

Teaching arrangements
Two hours of lectures per week.

Prerequisites
Basic ideas about Groups and Symmetries as taught in a second year UG course; a good knowledge of vector spaces and linear maps; elements of real analysis.
Note – A relatively high level of mathematical ability is required for this course.

Books
There is no book that covers all the material in the same way as the course, but the following may be useful:

- Baker, *Matrix groups*, Springer, 2002
- J. Fuchs, C. Schweigert, *Symmetries, Lie algebras and representations*, CUP 1997
- J. Humphreys, *Introduction to Lie Algebras and Representation Theory*, Springer, 1972
- H. Jones, *Groups, Representations and Physics*, IoP, 1998
- A. Kirillov Jr., *Introduction to Lie Groups and Lie Algebras*, CUP, 2008

Assessment
One 2 hour written examination at the end of the academic year.
Assignments: Weekly problem sheets. Solutions will be provided.

4211 Statistical Mechanics

Aims of the course

Consolidation of previous knowledge and understanding of Statistical and Thermal Physics within the context of a more mature framework. Introduction to the ideas and concepts of interacting systems. Introduction to the ideas and concepts of phase transitions including some specific examples. Introduction to the ideas and concepts of irreversibility: non-equilibrium statistical mechanics and irreversible thermodynamics.

Objectives

On completion of the course, students should be able to:

- explain the difference between the macroscopic and the microscopic descriptions macroscopic phenomena;
- explain the essential concepts in the laws of thermodynamics from both macroscopic and microscopic perspectives;
- apply the methods of statistical mechanics to simple non-interacting systems;
- demonstrate how weakly-interacting systems may be studied through approximation schemes;
- describe the phenomena and classification of phase transitions;
  explain and demonstrate some of the approximate methods of treating phase transitions, including the van der Waals method, mean-field approaches;
- describe and demonstrate how the Landau theory provides a general framework for the understanding of phase transitions;
- explain how irreversibility and the transition to equilibrium may be understood in terms of fluctuations;
- show how the Langevin equation provides a link between transport coefficients and equilibrium fluctuations.

Syllabus

The Methodology of Statistical Mechanics (5 lectures)

- Relationship between statistical mechanics and thermodynamics – emergence.
- Review of equilibrium statistical mechanics.
- The grand canonical ensemble. Chemical potential. The Bose and Fermi distribution functions.
- The classical limit, phase space, classical partition functions.

Weakly Interacting Systems (7 lectures)

- Non-ideal systems. The imperfect gas and the virial expansion, Mayer's *f* function and cluster integrals. (2 lectures)
- The second virial coefficient for the hard sphere, square-well and Lennard-Jones potentials. (2 lectures)
- Throttling and the Joule-Kelvin coefficient. (1 lecture)
- The van der Waals gas as a mean field paradigm. (2 lectures)

Strongly Interacting Systems (13 lectures)

- The phenomenology of phase transitions, definitions of critical exponents and critical amplitudes. (2 lectures)

- Scaling theory, corresponding states. (2 lectures)
- Introduction to the Ising model. Magnetic case, lattice gas and phase separation in alloys and Bragg-Williams approximation. Transfer matrix method in 1D. (3 lectures)
- Landau theory. Symmetry breaking. Distinction between second order and first order transitions. Discussion of ferroelectrics. (3 lectures)
- Broken symmetry, Goldstone bosons, fluctuations, scattering, Ornstein Zernike, soft modes. (3 lectures)

Dissipative Systems (5 lectures)
- Fluctuation-dissipation theorem, Brownian motion, Langevin equation, correlation functions. (5 lectures)

Prerequisites
Classical and Statistical Thermodynamics course at 2nd year level.

Text Books
B. Cowan, *Topics in Statistical Mechanics*, 2005, Imperial College Press.
R. Bowley & M. Sánchez, *Introductory Statistical Mechanics*, 1999, OUP
Other books and publications will be referred to by the lecturer.

Course notes and other material available on the course web pages at
http://personal.rhul.ac.uk/UHAP/027/PH4211/

Methodology and Assessment
30 lectures and 3 problem class/discussion periods. Lecturing supplemented by homework problem sets. Written solutions provided for the homework after assessment. Links to information sources on the web provided on the course web page.

Written examination of 2½ hours contributing 90%, coursework contributing 10%

4215 Phase Transitions

Aims and objectives

Phase transitions are ubiquitous in condensed matter physics, and their existence gives rise to important material properties that are exploited in many physics-based technologies, including electronics, sensors and transducers. Many important phase transitions are found in materials that are more complex than the simple materials traditionally covered in condensed matter physics teaching. The aim of this module is to expose students to the wealth of physics contained within the study of phase transitions, to equip students with the skills required to manipulate the theory and analyse associated data, and to understand why phase transitions are so important for modern technologies. A key feature of this course is the link between theory and data for real systems, studied using a number of case studies.

Syllabus

The course consists of eleven 3-hour sessions. The syllabus is divided into seven topics, some of which span more than one session.

Topic 1: Phenomenology (6 hours)

How we define a phase transition; Role of symmetry, including translational symmetry; Survey of various types of phase transitions, including displacive phase transitions and a diversity of order–disorder transitions (spin systems, orientational disorder, liquid crystal, alloys and atomic site ordering); Quantification of a phase transition via the order parameter; Experimental methods to study phase transitions, including macroscopic and microscopic techniques; Role of free energy; Susceptibility and heat capacity; Introduction to mean-field approaches, with some worked examples for simple systems and comparison with simulation data; Critical analysis of mean-field theories; Domain formation and hysteresis.

Topic 2. Landau theory (6 hours)

Expected shape of free energy curves above and below the phase transition, with separate contributions from potential energy and entropy term; Model for second-order phase transition and predictions (order parameter, heat capacity, susceptibility, and order parameter vs field at the phase transition; Fluctuations and correlation length; Analysis on the thermodynamic validity of Landau theory; Connection with predictions from mean field theory; Model for first-order phase transitions, noting tricritical as the in-between case; Effects of coupling to strain; Worked examples and comparison with experiment data (including PbTiO3).

Topic 3. Role of symmetry (3 hours)

Review of point symmetry, with examples of loss of symmetry at phase transitions; Translational symmetry and space groups; Irreducible representations and character tables for simple system; Symmetry of strain and its relationship from the symmetry associated with the order parameter; Multiple order parameters; Worked examples.

Topic 4. Soft modes and displacive phase transitions (6 hours)

Phenomenology of ferroelectric phase transitions, extended to other displacive phase transitions; Lyddane-Sachs-Teller relation for dielectric constant implies transverse optic mode frequency falling to zero at the phase transition; Review of phonon dispersion relations, and role of potential energy surface in the space of normal mode coordinates in determining phonon frequency; Discussion of how unstable phonon modes give rise to negative squared frequencies, and hence the suggestion of soft modes; Experimental data; Renormalised phonon theory to describe origin of soft mode; Phonon theory of thermodynamics of low-temperature phase; Phi-4 model, described with very simple mean-field solution; Rigid unit mode model, giving insights into *a*) why materials can deform easily, *b*) what determines the transition temperature, *c*) why mean field theory works, *d*) structural disorder in high-temperature phase.

Topic 5. Order-disorder phase transitions (3 hours)
Different types of order-disorder phase transitions, including atom ordering, orientational disorder, liquid crystals, H-bonding transitions, fast ion conductors; Bragg-Williams model for atomic site-ordering phase transitions, comparison with experiments and simulation; Beyond Bragg-Williams: Cluster Variation Method for bonds; Monte Carlo methods.

Topic 6. Critical point phenomena (6 hours)
Basic phenomena, including critical point exponents, universality, role of spatial dimension; Predictions of critical point exponents for different models; Correlation functions and role of correlation lengths; Scaling arguments giving rise to scaling relations between critical exponents; Introduction to renormalisation group theory.

Topic 7. Combining temperature and pressure (3 hours)
Polymorphism in the solid state and reconstructive phase transitions; High-pressure phase transitions and phase diagrams, including ice; Clausius-Clapeyron relation and explanation of shapes of solid-state phase diagrams. Theories of melting.

Teaching arrangements
Lectures, 33 hours delivered in 11 sessions of 3 hours each.

Prerequisites
Condensed Matter Physics course

Books
Dove, *Structure and Dynamics* (Oxford University Press)
Yeomans, *Statistical Mechanics of Phase Transitions* (Oxford University Press)
Fujimoto, *The Physics of Structural Phase Transitions* (Springer)

http://qmplus.qmul.ac.uk/course/view.php?id=3316

Assessment
Written examination of 2½ hours contributing 90%, coursework 10%

4226 Advanced Quantum Theory

This course aims to

- review the basics of quantum mechanics so as to establish a common body of knowledge for the students from the different Colleges on the Intercollegiate MSci programme;
- extend this, by discussing these basics in more formal mathematical terms;
- explore the WKB approximation, as a method for studying tunnelling and quantum wells;
- explore advanced topics in the dynamics of quantum systems; including time-dependent perturbation theory, and the dynamics of open quantum systems;
- provide students with the techniques and terminology which they can apply in specialist courses and in their research projects.

Syllabus (Approximate allocation of lectures is shown in brackets below)

Formal quantum mechanics [10.5 hours]
[Partly revision] Abstract vector spaces; norm, inner product, basis, linear functionals, operators, column vector and matrix representations of abstract vectors and operators, Dirac notation, Hermitian and unitary operators, projectors. Expectation values.
Postulates of quantum mechanics.
Representations of continuous variables, position and momentum.
Compound systems, tensor product, entanglement.
Statistical state preparation and mixed states, density operator formalism, density operators to describe sub-systems of entangled systems

Advanced wave mechanics - WKB approximation [4.5 hours]
WKB Ansatz and derivation of WKB approximation wave-functions. The failure of these wave-functions at classical turning points. The role of connection formulae. Application to quantum wells and quantum tunnelling in one-dimension.

Atoms, light and their interaction [3 hours]
[Revision of] Quantum Harmonic oscillator, Wave equation and quantisation of light. Optical cavities and concept of a light mode. Two-level atom and dipole approximation. Rotating Wave Approximation and Jaynes-Cummings model.

Advanced topics in time-dependence 1 - Unitary Evolution [3 hours]
Unitary evolution under the Schrödinger equation, Split operator method and Tsuzuki-Trotter decomposition. Heisenberg picture, Interaction picture. Example: Jaynes-Cummings model in the interaction picture.

Advanced topics in time-dependence 2) - Time-dependent perturbation theory [6 hours]
Dirac's method as application of interaction picture. Time-dependent perturbation theory. First-order time-dependent perturbation theory. Higher-order time-dependent theory. Examples: constant perturbation and harmonic perturbation. Fermi's Golden Rule with examples of its application.

Advanced topics in time-dependence 3) - Open quantum systems [6 hours]
Von Neumann equation for density matrices. Interaction with environment. Evolution of a sub-system. Markov approximation.
Abstract approach to non unitary evolution. Completely positive maps. Kraus operators.
Master equations. Lindblad form, derivation from Kraus operator Ansatz. Quantum trajectories and jump operators. Example: Damped quantum harmonic oscillator.

Prerequisites
Students will be expected to have attended and passed their department's introductory and intermediate quantum mechanics course. For example, at UCL these will be PHAS2222: Quantum Physics and PHAS3226: Quantum Mechanics.

The following topics will be assumed to have been covered:

- Introductory material: states, operators and time-independent Schrödinger equation, the Born interpretation of the wave function, transmission and reflection coefficients, Dirac notation
- Harmonic oscillator: energy eigenvalues, ladder operators
- Time-independent perturbation theory: including the non-degenerate and degenerate cases and its application to the helium atom ground state, Zeeman effect and spin-orbit interactions.

This is a theory course with a strong mathematical component to this course, and students should feel confident in their ability to learn and apply new mathematical techniques.

Books
Those which are closest to the material and level of the course are (in alphabetical order)

- B.H. Bransden and C.J.Joachain, *Introduction to Quantum Mechanics*, Longman (2^{nd} Ed, 2000),) (available at a discount from the physics departmental Tutor),
- C.Cohen-Tannoudji, B.Diu and F.Laloe, *Quantum Mechanics*, (2 Vols) Wiley,
- S.Gasiorowicz, *Quantum Physics,* Wiley, (1996)
- F.Mandl, *Quantum Mechanics*, Wiley (1992)
- E.Merzbacher, *Quantum Mechanics*, (3rd Ed.) Wiley, (1998)
- M. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory* Addison Wesley
- J. J. Sakurai, *Modern Quantum Mechanics*, Addison Wesley, (2010)

John Preskill (Caltech) *Lecture notes on Quantum Computation*,
Chapter 2, "States and Ensembles"
http://www.theory.caltech.edu/people/preskill/ph229/notes/chap2.pdf
Chapter 3, "Measurement and evolution"
http://www.theory.caltech.edu/people/preskill/ph229/notes/chap3.pdf

Assessment
Examination of 2½ hours duration contributing 90%, coursework 10%

4228 Advanced Topics in Statistical Mechanics

Aims and Objectives

- To develop students' understanding of statistical physics beyond an introductory module.
- To use statistical mechanics to deduce the properties of systems of interacting particles, with emphasis on the liquid state, interfaces and small clusters, and to discuss the nucleation of phase transitions.
- To introduce the mathematics of stochastic processes, including the Langevin equation and Fokker-Planck equation.
- To understand how stochastic dynamics may be derived from deterministic dynamics.
- To introduce the techniques of stochastic calculus, noting the distinct Ito and Stratonovich rules, and apply them to solve various problems, such as Brownian motion, including their use in areas outside science such as finance.
- To consider the meaning of entropy and its production in statistical physics, with reference to the reversibility paradox and Maxwell's demon.
- To develop the concepts of work, heat transfer and entropy production within a framework of stochastic thermodynamics, and to derive fluctuation relations.

Notes

This module will suit students who wish to explore applications of the ideas of statistical physics in an advanced setting. It also offers exposure to the advanced mathematics used to describe the dynamics of random events. It is a successor to the long running and popular module 4211 *Statistical Mechanics*.
It is intended to be complementary to the module 4215 *Phase Transitions* in that illustrations will be taken from the field of soft molecular matter rather than magnetic systems, and it will cover nonequilibrium processes as a central topic. It may be taken alongside that module without conflict.
Modules 4820 *Equilibrium Analysis of Complex Systems* and 4830 *Dynamical Analysis of Complex Systems* cover similar mathematics of stochastic processes, but the approach used in this module, and the prerequisites, are intended to be suitable for physics students rather than those with a more formal mathematical background. Furthermore, a particular aim of the module is to convey a modern understanding of entropy and the second law

Syllabus:
Part 1 Interacting particle systems

- Simulation techniques
- Analytical techniques
- Phase transitions
- Thermodynamics of interfaces
- Nucleation

Part 2 Stochastic processes

- Random walks and Brownian motion
- Fokker-Planck equation
- Langevin equation

- Ito calculus
- Kubo relations

Part 3 Irreversibility

- Philosophical issues
- Entropy production in classical thermodynamics
- Entropy production in statistical mechanics
- Fluctuation relations
- Coarse graining and projection
- Caldeira-Leggett model
- Maxwell's Demon

Recommended reading:

Ford, *Statistical Physics, an Entropic Approach*, Wiley
Reif, *Fundamentals of Statistical and Thermal Physics*, McGraw-Hill
Cowan, *Topics in Statistical Mechanics*, Imperial College Press
Kalikmanov, *Nucleation Theory*, Springer
Van Kampen, *Stochastic Processes in Physics and Chemistry*, Elsevier
Gardiner, *Stochastic Methods*, Springer
Risken, *The Fokker-Planck Equation*, Springer
Lemon, *An Introduction to Stochastic Processes in Physics*, Johns Hopkins Press
Sekimoto, *Stochastic Energetics*, Springer
Zwanzig, *Nonequilibrium Statistical Mechanics*, Oxford
Leff and Rex, *Maxwell's Demon 2*, IOP Press

Prerequisites

An introductory course in statistical mechanics and core mathematics for physicists.

Teaching methods

One 3 hour lecture per week. Revision lecture before exam.

Assessment

Problem sheets contributing 10%
Written examination of 2½ hours contributing 90%

4242 Relativistic Waves and Quantum Fields

Classical field theories, Special Relativity and Quantum Mechanics (part revision):

Elements of Classical field theories: variational principle, equations of motion and Noether theorem.

Short introduction to Special Relativity: 4-vector notation, Lorentz transformations, Lorentz invariance/covariance.

Quantum Mechanics: Schroedinger equation, wavefunctions, operators/observables, symmetries and conservation laws in QM, Fock space for non-relativistic theories

Relativistic Wave equations
Klein-Gordon equation: plane wave solutions, positive and negative energy solutions.

Dirac equation: Gamma matrices in 4D (Dirac, Weyl and Majorana representations); Gamma matrices in 2D and 3D; Lorentz transformations and covariance of Dirac equation: non-relativistic limit, Dirac equation in an electromagnetic field; discrete symmetries: C & P & T symmetry

Quantum Field Theory
Scalar fields: canonical quantisation and Fock space interpretation of the free complex and real Klein-Gordon field; vacuum energy; Causality, commutators and time ordered products, the Feynman propagator; Dyson expansion; S-matrix, tree-level scattering amplitudes; examples of an interacting scalar theory with three flavours; Wick's theorem. Quantisation of Dirac fermions: spin-statistics connection.

Prerequisites
A 3rd year quantum mechanics course (including canonical commutation relations, operator formalism, bra and ket spaces, simple harmonic oscillator and angular momentum in the raising and lowering operator formalism); a course on analytic mechanics (Lagrangian and Hamiltonian formalism); familiarity with the four-vector notation in Special Relativity.

Books
M Maggiore, *A Modern Introduction to Quantum Field Theory*, OUP
F Mandl and G Shaw, *Quantum Field Theory*, John Wiley and Sons Ltd
M E Peskin, D V Schroeder, *An Introduction to Quantum Field Theory,* Addison Wesley

http://qmplus.qmul.ac.uk/course/view.php?id=3307

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%

4245 Advanced Quantum Field Theory

Building on the fundamental concepts of Quantum Field Theory introduced in 4242 Relativistic Waves and Quantum Fields, this course will cover the following topics:

1 Classical Field Theory and Noethers Theorem, Quantisation of free spin 0, 1/2 and 1 fields (revision)

2 Perturbation Theory and Feynman Diagrams:
Dyson formula and the S-matrix, in and out states, evaluation of S-matrix elements using Wick's theorem and LSZ reduction formula, formulation in terms of Feynman diagrams (part revision)

3 Quantum Electrodynamics
Feynman diagrams for QED, simple scattering processes at tree level such as $e^- e^-$ and $e^- e^+$ scattering, cross sections, spin sums

4 Renormalisation
Renormalisation of φ^4 and QED at one-loop level, regularisation (dimensional and Pauli-Villars), Running coupling, corrections to electron anomalous moment

5 If time permits
Elements of non-Abelian gauge theories, path integrals and ghosts, anomalies, modern, twistor inspired methods to calculate amplitudes.

Four sessions will be devoted to a discussion of coursework problems and their solutions.

Prerequisites
4242 Relativistic Waves and Quantum Fields

Books
F. Mandl and G. Shaw, *Quantum Field Theory*, John Wiley and Sons Ltd
L.H. Ryder, *Quantum Field Theory*, Cambridge University Press
J. Bjorken and S. Drell, *Relativistic Quantum Mechanics* and *Relativistic Quantum Fields*, McGraw-Hill
S. Weinberg, *TheQuantum Theory of Fields*, Volume I, Cambridge University Press

http://qmplus.qmul.ac.uk/course/view.php?id=3309

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%

4246 Functional Methods in Quantum Field Theory

The module will introduce Feynman's path integral formulation of Quantum Mechanics and apply it to study of Quantum Field Theory (QFT). Emphasis will be given to the role of symmetries (Ward identities), the renormalisation group and the idea of effective action. The concept of Wilson's effective action and the different nature of (ir)relevant/marginal terms will be discussed. Simple scalar theories will provide the example where to apply the concepts and the techniques introduced. The course will also touch on some more advanced topics, such as quantum anomalies and conformal field theories.

Prerequisites
Relativistic Waves & Quantum Fields (SPA7018U/P)

Books
Le Bellac: *Quantum and Statistical Field Theory* Oxford University Press
Amit- Mayor *Field Theory, the renormalisation groups, and critical phenomena*. World Scientific

http://qmplus.qmul.ac.uk/course/view.php?id=4584

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%

4247 Differential Geometry in Theoretical Physics

Synopsis
The aim of this course is to provide the student with a number of advanced mathematical tools from differential geometry, essential for research in modern Theoretical Physics, and apply them to certain physical contexts. More specifically, the notation of differential forms will be introduced and the geometric aspects of gauge theory will be explored. Gravity will be interpreted as a gauge theory in this geometric setting. Manifolds will be introduced and studied, leading to the definition of fibre bundles. Finally, we will explore the Dirac and 't Hooft-Polyakov monopoles, the Yang-Mills instanton and the gravitational instanton and their associated understanding in fibre bundle language.

Prerequisites
A first course in General Relativity, including familiarity with tensor manipulations. Some basic group theory is essential. It is strongly recommended that this course is taken in conjunction with 4242 Relativistic Waves and Quantum Fields.

Syllabus
- **Exterior algebra** (Vector spaces - Dual basis - Alternating forms - Wedge product - Inner derivative - Pullback - Orientation - Vector-valued forms)

- **Differential forms on open subsets of R^n** (Tangent vectors - Frames - Differential forms - Tangent mapping - Pullback of differential forms - Exterior derivative - The Poincaré lemma and de Rham cohomology - Integration of n-forms - Integration of p-forms)

- **Metric structures** (Metric on vector spaces - Induced metric on dual space - Hodge star - Isometries - Metric on open subset of R^n - Holonomic and orthonormal frames - Isometries for open subsets of R^n - Coderivative)

- **Gauge theories** (Maxwell's equations - Connection = potential - Curvature = field strength - Exterior covariant derivative - Yang-Mills theories)

- **Einstein-Cartan theory** (Equivalence principle - Cartan's structure equations - Metric connections - Action and field equations - A farewell to the connection - Einstein gauge - Geodesics - Geometric interpretation of curvature and torsion)

- **Manifolds** (Differential manifolds - Differentiable mappings - Cartesian product on manifolds - Submanifolds)

- **Fibre bundles** (Notion of fibre bundles - Bundle maps - Examples - Associated bundle - Sections)

- **Monopoles, instantons and related fibre bundles** (Dirac monopole - 't Hooft-Polyakov monopole - Yang-Mills instanton - Dirac monopole as a connection on a nontrivial bundle - Recovering the Dirac monopole from the 't Hooft-Polyakov monopole - Instanton bundle - Chern classes)

Recommended Reading
Göckeler and Schücker, *Differential geometry, gauge theories and gravity* (Cambridge Monographs on Mathematical Physics); the main textbook for this course.

Carroll, *Spacetime and Geometry: An introduction to General Relativity* (Pearson); the first chapters of this textbook also cover differential geometry from a more physical viewpoint.

Nakahara, *Geometry, topology, and physics* (IoP Publishing); for additional reading on mathematical concepts and applications.

Manton and Sutcliffe, *Topological Solitons* (Cambridge Monographs on Mathematical Physics); for additional reading on solitons and instantons.

Tong, *TASI Lectures on Solitons*; for additional reading on solitons and instantons.

http://qmplus.qmul.ac.uk/course/view.php?id=6575

Teaching arrangements
11 3-hour lectures for a total of 33 hours

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%

4319 Galaxy Dynamics, Formation and Evolution

Aims of the Course
This course aims to:

- Give a detailed description of a many-body system under the influence of gravitational forces, with special emphasis on the structure of galaxies and stellar clusters.
- Present the basics of structure formation and evolution in a cosmological context, in order to understand the formation process of galaxies.
- Show the kinematic properties of stellar motions in the Milky Way galaxy, as a special case of a dynamical system under gravity.
- Explain the process of galactic chemical enrichment as a tool to understand the evolution of galaxies.

Objectives
After completing this course students should be able to:

- Identify the dynamical processes that operate within stellar systems.
- Explain the observed characteristics of stellar motions within the Milky Way.
- Use this information to elucidate the internal structure of galaxies and stellar clusters
- Understand how galaxies have formed and are evolving.

Syllabus
(The approximate allocation of lectures to topics is shown in brackets below)

The observational properties of galaxies and clusters [3 lectures]
Basic concepts of observational astronomy focused on extragalactic systems.

The mathematical foundations of stellar dynamics [3 lectures]
Potential theory; The Collisionless Boltzmann Equation (CBE); The solution of the CBE; Time-independent solution of the CBE; Jeans' theorem; Distribution function of simple systems; Jeans' equations and applications to simple cases.

The Milky Way I: Individual motions [3 lectures]
Galactic coordinates and the Local Standard of Rest; Galactic rotation in the solar neighbourhood; The determination of Oort's constants; Differential motion and epicyclic orbits; Motion perpendicular to the galactic plane.

The Milky Way II: The Collisionless Boltzmann Equation [3 lectures]
The CBE in galactic coordinates; Surfaces of Section; The third integral; Probing deeper into the Galaxy; The Oort substitution; The density distribution from individual orbits.

Evolution of dynamical systems [3 lectures]
Two-body encounters and collisions; The relaxation timescale; The relative importance of close and distant encounters; Comparison with crossing time and age; The Fokker-Planck equation; Dynamical friction; The virial theorem and applications.

Stellar clusters [3 lectures]
Evaporation of clusters; Models of globular clusters; Tidal forces in stellar clusters; Dynamical evolution; Other long-term evolutionary effects; The importance of binaries.

Galaxy dynamics applied to Disc and Elliptical galaxies [3 lectures]
Instabilities and the Toomre criterion; Spiral arms and density wave theory; Scaling relations; Dynamical modeling of elliptical galaxies.

Galaxy formation basics I & II [3+3 lectures]
Structure formation in an expanding background; The need for dark matter; Spherical collapse: Cooling and the sizes of galaxies; Hierarchical growth; Press-Schechter formalism; Probing dark matter halos; Galaxy mergers; Galaxy formation and environment; The "baryon" physics of galaxy formation.

Chemical Evolution of Galaxies [3 lectures]
Overview of stellar evolution; Stellar yields; The stellar initial mass function; Basic equations of chemical enrichment.

Prerequisites
This course focuses on galaxy dynamics and structure formation. Therefore, a good background on the basics of classical mechanics and calculus is essential. Familiarity with the physical concepts of statistical mechanics is helpful.

Textbooks
- *Galaxy dynamics* (J. Binney, S. Tremaine, Princeton, 2nd edition, 2008)
- *Galaxies in the Universe: An introduction* (L. Sparke, J. Gallagher, Cambridge, 2nd edition, 2007)
- *Galaxy formation and evolution* (H. Mo, F. van den Bosch, S. White, Cambridge, 2010)
- *An introduction to galaxies and cosmology* (M. H. Jones, R. J. A. Lambourne, S. Serjeant, Cambridge, 2015)

Methodology and Assessment
30 lectures and 3 problem class/discussion periods.

Written examination of 2½ hours contributing 90% and four problem sheets contributing 10%

4336 Advanced Physical Cosmology

Course aims

The aim of the course is to provide an advanced level exposition of modern theoretical and observational cosmology, building upon the foundations provided by the third year course PHAS3136. The emphasis will be on developing physical understanding rather than on mathematical principles.

Over the past two decades, cosmology has made dramatic advances. A flood of data has transformed our understanding of the basic parameters of the universe -- the expansion rate, the densities of various types of energy and the nature of the primordial density variations. The basic Big Bang picture, underpinned by General Relativity, continues to hold good, explaining the expansion of the universe, the cosmic microwave background radiation, the synthesis of light chemical elements and the formation of stars, galaxies and large-scale structures. However, there are important gaps in our understanding including the nature of the dark matter, the cause of the observed late-time acceleration of the universe and the classic puzzles of the initial singularity and what caused the Big Bang.

This course will develop the standard Big Bang cosmology and review its major successes and some of the challenges now faced at the cutting-edge of the field. After the completion of this course, students will have an appreciation of the basic theoretical foundations of physical cosmology, as well as an advanced understanding of the physics of several observational results critical to our current picture of the Universe.

Objectives

Specifically, after this course the students should be able to:

- understand the concepts of the metric and the geodesic equation, and to apply the mathematical language of General Relativity to the flat Friedmann-Robertson-Walker (FRW) metric.
- state the Einstein equation; derive the Einstein tensor in a flat FRW universe; describe physically the components of the energy-momentum tensor and write them down for dust and for a perfect fluid; derive the continuity and Euler equations from conservation of the energy momentum tensor; derive from the Einstein equation the Friedmann equations for a flat FRW universe.
- understand how the cosmological principle leads to the general FRW metric; to derive and use the Friedmann equations in a general FRW metric.
- understand and calculate the dynamics of the FRW universe when its equation of state is dominated by matter, radiation, curvature, and a cosmological constant; to understand the relationship between spatial curvature and the destiny of the universe, and how this relationship is modified in the presence of a cosmological constant.
- understand and calculate time and distance measurements in the FRW background.
- describe in GR language general particle motion in the FRW background, and to understand and use the derivation of the energy momentum tensor for a scalar field from the principle of least action (variational calculus will be reviewed).
- Describe the standard Big Bang puzzles and their resolution via inflation; understand the implementation of inflation via a scalar field; describe qualitatively how measurements of the primordial power spectrum allows us to test the theory.

- understand and use the basic statistical properties imposed on cosmological fields (such as the matter overdensity) by the assumption that they respect the symmetries of the FRW background (i.e. isotropy and homogeneity).
- understand and use cosmological perturbation theory, in particular to derive and describe the evolution of density perturbations during matter and radiation domination.
- understand and derive the morphology of the cosmic microwave background acoustic peak structure using the forced/damped simple harmonic oscillator equation.
- understand and use some key results from structure formation, including the linear power spectrum of matter fluctuations, two point correlation function, Limber's approximation, redshift space distortions in linear theory, spherical collapse, and the Press-Schecter formalism.

Detailed Syllabus

Part I: The homogeneous universe [10]

The metric	[1]
The geodesic equation	[1]
The Einstein equation	[1]
The general Friedmann-Robertson-Walker metric in GR	[2]
Time and distance in GR	[1]
Particles and fields in cosmology	[2]
Inflation	[2]

Part II: The perturbed Universe [10]

Statistics of random fields	[2]
Perturbation theory	[2]
Comoving curvature perturbation	[2]
The cosmic microwave background	[4]

Part III: Structure formation [10]

The linear-theory matter power spectrum	[3]
Two-point correlation function and Limber's approximation	[1]
Redshift space distortions in linear theory	[2]
Spherical collapse and the Press-Schechter formalism	[2]
Latest cosmological results/methods (non examinable)	[2]

The last (non-examinable) part of the course will review the latest measurements of cosmological parameters from current data.

Prerequisites

This course requires PHAS3137 or similar & a knowledge of MATH3305 (Maths for GR).

Recommended Texts

Modern Cosmology by Dodelson
An Introduction to General Relativity, Space-time and Geometry by Carroll
Cosmology by Weinberg

Proposed Assessment Methodology

The course is based on 30 lectures plus 3 mandatory sessions which are used for reviewing homeworks and practicing solving new problems. There are 4 problem sheets, which include both essay work and calculation of numerical results for different cosmological models.

Written examination of 2½ hours contributing 90% and problem sheets 10%

4421 Atom and Photon Physics

Aims of the Course

This course aims to provide:

- a modern course on the interactions of atoms and photons with detailed discussion of high intensity field effects e.g. multiphoton processes and extending to low field effects e.g. cooling and trapping.

Objectives

On completion of the course the student should be able to:

- describe the single photon interactions with atoms as in photo-ionization and excitation and the selection rules which govern them;
- explain the role of A and B coefficients in emission and absorption and the relation with oscillator strengths;
- describe the operation of YAG, Argon Ion and Dye Lasers and derive the formulae for light amplification;
- explain the forms of line broadening and the nature of chaotic light and derive the first order correlation functions;
- explain optical pumping, orientation and alignment;
- describe the methods of saturation absorption spectroscopy and two photon spectroscopy;
- derive the expression for 2-photon Doppler free absorption and explain the Lambshift in H;
- describe multiphoton processes in atoms using real and virtual states;
- explain ponder motive potential, ATI, stark shift and harmonic generations;
- describe experiments of the Pump and Probe type, the two photon decay of H and electron and photon interactions;
- derive formulae for Thompson and Compton scattering and the Kramers-Heisenberg formulae,
- describe scattering processes; elastic, inelastic and super elastic;
- derive the scattering amplitude for potential scattering in terms of partial waves;
- explain the role of partial waves in the Ramsauer-Townsend effect and resonance structure;
- derive the formulae for quantum beats and describe suitable experiments demonstrating the phenomena;
- describe the interactions of a single atom with a cavity and the operation of a single atom maser;
- describe the operation of a magneto-optical-trap and the recoil and Sisyphus cooling methods;
- explain Bose condensation.

Syllabus

(The approximate allocation etc., of lectures to topics is shown in brackets below.)

1. Atomic transitions [2.5 lectures – 7.5 hrs]

- Excitation, ionisation and auto-ionisation
- Electric dipole transitions
- Electric quadrupole transitions and magnetic dipole transitions
- Einstein *A* and *B* coefficients and oscillator strengths

- Excited-state lifetimes
- Coherent atom-field interactions: Rotating wave approximation, Rabi oscillations, Autler-Townes splitting
- AC Stark shifts: electric dipole polarisability

2. Precision measurement [2 lectures – 6 hrs]
- Ramesy interferometry
- Two-photon transitions
- Doppler-free spectroscopy
- 1S-2S transition in atomic hydrogen and positronium
- Frequency combs: absolute frequency calibration
- Lamb shift in atomic hydrogen and other one-electron systems

3. Atoms in strong laser fields [2 lectures – 6 hrs]
- Multiphoton ionisation in strong laser fields
- Semiclassical 3-step model of atom-field interaction
- Above threshold ionisation
- High-harmonic generation and attosecond pulses
- Non-sequential multi-electron ionisation and electron spectra
- Free electron lasers: characteristics and interaction with atoms/molecules

4. Single photon effects and cavity quantum electrodynamics [2 lectures – 6 hrs]
- Single-photon production/sources
- Photon antibunching: Hanbury-Brown—Twiss experiments
- Jaynes-Cummings model
- Single-atom maser
- Quantum non-demolition measurements

5. Ultracold atoms [2.5 lectures – 7.5 hrs]
- Laser cooling methods
- Optical dipole traps
- Optical lattices
- Cold atom scattering
- BEC-BCS crossover in ultracold atoms

Prerequisites
Knowledge of quantum physics and atomic physics to at least second year level, e.g. UCL courses PHAS2222 and PHAS2224.

Textbooks
Optoelectronics, Wilson and Hawkes (Chapman and Hall 1983)
Atomic and Laser Physics, Corney (Oxford 1977)
Quantum Theory of Light, Loudon (Oxford 1973)
Physics of Atoms and Molecules, Bransden and Joachain (Longman 1983)
Laser Spectroscopy, Demtröder (Springer 1998)
Where appropriate references will be given to some research papers and review articles. There is no one book which covers all the material in this course.

Methodology and Assessment

The course consists of 30 lectures of course material which will also incorporate discussions of problems and question and answer sessions. Two hours of revision classes are offered prior to the exam.

Written examination of 2½ hours contributing 90% and three problem sheets 10%

4425 Photonics and Metamaterials (previously Advanced Photonics)

Aims of the Course

The aim of the course is to provide a comprehensive overview of theoretical and practical aspects of major modern photonic technologies with special emphasis on novel trends and applications of nanophotonics.

Students will be exposed to modern concepts in photonics and understand the main physical principles behind modern photonic technologies, such as optical communications, nanophotonics, plasmonics, metamaterials, biosensing and bio-imaging and their applications in everyday life.

Objectives

The successful student should be able to:

- Demonstrate comprehension of the concepts of photonics. Link and apply these concepts to a range of physical situations, solving simplified model problems
- Demonstrate problem formulation and solving (both numerical and symbolic), written and verbal communication skills

Syllabus

- The course will cover aspects of optics and materials science as applied in photonics. (throughout the course)
- The course will survey the main types of photonic applications and concepts. (throughout the course)

The course will address these aspects by covering the following specific topics:

- Light manipulation at the micro and nano scale:
  - **optical waveguides** (4.5 lectures). This section of the course will introduce and develop the formalism necessary to describe the emergence of modes in planar dielectric geometries.
  - **surface plasmons polaritons (SPPs) and their devices** (7.5 lectures). Building on the previous section, this part of the course will develop the concepts necessary to understand a keystone building block of nanophotonics: SPPs. The field distribution of those modes will be derived in simple planar systems along with their dispersion and general properties, including optical coupling, hybridization in complex multilayers, etc. The manipulation of these waves will be discussed thoroughly for various structures, such as dielectric-loaded wavequides, metal-insulator-metal structures, amongst other geometries relevant for the design of integrated devices.
  - **photonic and plasmonic crystals** (4.5 lectures). Periodic structures often demonstrate unique physical properties. This is true for electronic properties in atomic crystals and is equally true for both photonic and plasmonic crystals. This part of the course will use the fundamental concepts presented in the previous section and apply them to periodic nanostructured metallo-dielectric interfaces. Simple models will be presented to understand the formation of plasmonic bands (Bloch modes) and their properties, including dispersion, reflection, refraction, localization, coupling to localized modes, interaction with light, etc.

- **localized surface plasmons (LSPs)** (3 lectures). This part of the course will touch on another important keystone building block in nanophotonics: LSPs. Here again, the formalism necessary to understand the optical response of these nanoscopic metallic resonators will be presented. Selected geometries will be discussed to give an understanding of their strong potential for sensing applications, optical cloaking, as well as their use as building blocks in metamaterials.
- **metamaterials** (7.5 lectures). This part of the course will introduce the conceptual ideas behind metamaterials and introduce their major historical development. Moving on, the course will introduce electric and magnetic metamaterials. The former, which can exhibit hyperbolic dispersion, open up the possibility tailor the effective plasma frequency for differently polarized waves in the media, while the former further combine magnetic resonances to produce so-called double negative (DNG) metamaterials (negative magnetic permeability) leading to exotic effects such as negative refraction, optical cloaking, and both super- and hyper-lenses.

- Modern applications of photonics
    - **biophotonics, sensing, and energy** (1.5 lectures). This part of the course will focus on the implementation of modern photonics and plasmonic approaches to tackle inter-disciplinary problems where optical techniques have distinct advantages over conventional techniques. These advantages will be illustrated and discussed.
    - **advanced optical characterization techniques** (1.5 lectures): As the drive toward the miniaturisation of photonics devices gathers pace, researchers and industrial players require instrumentation that can characterize nanoscale functional media and devices with resolution, both temporal and spatial, that surpass conventional microscopic techniques. Here, the course will centre on state-of-the-art techniques such as Scanning Near-Field Optical Microscopy and Cathodoluminesence. This part of the course will include a tour of the facilities at KCL.

Prerequisites
Electromagnetism and optics at a typical second year level is essential. Quantum mechanics, optics, and condensed matter physics at a typical third year level is desirable but not essential.

Textbooks
1. *Fundamentals of Photonics*, H. Saleh
2. *Principles of Nano-Optics*, L. Novotny and B. Hecht
3. *Introduction to Nanophotonics*, S. V. Gaponenko
4. *Optical Metamaterials: Fundamentals and Applications*, W. Cai, V. Shalaev

Methodology and Assessment
The course comprises 10 lectures of 3 hours over a 10-week period.

Written examination of 3 hours contributing 100%

4427 Quantum Computation and Communication

Aims

The course aims to

- provide a comprehensive introduction to the emerging area of quantum information science
- acquaint the student with the practical applications and importance of some basic notions of quantum physics such as quantum two state systems (qubits), entanglement and decoherence
- train physics students to think as information scientists, and train computer science/mathematics students to think as physicists
- arm a student with the basic concepts, mathematical tools and the knowledge of state of the art experiments in quantum computation & communication to enable him/her embark on a research degree in the area

Objectives

After learning the background the student should

- be able to apply the knowledge of quantum two state systems to any relevant phenomena (even when outside the premise of quantum information)
- be able to demonstrate the greater power of quantum computation through the simplest quantum algorithm (the Deutsch algorithm)
- know that the linearity of quantum mechanics prohibits certain machines such as an universal quantum cloner

After learning about quantum cryptography the student should

- be able to show how quantum mechanics can aid in physically secure key distribution
- be knowledgeable of the technology used in the long distance transmission of quantum states through optical fibers

After learning about quantum entanglement the student should

- be able to recognize an entangled pure state
- know how to quantitatively test for quantum non-locality
- be able to work through the mathematics underlying schemes such as dense coding, teleportation, entanglement swapping as well their simple variants
- know how polarization entangled photons can be generated
- be able to calculate the von Neumann entropy of arbitrary mixed states and the amount of entanglement of pure bi-partite states

After learning about quantum computation the student should

- know the basic quantum logic gates
- be able to construct circuits for arbitrary multi-qubit unitary operations using universal quantum gates
- be able to describe the important quantum algorithms such as Shor's algorithm & Grover's algorithm

After learning about decoherence & quantum error correction the student should

- be able to describe simple models of errors on qubits due to their interaction with an environment

- be able to write down simple quantum error correction codes and demonstrate how they correct arbitrary errors
- be able to describe elementary schemes of entanglement concentration and distillation

After learning about physical realization of quantum computers the student should

- be able to describe quantum computation using ion traps, specific solid state systems and NMR
- be able to assess the merits of other systems as potential hardware for quantum computers and work out how to encode qubits and construct quantum gates in such systems

Syllabus

Background [3]: The qubit and its physical realization; Single qubit operations and measurements; The Deutsch algorithm; Quantum no-cloning.

Quantum Cryptography [3]: The BB84 quantum key distribution protocol; elementary discussion of security; physical implementations of kilometers.

Quantum Entanglement [8]: State space of two qubits; Entangled states; Bell's inequality; Entanglement based cryptography; Quantum Dense Coding; Quantum Teleportation; Entanglement Swapping; Polarization entangled photons & implementations; von-Neumann entropy; Quantification of pure state entanglement.

Quantum Computation [8]: Tensor product structure of the state space of many qubits; Discussion of the power of quantum computers; The Deutsch-Jozsa algorithm; Quantum simulations; Quantum logic gates and circuits; Universal quantum gates; Quantum Fourier Transform; Phase Estimation; Shor's algorithm; Grover's algorithm.

Decoherence & Quantum Error Correction [4]: Decoherence; Errors in quantum computation & communication; Quantum error correcting codes; Elementary discussion of entanglement concentration & distillation.

Physical Realization of Quantum Computers [4]: Ion trap quantum computers; Solid state implementations (Kane proposal as an example); NMR quantum computer.

Prerequisites

Previous exposure to quantum mechanics in the Dirac notation is useful

Books

Quantum Computation and Quantum Information by Nielsen and Chuang, CUP 2000

Methodology and Assessment

The course consists of 30 lectures of course material which will also incorporate discussions of problems and question and answer sessions. Two hours of revision classes are offered prior to the exam.

Written examination of 2½ hours contributing 90% and three problem sheets 10%

4428 Quantum Electronics of Nanostructures

Aims and objectives

This course will provide an overview of the rapidly developing field of superconducting quantum circuits, originally proposed as basic elements for quantum computers. The course will give an introduction to basic phenomena of on-chip quantum optics in the microwave range, explain the quantum mechanical approach to electronic circuits, study the interaction of electromagnetic waves with artificial atoms and provide examples of theoretical understanding and experimental realisations of these effects. Prior knowledge of quantum theory at the level of bra-ket notation and quantum evolution will be assumed. Knowledge of superconductivity is not required.

Objectives

By the end of the course students should be able to:

- Describe electric circuits and fields in quantum mechanical terms.
- Describe different types of artificial atoms as quantum on-chip circuits and derive the Hamiltonians of the charge and flux based superconducting quantum systems. Calculate time-evolution of the driven two-level system and map it on the Bloch sphere.
- Explain at an advanced level physical meaning of strong interaction of artificial atoms with different elements and fields; describe the interaction of quantized electromagnetic fields with artificial atoms; explain difference between natural and artificial atoms and advantage of the latter ones for particular applications. Explain at an advanced level the fundamental quantum optical phenomena with the single artificial atoms; operation of on-chip quantum optical devices; explain how to experimentally realize basic quantum optical phenomena on-chip.

Syllabus

Quantum Optics in 1D

- Harmonic oscillators and non-linear oscillators
- Photons and fields
- Atoms interacting with quantized electromagnetic fields
- Quantum mechanics of electrical circuits
- Transmission lines and transmission line resonators
- Traveling and standing waves. Solid-state quantum bits

Artificial atoms. Control and manipulation of energies and quantum states

- Charge and flux quantization in superconducting circuits
- Alternative superconducting quantum systems
- Superconducting qubits and artificial atoms

Artificial atoms interacting with electromagnetic fields

- Quantum optics on artificial atoms
- Strong coupling of an atom to the fields
- Fock states and coherent states
- Scattering of propagating electromagnetic waves by a two-level system
- Artificial quantum systems and natural atoms

- Quantum-state control and manipulation in qubits

Experimental realization of fundamental quantum phenomena on-chip

- Jaynes-Cummings Hamiltonian
- Lamb shift and Stark effect
- Generating of the Fock states with artificial atoms
- Single-photon source
- Spontaneous and stimulated emission
- Lasing with single artificial atoms
- Electromagnetically induced transparency

Teaching arrangements

28 lectures and 5 tutorials
Three hours of lectures per week including 5 tutorials

Prerequisites

Third year Quantum Theory is required. Knowledge of bra-ket notation.

Books

M. Orszag, *Quantum Optics: Including Noise Reduction,* Trapped *Ions, Quantum Trajectories, and Decoherence, 2nd edition, Springer-Verlag, 2007*

Assessment

Examination of 2½ hours contributing 90%, coursework 10%

4431 Molecular Physics

Aims of the Course

This course aims to provide:

- an introduction to the physics of small molecules including their electronic structure, molecular motions and spectra.

Objectives

On completion of the course the student should be able to:

- describe the components of the molecular Hamiltonian and their relative magnitude
- state the Born-Oppenheimer approximation
- describe covalent and ionic bonds in terms of simple wave functions
- state the Pauli Principle, how it leads to exchange and the role of exchange forces in molecular bonding
- describe potential energy curves for diatomic molecules and define the dissociation energy and united atom limits
- analyse the long range interactions between closed shell systems
- describe rotational and vibrational motion of small molecules and give simple models for the corresponding energy levels
- give examples of molecular spectra in the microwave, infrared and optical
- state selection rules for the spectra of diatomic molecules
- interpret simple vibrational and rotational spectra
- explain the influence of temperature on a molecular spectrum
- describe experiments to measure spectra
- describe Raman spectroscopy and other spectroscopic techniques
- describe the selection rules obeyed by rotational, vibrational and electronic transitions
- describe the effect of the Pauli Principle on molecular level populations and spectra
- describe possible decay routes for an electronically excited molecule
- describe the physical processes which occur in CO_2 and dye laser systems
- state the Franck-Condon principle and use it to interpret vibrational distributions in electronic spectra and electron molecule excitation processes
- describe the possible relaxation pathways for electronically excited polyatomic molecules in the condensed phase
- explain how solvent reorganization leads to time-dependent changes in emission spectra

Syllabus

(The approximate allocation of lectures to topics is shown in brackets below)

Molecular structure [15]

Brief recap of atomic physics and angular momentum: n,l,m,s; variational principle, Pauli exclusion principle, He atom, many electron atoms, molecular Hamiltonian and Born-Oppenheimer approximation, potential energy hyper surface, vibrational and rotational structure, molecular orbitals from LCAO method, H_2^+ molecule, homo- and hetero-nuclear diatomics, types of chemical bonds, molecular dipole moment, Coulomb and exchange integrals, Hartree-Fock equations, Slater-type and

Gaussian-type basis sets, examples and accuracy of Hartree-Fock calculations, labelling schemes for electronic, vibrational and rotational states.

Molecular spectra [15]
Dipole approximation, Fermi's Golden Rule, selection rules, induced dipole moment, IR spectrum harmonic oscillator, anharmonicity corrections, normal modes, IR spectra of polyatomic molecules, selection rules for diatomics, R and P branch, corrections for vibration-rotation and centrifugal distortion, intensity of absorption lines, worked example HCl, role of nuclear spin, ortho- and para-H_2, Franck-Condon principle, electronic spectrum of O_2, fluorescence and phosphorescence, Stokes shift, Lambert-Beer law, spectral broadening, Jablonski diagram, vibrational Raman spectroscopy, rotational Raman spectroscopy, selection rules and intensity patterns, Examples: O_2, N_2, acetylene.

Prerequisites
An introductory course on quantum mechanics such as UCL courses PHAS2222 Quantum Physics. The course should include: Quantum mechanics of the hydrogen atom including treatment of angular momentum and the radial wave function; expectation values; the Pauli Principle. Useful but not essential is some introduction to atomic physics of many electron atoms, for instance: UCL courses PHAS2224 Atomic and Molecular Physics or PHAS3338 Astronomical Spectroscopy. Topics which are helpful background are the independent particle model, addition of angular momentum, spin states and spectroscopic notation.

Textbooks
- *Physics of Atoms and Molecules*, B H Bransden and C J Joachain (Longman, 1983) (Covers all the course but is not detailed on molecular spectra)
- *Molecular Quantum Mechanics*, P W Atkins (Oxford University) (Good on molecular structure)
- *Fundamentals of Molecular Spectroscopy,* 4th Edition, C.W. Banwell and E. McGrath (McGraw-Hill, 1994) (Introductory molecular spectroscopy book)
- *Spectra of Atoms and Molecules*, P F Bernath (Oxford University, 1995) (A more advanced alternative to Banwell and McGrath)
- *Molecular Fluorescence (Principles and Applications)*, B. Valeur (Wiley-VCH, 2002) (Condensed phase photophysics and applications of fluorescence)

Methodology and Assessment
The course consists of 30 lectures of course material which will also incorporate discussions of problems and question and answer sessions. Two hours of revision classes are offered prior to the exam.

Written examination of 2½ hours contributing 90% and three problem sheets 10%

4442 Particle Physics

Aims of the Course

- introduce the student to the basic concepts of particle physics, including the mathematical representation of the fundamental interactions and the role of symmetries
- emphasise how particle physics is actually carried out with reference to data from experiment which will be used to illustrate the underlying physics of the strong and electroweak interactions, gauge symmetries and spontaneous symmetry breaking

Objectives

On completion of this course, students should have a broad overview of the current state of knowledge of particle physics. Students should be able to:

- state the particle content and force carriers of the standard model
- manipulate relativistic kinematics (Scalar products of four-vectors)
- state the definition of cross section and luminosity
- be able to convert to and from natural units
- state the Dirac and Klein-Gordon equations
- state the propagator for the photon, the W and the Z and give simple implications for cross sections and scattering kinematics
- understand and draw Feynman diagrams for leading order processes, relating these to the Feynman rules and cross sections
- give an account of the basic principles underlying the design of modern particle physics detectors and describe how events are identified in them
- explain the relationship between structure function data, QCD and the quark parton model;
- manipulate Dirac spinors
- state the electromagnetic and weak currents and describe the sense in which they are 'unified'
- give an account of the relationship between chirality and helicity and the role of the neutrino
- give an account of current open questions in particle physics;

Syllabus Broken down into eleven 2.5 hr sessions.

1. Introduction, Basic Concepts

Particles and forces; Natural units; Four vectors and invariants; Cross sections & luminosity; Fermi's golden rule; Feynman diagrams and rules.

2. Simple cross section Calculation from Feynman Rules

Phase space; Flux; Reaction rate calculation; CM frame; Mandelstam variables; Higher Orders; Renormalisation; Running coupling constants.

3. Symmetries and Conservation Laws

Symmetries and Conservation Laws; Parity and C symmetry; Parity and C-Parity violation, CP violation.

4. Relativistic Wave Equations without interactions

From Schrodinger to Klein Gordon to the Dirac Equation; Dirac Matrices; Spin and anti-particles; Continuity Equation; Dirac observables.

5. Relativistic Maxwell's equations & Gauge Transformations
Maxwell's equations using 4 vectors; Gauge transformations; Dirac equation + EM, QED Lagrangians.

6. QED & Angular Distributions
QED scattering Cross Section calculations; helicity and chirality; angular distributions; forward backward asymmetries

7. Quark properties, QCD & Deep Inelastic Scattering
QCD - running of strong coupling, confinement, asymptotic freedom. Elastic electron-proton scattering; Deep Inelastic scattering; Scaling and the quark parton model; Factorisation; Scaling violations and QCD; HERA and ZEUS; Measurement of proton structure at HERA; Neutral and Charged Currents at HERA; Running of strong coupling; Confinement; QCD Lagrangian

8. The Weak Interaction-1
Weak interactions; The two component neutrino; V-A Weak current; Parity Violation in weak interactions; Pion, Muon and Tau Decay.

9. The Weak Interaction-2
Quark sector in electroweak theory; GIM mechanism, CKM matrix; detecting heavy quark decays.

10. The Higgs and Beyond The Standard Model
Higgs mechanism; alternative mass generation mechanisms; SUSY; extra dimensions; dark matter; Neutrino oscillations and properties.

11. Revision & problem sheets

Prerequisites
Students should have taken the UCL courses: Quantum Mechanics PHAS3226 and Nuclear and Particle Physics PHAS3224 or the equivalent and additionally have familiarity with special relativity, (four-vectors), Maxwell's equations (in differential form) and matrices.

Textbooks
Main recommended book:
- *Modern Particle Physics*: M. Thomson

Also:
- *Introduction to Elementary Particles:* D. Griffiths
- *Quarks and Leptons:* F. Halzen and A. D. Martin.
- *Introduction to High Energy Physics (4^{th} ed):* D.H. Perkins.

http://www.hep.ucl.ac.uk/~markl/teaching/4442

Methodology and Assessment
The course consists of 30 lectures of course material which will also incorporate discussions of problem sheets and question and answer sessions.

Written examination of 2½ hours contributing 90% and three problem sheets 10%

4450 Particle Accelerator Physics

Aims of the course
This course aims to:

- Introduce students to the key concepts of modern particle accelerators
- Apply previously learned concepts to the acceleration and focusing of charged particle beams
- Appreciate the use of particle accelerators in a variety of applications including particle physics, solid state physics, and medicine

Objectives
On completion of the course the students should be able to:

- Understand the principles and methods of particle acceleration and focusing
- Describe the key elements of particle accelerators and important applications
- Understand the key principles of RF systems and judge their applicability to specific accelerators
- Understand the key diagnostic tools and related measurements that are crucial to accelerator operation and evaluate their expected performance in key sub-systems

Syllabus
(The proximate allocation of lectures to topics is shown in brackets below.)

Introduction (2)
History of accelerators; Development of accelerator technology; Basic principles including centre of mass energy, luminosity, accelerating gradient

Characteristics of modern accelerators (2)
Colliders; 3rd and 4th generation light sources; compact facilities

Transverse beam dynamics (8)
Transverse motion, principles of beam cooling; Strong focusing and simple lattices; Circulating beams

Longitudinal dynamics (4)
Separatrix, Phase stability; Dispersion

Imperfections (2)
Multipoles, non-linearities and resonances

Accelerating structures (1)
Radio Frequency cavities, superconductivity in accelerators

Electrons (3)
Synchrotron radiation, electron beam cooling, light sources

Applications of accelerators (2)
Light sources; Medical and industry uses; Particle physics

Future (2)
ILC, neutrino factories, muon collider, laser plasma acceleration, FFAG

Prerequisites
Mathematics and Electromagnetism

Text Books
Recommended
- E. Wilson, *An Introduction to Particle Accelerators*, Oxford University Press
- S. Y. Lee *Accelerator Physics* World Scientific (2nd Edition)

Optional
- Sessler and E. Wilson, *Engines of DISCOVERY: A Century of Particle Accelerators*, World Scientific, 2007
- M.G. Minty and F. Zimmermann, *Measurement and Control of Charged Particle Beams,* Springer, 2003
- H. Wiedemann, *Particle Accelerator Physics, Parts I and II*, Second Edition, Springer, 2003

Website
http://moodle.rhul.ac.uk/

Formal registration to the course to obtain password is required

The following material will be available
- Course outline
- Lecture notes/summaries
- Additional notes
- Links to material of interest
- Problem assignments
- Links to past examination papers

Methodology and Assessment
26 lectures and 4 seminars/tutorials; 120 hours private study time, including problem solving and other coursework, and examination preparation.

Exam: (90%) (2½ hour) Three questions to be answered out of five.

Coursework: (10%) 5 sets of assessed problems.

Deadlines: Coursework deadlines are within 2 weeks from the issues of the problem set, unless otherwise advised by the lecturer.

4455 Collider Physics

Aims and Objectives
Upon completing the course, students should be able to:

- Describe the theories underlying modern particle collider experiments (e.g. the Large Hadron Collider)
- Understand how to apply these theories to calculate experimentally measured observables
- Explain the theory underlying modern software tools for particle physics analyses
- Describe which software tools are relevant for which type of analysis
- Describe different types of new physics that may be discovered at colliders, and how to look for different types of signal
- Engage with current research literature in particle physics phenomenology and experiment

Syllabus
1. Introduction
Types of particle collider. Review of relativistic kinematics (e.g. 4 vectors). Collider properties and detector geometry: luminosity, cross-sections, rapidity and azimuthal angle variables.

2. Quantum Chromodynamics (QCD)
Review of Quantum Electrodynamics (QED) as a gauge theory. Nonabelian gauge theories and definition of QCD: Lagrangian; Feynman rules; Renormalisation; Cross-sections and decay rates at leptonic colliders; cross-sections at hadron colliders and parton distribution functions.

3. Software tools
Parton shower algorithms for initial and final state radiation. Matching to tree-level matrix elements. Matching to next-to-leading order matrix elements. Review of publicly available implementations.

4. Jet Physics
Clustering algorithms and infrared safety. Jet substructure methods, and boosted physics. Analytic optimization of jet parameters.

5. New Physics
Brief survey of new physics models (e.g. supersymmetry, extra dimensions); types of new physics search (e.g. resonances, kinematic endpoints); effective field theory.

Teaching Arrangements
The course will take place in the second semester, and consist of eleven 3-hour lectures, making 33 hours in total.

Prerequisites
Students should have previously studied advanced quantum mechanics and quantum field theory. In particular, prior knowledge of Quantum Electrodynamics (including Feynman diagrams and rules) will be assumed, such as is contained in the

4242 Relativistic Waves and Quantum Fields course in semester A. It would be a significant advantage to take 4245 Advanced Quantum Field Theory as a co-requisite in semester B.

Books
A full set of written lecture notes will be provided as part of the course. However, students may also find the following books and monographs helpful:

QCD and Collider Physics, R. K. Ellis, W. J. Stirling and B. R. Webber, Cambridge University Press.

Quantum Field Theory and the Standard Model, M. D. Schwartz, Cambridge University Press.

Towards Jetography, G. Salam, Eur. Phys. J. C67 (2010) 637-686 (arXiv:0906.1833)

Gauge theories in particle physics, I. J. R. Aitchison and A. J. G. Hey, Taylor & Francis.

Modern Particle Physics, M. Thomson, Cambridge University Press.

Assessment
There will be a 2½ hour exam during the summer exam period, which counts for 90% of the marks. During the course, students will write a review of a research paper chosen from a list presented in the course (or an alternative topic to be agreed with the lecturer). This will count for 10% of the marks.

4471 Modelling Quantum Many-Body Systems

Aims of the Module

This module aims to provide an introduction to the theory and applications of quantum many-body systems. Topics include harmonic oscillators, second quantization for bosons and fermions, model Hamiltonians, collective excitations, correlation functions, path integrals and links to statistical mechanics. The module will focus primarily on systems at or close to equilibrium, with a view towards non-equilibrium quantum systems.

Objectives

On completion of this module, students should understand:

- The experimental motivation for studying quantum many-body systems
- The use of model Hamiltonians for describing collective phenomena
- The computation of physical observables, using operator methods and path integral techniques

Syllabus

The approximate allocation of lectures to topics is shown in brackets below. The lectures are supplemented by homework problem sets and problem classes.

Experimental Motivation (2)

Illustrative examples of the novel behaviour displayed by quantum many-body systems in condensed matter and cold atomic gases.

Second Quantization (2)

Simple harmonic oscillators; creation and annihilation operators; coupled oscillators; Fourier transforms; phonons; second quantization for bosons and fermions.

Quantum Magnetism (4)

Spin operators; quantum ferromagnets and antiferromagnets; spin wave theory, magnons and the Holstein-Primakoff transformation; low-dimensional systems, fermionization and the Jordan-Wigner transformation.

Path Integrals (6)

Principle of least action; calculus of variations; classical fields; Noether's theorem; path integrals for a single particle including the simple harmonic oscillator; canonical quantization; path integrals for fields; generating function; propagators; statistical field theory; coherent states; Grassmann numbers; path integrals for fermions.

Interacting Bosons (2)

Superfluidity; Bogoliubov theory of the weakly interacting Bose gas; broken symmetry; Goldstone bosons.

Interacting Fermions (2)

Metals; BCS theory of superconductivity.

Relativistic Fermions (2)

The Dirac equation; representations of the gamma matrices; applications of the Dirac Hamiltonian in low-dimensions, including one-dimensional electrons and graphene.

Prerequisites
There are no formal prerequisites. Normally we expect students taking this module to have knowledge equivalent to the following modules available at King's: 5CCP2240 Modern Physics, 6CCP3221 Spectroscopy and Quantum Mechanics.

Textbooks

- T. Lancaster and S. J. Blundell, *Quantum Field Theory for the Gifted Amateur,* Oxford University Press, 1st Edition (2014).
- A. Altland and B. D. Simons, *Condensed Matter Field Theory,* Cambridge University Press, 2nd Edition (2010).
- J. M. Ziman, *Elements of Advanced Quantum Theory,* Cambridge University Press, (1969).
- A. L. Fetter and J. D. Walecka, *Quantum Theory of Many-Particle Systems,* Dover (2003).
- A. M. Zagoskin, *Quantum Theory of Many-Body Systems: Techniques and Applications,* Springer, 2nd Edition (2014).
- R. P. Feynman and A. R. Hibbs, *Quantum Mechanics and Path Integrals,* Dover (2010).
- J. W. Negele and H. Orland, *Quantum Many-Particle Systems,* Advanced Book Classics, Westview Press (1998).
- G. D. Mahan, *Many-Particle Physics,* Kluwer Academic/Plenum Publishers, 3rd Edition (2000).

Methodology and Assessment
20 lectures and 10 problem classes. The lectures are supplemented by homework problem sets for discussion in the problem classes.

Written examination of 3 hours contributing 100%

4472 Order and Excitations in Condensed Matter

Syllabus
The allocation of topics to sessions is shown below. Each session is approximately three lectures.

Atomic Scale Structure of Material (session 1): The rich spectrum of condensed matter; Energy and time scales in condensed matter systems; Crystalline materials: crystal structure as the convolution of lattice and basis; Formal introduction to reciprocal space.

Magnetism: Moments, Environments and Interactions (session 2) Magnetic moments and angular momentum; diamagnetism and paramagnetism; Hund's rule; Crystal fields; Exchange interactions

Order and Magnetic Structure (session 3) Weiss model of ferromagnetism and antiferromagnetism; Ferrimagnetism; Helical order; Spin Glasses; Magnetism in Metals; Spin-density waves; Kondo effect

Scattering Theory (sessions 4 and 5) X-ray scattering from a free electron (Thomson scattering); Atomic form factors; Scattering from a crystal lattice, Laue Condition and unit cell structure factors; Ewald construction; Dispersion corrections; QM derivation of cross-section; Neutron scattering lengths; Coherent and incoherent scattering

Excitations of Crystalline Materials (session 6) Dispersion curves of 1D monoatomic chain (revision); Understanding of dispersion curves in 3D materials; Examples of force constants in FCC and BCC lattices; Dispersion of 1D diatomic chain; Acoustic and Optic modes in real 3D systems; Phonons and second quantization; Anharmonic interactions

Magnetic Excitations (session 7) Excitations in ferromagnets and antiferromagnets; Magnons; Bloch $T^{3/2}$ law; Excitations in 1, 2 and 3 dimension; Quantum phase transitions

Sources of X-rays and Neutrons (session 8) Full day visit to RAL. Neutron Sources and Instrumentation. Synchrotron Radiation. Applications of Synchrotron Radiation

Modern Spectroscopic Techniques (session 9)
Neutron scattering: triple-axis spectrometer, time-of-flight, polarized neutrons
X-ray scattering: X-ray magnetic circular dichroism, resonant magnetic scattering, reflectivity

Phase transitions and Critical Phenomena (session 10) Broken symmetry and order parameters in condensed matter. Landau theory and its application to structural phase transitions, ferromagnetism, etc. Ising and Heisenberg models. Critical exponents. Universality and scaling

Local Order in Liquids and Amorphous Solids (session 11) Structure of simple liquids; Radial distribution function; Dynamics: viscosity, diffusion; Modelling; Glass formation; Simple and complex glasses; Quasi-crystals

Prerequisites
UCL's PHYS3C25 – Solid State Physics, or an equivalent from another department

Textbooks
Main texts: Structure and Dynamics: An Atomic View of Materials, Martin T. Dove (OUP); Magnetism in Condensed Matter, Stephen Blundell (OUP)
Additional texts: Elements of Modern X-ray Physics, Jens Als-Nielsen and Des McMorrow (Wiley); Introduction to the Theory of Thermal Neutron Scattering, G.L. Squires (Dover)

Assessment
Written examination of 2½ hours contributing 90%, coursework 10%

4473 Theoretical Treatments of Nano-systems

Aims of the Course

This course provides an introduction to the rapidly growing area of atomistic-based theoretical modelling in nano-science, based on fundamental quantum theory. It introduces the physics of many electron systems as well as the theoretical background of some state of the art techniques needed to successfully model the structure and dynamical evolution of functional nano-sized systems. The role of symmetry in describing the systems electronic structure and the role of statistical averaging in dealing with rare events and bridging to higher length scales are also highlighted throughout the course.

Concrete examples of research applications are also provided, involving modern concepts on the nano-scale behaviour of functional materials. Guest speakers are invited to give short seminars addressing their cutting-edge current research.

Objectives

On successfully completing this course, a student should:

- Be familiar with the fact that the physical properties of complex nano-systems can be described within a coherent quantum mechanical framework, in particular that the many-electron QM problems can be attacked by mean-field techniques at different levels of complexity, and by Monte Carlo methods

- Appreciate how theories underpinning the current research on nano-systems such as Density Functional Theory, Fick's Diffusion and Orbital Representation can be rationalised at a more fundamental level in terms of modern mathematical tools such as Legendre Transformations, Stochastic Processes, Bayesian Inference and Group Theory

- Understand how these theories and tools can be used to generate accurate quantitative predictions on the behaviour of materials systems at the nanometre/picosecond size- and time- scales and above, enabled by QM-accurate potential energy surfaces and inter-atomic forces used within Molecular Dynamics simulations

Topics

Many-body problem and quantum mechanics of identical particles (1)

Schroedinger equation for a many-body system. The particle exchange operator, symmetry of a two-body wave function with spin. Wavefunction classes constructed from spin orbitals. Reminder of perturbation theory: perturbative approach of the ground state and the first excited state of the Helium atom.

Variational method (2)

Reminder of the variational approach. Definition of a functional and functional derivative. Lagrange multipliers method. Examples: i) virial theorem for Coulombic systems, ii) ground state energy of the Helium atom through trial wavefunction with one variational parameter, and iii) Hartree equation for the ground state of the Helium atom.

The Hartree-Fock method (3)
Pauli principle and Slater determinants. Derivation of the Hartree-Fock equations. Self-consistent field approach. Electronic correlation in many-electron systems. Koopman's theorem. Success and shortcomings of the HF method.

Density Functional Theory (4)
Hohenberg-Kohn theorem. Constrained-search algorithm, and v- and N-representability of densities. Kohn-Sham equations. Brief discussion of DFT in terms of a Legendre transformation. Making DFT practical: Local Density Approximation and beyond. Brief discussion of extension of DFT. Success and shortcomings of DFT.

Beyond self-consistent fields and static atoms: Variational Monte Carlo and QM forces (5)
Electronic structure methods for correlation energy: Importance sampling, Metropolis Algorithm and Variational Monte Carlo. Quantum molecules: the Hamiltonian operator, the Born-Oppenheimer approximation, the Hellman-Feynman theorem. QM-based forces on atoms.

Quantum and classical interatomic force-fields, molecular dynamics (6)
The Verlet Algorithm and First-Principles Molecular Dynamics. Classical potentials, the problem of accuracy and transferability. A coarse graining technique example from supramolecular assembly. The problem of validation: fitting force fields from QM data. Bayes Theorem, and elements of Machine Learning techniques for atomistic modelling.

Molecular dynamics used within statistical methods (7)
Modelling free energy barriers via thermodynamic integration. Classical dynamics and stochastic processes. Modelling the diffusion of point defects in crystalline solids. The central limit theorem and the evolution of a distribution function. The diffusion coefficient. Derivation of Fick's laws. Examples and exercises.

LCAO method in quantum chemistry and DFT; symmetry operations (8)
Formulation of Hartee-Fock and Kohn-Sham methods using localised basis set. Slater and Gaussian type atomic orbitals. Generalised eigenproblem in non-orthogonal basis set. Cholesky factorisation. Problems related to localised basis set (completeness, BSSE, Pulay). Example: two level system. Change of the basis. Naphthalene molecule. Symmetry operations of molecules: rotations, reflections, inversion.

Group theory (9,10)
Abstract group theory (definition, properties, subgroup, direct product, cosets, shift, class, generators). Point groups. Action of an operation on a function. Action on atomic orbitals. Theory of group representations. Unitary representation, reducible and irreducible representations, Schur's lemmas, orthogonality relations, characters, decomposition of a reducible representation, regular representation, projection operator method. Quantum mechanics and symmetry. Wigner's theorem. Example: quasidiagonalisation for a square molecule. Periodic systems. Translational group and its irreducible representations. Brillouin zone. Symmetry adapted functions and Bloch theorem. Main ideas for implementation of HF and KS equations for periodic systems.

Space groups. Bravais lattices. Crystal classes. Space group operations. Fedorov's theorem. International Tables of Crystallography.

Pre-requisites
Spectroscopy and Quantum Mechanics or equivalent

Bibliography

B.H.Bransden and C.J.Joachain, *Physics of Atoms and Molecules*, Longman.
M.Finnis, *Interatomic Forces in Condensed Matter*, Oxford University Press.
M.P.Allen and D.J.Tildesley, *Computer Simulations of Liquids*, Oxford University Press.
D.Frenkel and B.Smit, *Understanding Molecular Simulations*, Academic Press.
C. Bradley and A. Cracknell, *The Mathematical Theory of Symmetry in Solids: Representation Theory for Point Groups and Space Groups* (Oxford Classic Texts in the Physical Sciences), 2009.
M. Hamermesh, *Group Theory and Its Application to Physical Problems* Dover Books on Physics, 2003,
L. Kantorovich*, Quantum theory of the solid state: An introduction: Dover, 2004.*
J. P. Elliott and P. G. Dawber, *Symmetry in Physics: Principles and Simple Applications***,** Oxford, 1985
R. Knox, A. Gold1. *Symmetry in the solid state*, Benjamin, 1964.

Assessment
Written examination of 3 hours contributing 100%

4475 Physics at the Nanoscale

Overall aim of the course
Today an increasing amount of science and technology is concerned with processes at the nano-scale, typified by structures of the order of 10-1000 nanometre in dimension. At this scale, physics is determined by quantum processes. This course provides an introduction to the rapidly growing area of nano-science. Already, nano-structures are "familiar" to us in the structure of the current generation of computer chips, and the applications of nano-structures are predicted to contribute to the new technologies of this century. The course introduces the physics and technology of nano-structures, discusses their special properties, methods of fabricating them, and some of the methods of analysing them.

Objectives
On successfully completing this course, a student should:

- Appreciate the difference between the physics on the classical (macro-) scale and on the quantum (nano-) scale
- Understand the properties of nanostructures in 'zero', one and two dimensions
- Understand the fabrication and characterisation of nano-devices

Topics
Miniaturisation, Moore's law, electronics, microelectronics, nanoelectronics. Single electronics.
Coulomb blockade. Single Electron Transistor (SET). Applications of SET. Cooper-pair box.

Overview of key electron transport properties of metals / semiconductors:
Electron energy spectrum, energy bands, density of electron states. Effective mass. Fermi surface. Landau quantization and the role of electron scattering, Dingle temperature. De Haas-van Alphen and Shubnikov-de Haas effects.

Quantum interference of conduction electrons.
Weak localisation, spin-orbit scattering and anti-localisation. Aharonov-Bohm effect. Mesoscopic regime. h/e and $h/2e$ quantum oscillations. Universal conductance fluctuations.

Josephson effect in superconductors and Josephson quantum bits.
Flux and phase qubits. Read-out using Superconducting Quantum Interference Devices (SQUIDs) and Hybrid nano-interferometers.

Semiconductor nano-science

Electrons in a two-dimensional layer:
Density of electron states in low dimensional conductors. GaAs/AlGaAs structures. Quantum Hall effect.

Electrons in a one-dimensional system: formation in GaAs/AlGaAs.
Density of states. Diffusive and ballistic conduction. Quantised conduction.

Electrons in a zero-dimensional system: Quantum dots

***Carbon nanoelectronics*.**
Carbon nanotubes. Graphene.

'Top down' fabrication:
PVD thin layer deposition techniques by thermal and e-beam evaporation, laser ablation. Chemical vapour deposition (CVD) and MOCVD, plasma-assisted deposition, ion-implanted layers, epitaxial processes.

Nano-lithography:
Resolution limits. Electron-beam lithography. Proximity effect. Negative and positive lithographic processes. Electron beam resists. Ion beam etching and RIBE. Plasma-assisted etching. Alignment and self-alignment, Dolan technique. Focussed ion beam (FIB) nanotechnology, ion-beam lithography.

Nano-analysis:
SEM- and STEM-based methods. X-ray and electron spectroscopy.
Scanning tunneling microscopy. Atomic force microscopy and other scanning probe-based methods, including scanning near field optical microscopy.

'Bottom up' fabrication:
Scanning probe based nano-technology, molecular manufacturing.
Self-organised nano-structures.

Clean-room environment.

Prerequisites
Quantum mechanics and Condensed matter physics at a typical second year level is essential. Condensed matter physics at a typical third year level is desirable but not essential.

Books/references
Marc J. Madou, *Fundamentals of Microfabrication, The Science of Miniaturization*, 2nd ed, CRC Press, LLC (2002).
S. Washburn and R. A. Webb, *Quantum transport in small disordered samples from the diffusive to the ballistic regime*, Rep. Prog. Phys. 55, 1311-1383 (1992).
Michel Devoret and Christian Glattli, *Single-electron transistors*, Phys. World. Sep 1, 1998.

Assessment
Examination of 2½ hours contributing 90%, coursework 10%

4476 Electronic Structure Methods

Aims and objectives

Electronic structure methods – that is, computational algorithms to solve the Schrodinger equation – play a very important role in physics, chemistry and materials science. These methods are increasingly treated on equal footing with experiment in a number of areas of research, a sign of their growing predictive power and increasing ease of use. We now rely on electronic structure methods to understand experimental data, improve force-fields for use in more accurate and predictive simulations, and to achieve an understanding of processes not accessible to experiment. But which of the many available methods do we choose? How do we assess them? What are their strengths and weaknesses? This module aims to answer some of these and other questions: 1) To provide a detailed and understanding of modern electronic structure methods. 2) To give our students the experience of using them to solve various problems through the computational laboratory. 3) To achieve a high level of understanding of the strengths and weaknesses, both in the class (theory) and in the lab. 4) To develop a competence with using modern and widely used programs.

Syllabus

This course will cover the fundamental theoretical ideas in modern electronic structure theory. Some of these are:

- Hartree-Fock theory
- Correlated methods like Moller-Plesset perturbation theory, configuration interaction and coupled-cluster theory
- Density-Functional theory
- Intermolecular perturbation theory

The theoretical material will be complemented with a computational larboratory using state-of-the-art programs (NWChem and others) with the aim of aiding the development of a practical understanding of the methods, their strengths and their weaknesses.

Teaching arrangements

Lectures, 33 hours delivered in 11 sessions of 3 hours each.

Prerequisites

Intermediate Quantum Mechanics and Mathematical Methods for Physicists. Some knowledge of using Unix/Linux systems will be handy, but is not essential.

Books

1) *Modern Quantum Chemistry* by Szabo and Ostlund.

2) *Molecular Electronic Structure Theory* by Helgaker, Jorgensen and Olsen.

3) *Electronic Structure* by Richard Martin.

4) *A Chemist's Guide to Density Functional Theory* by Koch and Holthausen

5) *Electronic Structure Calculations for Solids and Molecules* by Jorge Kohanoff

http://qmplus.qmul.ac.uk/course/view.php?id=3317

Assessment

Written examination of 2½ hours contributing 60%, coursework 40%

4477 Computer Simulation in Condensed Matter

Aims and objectives

Computer simulations are a core part of research-level condensed-matter physics and an important skill for physics graduates in diverse fields of employment. This course will develop the techniques and applications of atomistic, spin and particle-based simulations in condensed matter and statistical physics. The course will cover the theoretical foundations, algorithmic and numerical techniques through to practical implementation. It will include an assessed practical programming element to develop specific and general computational skills. The Python language will be used throughout.

On completion of the course, students should be able:

- Understand the statistical mechanics foundations and principal numerical algorithms of both molecular dynamics and Monte Carlo simulation techniques and the role of these methods in the theory of solids and liquids
- Design and run computer experiments using a molecular dynamics or Monte Carlo program to predict basic properties of simple molecular liquid and spin models

Syllabus

The topics covered will be atomistic potential functions and their application to the structure phase transitions, kinetics and thermodynamics of solids and liquids, spin lattice models of magnetism, optimization algorithms, molecular dynamics and Monte Carlo simulations. There will be an emphasis on following the chain from the theoretical physics foundations with numerical methods, computer implementations and programming techniques up to designing and performing computer experiments.

Teaching arrangements

35 hours of contact time including lectures, practicals and revision lectures
115 hours private study time, including problem solving and other coursework, and examination preparation.

Prerequisites

This course requires knowledge of classical and statistical thermodynamics, solid state physics and scientific computing skills all at typical year 2 level.

Corequisites

4211 Statistical Mechanics

Books

J M Thijssen, *Computational Physics*, ISBN-13: 9780521833462
Daan Frenkel & Berend Smit, *Understanding Molecular Simulation* - ISBN: 978-0-12-267351-1
Further reading:
V. Brazdova & D. R. Bowler, *Atomistic Computer Simulations* – ISBN 978-3-527-41069-9

Assessment

Written examination of 2½ hours contributing 75%, Computational mini-project, assessed on submitted computer code plus short report contributing 25%

4479 Advanced Condensed Matter

Aims of the course

The purpose of this module is to provide an introduction to modern topics of condensed matter physics. This module will introduce the formalism required to understand complex quantum phenomena in condensed matter, such as the Kondo effect or the Wigner crystal. It will also discuss how quantum effects in materials can be probed by experiments, and how the experimental measurements can be analyzed with the help of theoretical tools and simple model Hamiltonians.

Objectives

On completion of this course, students should understand:

- The theoretical framework related to electronic properties of materials, the general concepts required to understand quantum phenomena in condensed matter
- The derivation of effective theories and model Hamiltonians used to describe the phenomenology
- The mathematical tools and numerical techniques used to make theoretical predictions
- The connection between the theoretical approaches and state-of-the-art experimental techniques used to probe quantum phenomena

Syllabus

Introduction (week 1)

- This lecture will cover introductory topics of condensed matter: band structure, Brillouin zone, Fermi surface, Nesting, density of states, Van Hove singularities

Second quantization (week 2)

- This lecture will introduce the second quantization and the representation of one- and two-body operators. Extensions will be discussed: the Bloch theorem, the Mott insulator, Wannier orbitals, hopping matrix elements, the atomic limit

Tight binding theory (week 3)

- This lecture will introduce the tight binding model. We will discuss the real space and reciprocal space representation of the theory, its diagonalization and the matrix notations. Applications to modern condensed matter topics will be discussed:
  - i) External magnetic field, Hofstadter butterfly, orbital currents
  - ii) Low dimensionality: graphene and semi-metallicity
  - iii) Disorder: the Anderson Impurity Model
  - iv) Correlation: The limit of the Wigner Crystal

Single electron Green's function (week 4)

- This lecture will discuss the single particle Green's function. The concepts of advanced and retarded Green's function will be introduced. We will introduce the equation of motion and spectral functions.

Linear response (week 5)

- In this lecture we will introduce the linear response. We will introduce the notation of magnetic susceptibility and polarization. In this lecture, we will also make connections with experimental probes (ARPES, STM, X-ray) and how the theory can model these experiments. We will also introduce the concept of screening via the discussion of the Friedel oscillations.

Quantum magnetism (week 6)

- We will in this lecture discuss the theory of quantum magnetism, and the origin of the magnetic moment in transition metal ions. We will discuss the eg-t2g orbitals, the Hund's rule, the crystal field effect, the super-exchange. We will introduce the Stoner criteria and extend further the discussion to modern topics:
  - i) Magnetic frustration and Mermin-Wagner theorem
  - ii) Jahn Teller, ferro-electricity
  - iii) Dzyaloshinskii-Moriya interactions
  - iv) The Kondo effect

Strong correlations (week 7)

- In this lecture we will extend the tight binding model to include the effect of electronic correlations. We will discuss the Hubbard model and the derivation of the low energy effective t-J model. We will derive the Anderson 'Resonating Valence Bond' theory of superconductivity from the t-J model. We will finally discuss the concept of quasi-particles and excitations.

Mean field theory (week 8)

- In this lecture we will give tools to the student to treat the electronic correlations via the mean-field approach. We will discuss the Bogoliubov - DeGennes theory.

Density functional theory (week 9)

- In this lecture we will introduce how electronic correlations can be included at the level of density functional theory (DFT) and provide an introduction to DFT+U

Effective low energy theories (week 10)

- In this lecture we will discuss how advanced DFT calculations (week 9) can be projected onto a low energy effective subspace spanned by Wannier functions (week 2). This allows deriving simple model Hamiltonians, which can be in turn solved with the techniques introduced in the lecture (tight binding, mean field theory). A short introduction to Quantum Espresso, an open source DFT package, and to Wannier90, an open source down-folding method, will be given via a hands-on session.

Prerequisites

Normally we expect students taking this module to have background knowledge equivalent to the content of the following modules available at King's: 5CCP2240 Modern Physics, 6CCP3221 Spectroscopy and Quantum Mechanics

Text books

[1] J. M. Ziman, *Elements of Advanced Quantum Theory*, ISBN-10: 0521099498, ISBN-13: 978-0521099493

[2] A. L. Fetter and J. D. Walecka, *Quantum Theory of Many-Particle Systems*, ISBN-10: 0486428273, ISBN-13: 978-0486428277
[3] Michael P. Marder, *Condensed Matter Physics*, ISBN-10: 0470617985, ISBN-13: 978-0470617984
[4] P. Taylor, *A Quantum Approach to Condensed Matter Physics*, ISBN-10: 0521778271, ISBN-13: 978-0521778275

Methodology and assessment
10 lectures 2 hours each followed by a 1 hour problem class. Solutions to the problem classes are provided in the next week's lecture.

Assessment is based on an end of year written 3 hour exam (100%)

4501 Standard Model Physics and Beyond

Aims of the course:
To introduce the student to the physics of the Standard Model of Particle Physics. In particular, the course will discuss the constituents of the Standard Model and the underlying Lie group structure, within the framework of gauge invariant quantum field theory, which will be introduced to the student in detail, discuss the physical mechanism for mass generation (Higgs), consistently with gauge invariance, and finally present some applications by computing, via appropriate tree-level Feynman graphs, cross sections or decay rates (to leading order in the respective couplings) of several physical processes, such as quantum electrodynamics processes, nucleus beta decays and other processes that occur within the Standard Model of electroweak interactions.

Objectives of the Course:
On completing the course, the students should have understood the basic features of the Standard model that unifies the electromagnetic and weak interactions of particle physics, in particular the students should be able to comprehend **(i)** The detailed gauge group structure and the associated symmetry breaking patterns underlying the electroweak model, **(ii)** the short range of the weak interactions, as being due to the massiveness of the associated gauge bosons that carry such interactions, **(iii)** the long-range of electromagnetism, as being due to the masslessness of the associated carrier, that is the photon, **(iv)** the detailed mechanism (Higgs) by means of which the weak interactions gauge bosons acquire their mass, as a consequence of the spontaneous breaking of gauge invariance. The students should also be capable of: **(v)** Computing fundamental processes within the standard model, at tree-level, such as the decays of the weak interaction gauge bosons, the nuclear beta decay and its inverse, or scattering processes within electrodynamics, such as electron-muon or electron-proton scattering. The students should be conversant in computing decay widths and cross sections (both differential and total).

Syllabus (33 hours)
(The **approximate** allocation of lectures/tutorial to topics is shown in brackets – by 'tutorials' it is meant an hour of lectures in which applications/problems of the material covered in the previous hours or homework exercises are analysed/solved in detail.)

1. Review of Lie Algebras, Lie Groups and their representations and their connection to Particle Physics – examples of Lie groups with physical significance **(3 hours)**

2. Free Relativistic Fields of spin 0 (scalar), spin ½ (fermions) and Spin 1 (massless (photons) and massive vector mesons: Lagrange formalism and Symmetries (space-time and continuous internal (gauge) symmetries- a first glimpse at gauge invariance) **(4 hours, 2 tutorials)**

3. Interacting Fields and Continuous Internal Symmetries in Particle Physics (global and local (gauge)) and methods of computing the associated Noether currents (e.g. the Gell-Mann-Levy method **(2 hours, 1 tutorial)**

4. Spontaneous Breaking of Global Continuous Symmetries – the Fabri-Picasso and Goldstone Theorems – Massless Goldstone modes **(2 hours, 1 tutorial)**

5. Spontaneous Breaking of local (gauge) Abelian (U(1)) and Non-Abelian symmetries – absence of massless Goldstone modes from the physical spectrum – mechanism for mass generation of gauge bosons, the Higgs particle **(4 hours, 2 tutorials)**

6. The Standard Model Lagrangian: $SU(2) \times U_Y(1)$ gauge group as the physical group unifying weak and electromagnetic interactions and its spontaneous breaking patterns to U_{em} (1) of electromagnetism; chiral spinors, lepton sectors, quark sectors, quark-lepton symmetry as far as weak interactions are concerned – Brief discussion on incorporating colour SU(3) group in the Standard Model, gauge-invariant fermion mass. **(4 hours, 2 tutorials)**

7. Applications of the Standard Model: Feynman Rules, Computing physical processes such as Nuclear Beta Decay Quantum Electrodynamics processes, such as electron-muon or electron-proton scattering (**3 hours, 3 tutorials)**

8. TWO Extra hours of Lectures on BEYOND THE STANDARD MODEL, such as the role of supersymmetry in view of the Higgs Discovery and Stability of the Electroweak Vacuum have been provided in the past years by John Ellis, Maxwell Professor of Physics at King's College London and this tradition is foreseen for several years to come. The material is not examinable but serves the purpose of broadening the students horizons

Prerequisites
Essential knowledge of Relativistic Quantum Fields (course offered in the MSci programme as prerequisite), including relativistic kinematics of fields of various spins. Excellent Knowledge of tensor calculus. Very Good knowledge of Particle Physics and a basic knowledge of Lie Groups, provided either through a specialized course on the subject or an equivalent one in the physics syllabus, such as symmetry in Physics. Knowledge of Lagrange equations are essential prerequisites for the course.

Study Material - Textbooks
Lecture Notes (N.E. Mavromatos) (Latex) provided

Textbooks:
Robert Mann, *An Introduction to Particle Physics the Physics of the Standard Model* (CRS Press, Taylor & Francis Book, 2010), ISBN 978-1-4200-8298-2 (hard cover).
The book provides a comprehensive and up-to-date description of the most important concepts and techniques that are used in the study of Particle Physics and the Physics of the Standard Model in particular.

I.J.R. Aitchison and A.G.J. Hey, two volumes: *Vol. 1: Gauge Theories in Particle Physics: From Relativistic Quantum Mechanics to QED* (Taylor & Francis Group, 2003), ISBN: 0-7503-0864-8, 978-0-7503-0864-9) and *Vol. 2: Gauge Theories in Particle Physics: QCD and the Electroweak Theory* (Graduate Student Series in Physics) (Paperback)

(IOP Publishing, 2004), ISBN: 0-7503-950-4.

Other more advanced textbooks on related topics (mostly gauge field theories), for students planning to continue into higher academic degrees in theoretical particle physics are

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

T.P. Cheng and L.F. Li, *Gauge Theory of Elementary Particle Physics* (Oxford, 1984, last reprint 2000)

S. Weinberg, *The Quantum Theory of Fields, Vols. I, II and III* (they cover several advanced topics, including supersymmetry) (Cambridge U.P. 1995, 1996, 2000).

The web page of the course can be found in this link (accessible upon proper registration):

http://keats.kcl.ac.uk/course/view.php?id=22727

Methodology and Assessment
33 hours of lectures and tutorials (three hours each week: either three hours of lectures or two hours of lectures, followed by one hour of tutorials, depending on the week). Weekly sets of exercises are provided to the students, who are then asked to solve them, usually within a week, and then the problems are solved in the tutorial hour, with written solutions provided through the course web page (see above).

Written examination of 3 hours contributing 100%

4512 Nuclear Magnetic Resonance

Aims of the Course
This course aims to:

- introduce students to the principles and methods of nuclear magnetic resonance
- apply previously learned concepts to magnetic resonance
- allow students to appreciate the power and versatility of this technique in a variety of applications

Objectives
On completion of this course, students should be able to:

- show how Larmor precession follows from simple microscopic equations of motion
- explain how the Bloch equations provide a phenomenological way of describing magnetic relaxation
- describe the duality of pulsed NMR and CW NMR
- obtain solutions of the Bloch equations in the pulsed NMR and CW NMR cases
- describe and discuss the instrumentation used for the detection of NMR in the CW and pulsed cases
- demonstrate the production and utility of spin echoes
- explain the principles underlying magnetic resonance imaging
- describe the different methods of MRI

Syllabus
(The approximate allocation of lectures to topics is shown in brackets below.)

Introduction (3)
Static and dynamic aspects of magnetism; Larmor precession; relaxation to equilibrium; T_1 and T_2; Bloch equations.

Pulsed and continuous wave methods (4)
Time and frequency domains; the rotating frame; manipulation and observation of magnetisation; steady-state solutions of Bloch equations; 90° and 180° pulses; free induction decay; pulse sequences for measuring T_2^*, T_2 and T_1.

Experimental methods of pulsed and CW NMR (4)
Requirements for the static field magnet; radio frequency coils; continuous wave spectrometers – Q-meter and Robinson oscillator; saturation; demodulation techniques; pulsed NMR spectrometer; single and crossed-coil configurations for pulsed NMR.

Signal to noise ratio in CW and pulsed NMR, and SQUID detection (3)
Calculation of signal size for both pulsed and CW NMR; noise sources in NMR; signal averaging; comparison of sensitivity of pulsed and CW NMR; Ernst angle; Detection of NMR using SQUIDs.

Theory of Nuclear Magnetic Relaxation (4)
Transverse relaxation of stationary spins; the effect of motion; correlation function and spectral density; spin lattice relaxation; dependence of relaxation on frequency and correlation time; rotational versus translational diffusion.

Spin Echoes (**1**)
Violation of the Second Law of Thermodynamics; recovery of lost magnetisation; application to the measurement of T_2 and diffusion.

NMR Imaging (2)
Imaging methods; Fourier reconstruction techniques; gradient echoes; imaging other parameters – T_1, T_2 and diffusion coefficient.

Analytical NMR (1)
Chemical shifts, J-coupling, metals, nuclear quadrupole resonance

Prerequisites
2nd year-level electromagnetism and quantum mechanics.

Text Books and Lecture Notes

- *Nuclear Magnetic Resonance and Relaxation*, B P Cowan CUP, 1st ed. 1997 and 2nd ed. 2005.
- *Lecture notes available as handouts and online.*

http://moodle.rhul.ac.uk/course/view.php?id=247

Methodology and Assessment
22 lectures and 8 problem class/seminars. Lecturing supplemented by homework problem sets.

Written examination of 2½ hours contributing 90% and four problem sheets contributing 10%

4515 Statistical Data Analysis

On completion of the course, students should be able to:

- Understand and be able to use effectively the statistical tools needed for research in physics through familiarity with the concepts of probability and statistics and their application to the analysis of experimental data.

Course content

- Probability: definition and interpretation, random variables, probability density functions, expectation values, transformation of variables, error propagation, examples of probability functions
- The Monte Carlo method: random number generators, transformation method, acceptance-rejection method, Markov Chain Monte Carlo
- Statistical tests: formalism of frequentist test, choice of critical region using multivariate methods, significance tests and p-values, treatment of nuisance parameters
- Parameter estimation: properties of estimators, methods of maximum likelihood and least squares, Bayesian parameter estimation, interval estimation from inversion of a test
- Overview of Bayesian methods, marginalisation of nuisance parameters, Bayes factors

Prerequisites

Familiarity with programming in a high-level language such as C++ (or PH3170 as co-requisite)

Books

Lecture notes provided online.

http://www.pp.rhul.ac.uk/~cowan/stat_course.html

G D Cowan, *Statistical Data Analysis*, Clarendon Press, 1998. (530.0285.COW)
R J Barlow, *Statistics: A Guide to the Use of Statistical Methods in the Physical Sciences*, John Wiley, 1989. (530.13.BAR)

Assessment

Written examination of 2½ hours contributing 80%, coursework contributing 20%

4534 String Theory and Branes

Aims and Objectives
The main aim of the course is to give a first introduction to string theory which can be used as a basis for undertaking research in this and related subjects.

Syllabus
Topics will include the following: classical and quantum dynamics of the point particle, classical and quantum dynamics of strings in spacetime, D-branes, the spacetime effective action, and compactification of higher dimensions.

Web page: http://www.mth.kcl.ac.uk/courses/

Teaching Arrangements
Two hours of lectures each week

Prerequisites
Note – A high level of mathematical ability is required for this course
The course assumes that the students have an understanding of special relativity and quantum field theory. In addition the student should be familiar with General Relativity, or be taking the Advanced General Relativity course concurrently.
4205 Lie Groups and Lie Algebras would be helpful

Reading List
The lecture notes taken during the lectures are the main source. However, some of the material is covered in:

- Green, Schwarz and Witten: *String Theory 1*, Cambridge University Press.
- B. Zwiebach: *A First Course in String Theory*, Cambridge University Press.

http://www.mth.kcl.ac.uk/courses/

Assignments
During the lectures problems will be given and complete solutions will be made available. It is crucial that students work through these problems on their own.

Assessment
Written examination of 2 hours contributing 100%

4541 Supersymmetry

Aims and objectives

This course aims to provide an introduction to two of the most important concepts in modern theoretical particle physics; gauge theory, which forms the basis of the Standard Model, and supersymmetry. While gauge theory is known to play a central role in Nature, supersymmetry has not yet been observed but nevertheless forms a central pillar in modern theoretical physics.

Syllabus

Maxwell's equations as a gauge theory. Yang-Mills theories. Supersymmetry. Vacuum moduli spaces, extended supersymmetry and BPS monopoles.

Web page: http://www.mth.kcl.ac.uk/courses/

Teaching arrangements

Two hours of lectures each week

Prerequisites

Note – A high level of mathematical ability is required for this course

Students should be familiar with quantum field theory, special relativity as well as an elementary knowledge of Lie algebras.

Books

The lecture notes taken during the lectures are the main source but see also

- D. Bailin and A. Love: *Supersymmetric Gauge Field Theory and String Theory*, Taylor and Francis.
- L. Ryder: *Quantum Field Theory*, Cambridge University Press
- P. West: *Introduction to Supersymmetry*, World Scientific

Assignments

During the lectures problems will be given and complete solutions will be made available. It is crucial that students work through these problems on their own.

Assessment

Written examination of 2 hours contributing 100%

4545 Supersymmetric Methods in Theoretical Physics

Aims and objectives

The main aim of this course is to introduce fundamental aspects of theoretical physics---symmetries and constraints on the behaviour of quantum systems, renormalization, and dualities---through the filter of supersymmetry. In particular, we will tackle various non-trivial examples of these phenomena in a manageable and calculable way. By spending most of the course in three space-time dimensions, we can learn some of the basics of quantum dynamics at strong coupling just using matter superfields and abelian gauge multiplets. This course is designed to be useful for students interested in various theoretical sub-disciplines like particle physics, condensed matter, and string theory.

Syllabus

Starting with supersymmetric quantum mechanics as a toy model, the course covers the supersymmetry algebra, its representations, the Witten Index, and the resulting constraints on quantum dynamics. We then move on to introduce supersymmetric field theories in three space-time dimensions consisting of scalars and fermions while giving a basic introduction to symmetry currents, the classical and quantum Wilsonian renormalization group flow, moduli spaces, spurions, and non-renormalization arguments. The course is designed to culminate with a study of dualities in three-dimensional supersymmetric abelian gauge theories. However, if time permits, we may also discuss basic aspects of dualities with broken supersymmetry, explicit applications of superspace techniques to condensed matter systems, or embeddings of some of our dualities in string theory.

Prerequisites

SPA6413 Quantum Mechanics B, SPA6324 Mathematical Techniques 4 or equivalents

Corequisites

SPA7018P Relativistic Waves and Quantum Fields or equivalent

Teaching arrangements

11 3-hour lectures for a total of 33 hours

Recommended Reading

1. Philip Argyres, *Introduction to Supersymmetry*, (Cornell University Physics Lectures); http://homepages.uc.edu/~argyrepc/cu661-gr-SUSY/susy1996.pdf
2. Matthew Strassler, *An Unorthodox Introduction to Supersymmetric Gauge Theory*, (Proceedings of TASI 2001); https://arxiv.org/pdf/hep-th/0309149.pdf
3. John Terning, *Modern Supersymmetry: Dynamics and Duality* (OUP Oxford; International Series of Monographs on Physics)
4. Steven Weinberg, *The Quantum Theory of Fields: Supersymmetry (Vol III)*, (Cambridge University Press)
5. Julius Wess and Jonathan Bagger, *Supersymmetry and Supergravity*, (Princeton University Press)

Assessment

Written examination of 2½ hours (90% of final score) & coursework (10% of final score)

4600 Stellar Structure and Evolution

Course outline
Stars are important constituents of the universe. This course starts from well known physical phenomena such as gravity, mass conservation, pressure balance, radiative transfer of energy and energy generation from the conversion of hydrogen to helium. From these, it deduces stellar properties that can be observed (that is, luminosity and effective temperature or their equivalents such as magnitude and colour) and compares the theoretical with the actual. In general good agreement is obtained but with a few discrepancies so that for a few classes of stars, other physical effects such as convection, gravitational energy generation and degeneracy pressure have to be included. This allows an understanding of pre-main sequence and dwarf stages of evolution of stars, as well as the helium flash and supernova stages.

Syllabus – Topics covered include
- Observational properties of stars, the H-R diagram, the main sequence, giants and white dwarfs

- Properties of stellar interiors: radiative transfer, equation of state, nuclear reactions, convection

- Models of main sequence stars with low, moderate and high mass

- Pre- and post-main sequence evolution, models of red giants, and the end state of stars

The course includes some exposure to simple numerical techniques of stellar structure and evolution; computer codes in Fortran.

Prerequisites
Some knowledge of Fluids, Electromagnetism, Stellar Structure

Books
Course Notes available
R Kippenhahn and A Weigert - *Stellar Structure and Evolution* Springer

http://qmplus.qmul.ac.uk/course/view.php?id=2268

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%

4601 Cosmology

Course outline

Cosmology is a rapidly developing subject that is the focus of a considerable research effort worldwide. It is the attempt to understand the present state of the universe as a whole and thereby shed light on its origin and ultimate fate. Why is the universe structured today in the way that it is, how did it develop into its current form and what will happen to it in the future? The aim of this course is to address these and related questions from both the observational and theoretical perspectives. The course does not require specialist astronomical knowledge and does not assume any prior understanding of general relativity.

Syllabus

- Observational basis for cosmological theories
- Derivation of the Friedmann models and their properties
- Cosmological tests; the Hubble constant; the age of the universe; the density parameter; luminosity distance and redshift
- The cosmological constant
- Physics of the early universe; primordial nucleosynthesis; the cosmic microwave background (CMB); the decoupling era; problems of the Big Bang model
- Inflationary cosmology
- Galaxy formation and the growth of fluctuations
- Evidence for dark matter
- Large and small scale anisotropy in the CMB

Prerequisites

Knowledge of Newtonian Dynamics and Gravitation, and Calculus.

Books

A. Liddle, *An Introduction to Modern Cosmology*, 2nd Edition (2003), Wiley.

An introduction to the field with almost no mathematics. Intended for undergraduates, but helpful as a gentle introduction to the course, containing much of the core material.

P. Coles & F. Lucchin, *Cosmology: The Origin and Evolution of Cosmic Structure*, 2nd Edition (2002) Wiley

An excellent graduate textbook. Its emphasis is on models of large--scale structure, but the first half contains much of what you need to know and is pitched at about the right level for the course.

http://qmplus.qmul.ac.uk/course/view.php?id=3371

Assessment

Written examination of 2½ hours contributing 90%, coursework contributing 10%

4602 Relativity and Gravitation

Course outline

Einstein's theory of relativity is one of the pillars of modern physics, and is currently enjoying a renaissance due to recent progress in cosmology and gravitational wave detection. This course is aimed at providing sufficient tools to understand the deep physics that underpins these advances, and to provide the foundational mathematics and physics required for more advanced study. This will begin with an introduction to differential geometry, before moving on to Einstein's gravitational field equations and their solutions. It will include the study of black hole physics and gravitational wave emission.

Syllabus

- Introduction to differential geometry, including an explanation of how physics should be understood in curved spaces.
- Presentation of Einstein's theory of general relativity, including some exact solutions to the field equations of the theory.
- Perturbative relativistic gravity, for use in the Solar System and for calculating the gravitational wave signals from inspiralling binaries.
- Modern developments in general relativity, including the LIGO detection of gravitational waves.

Prerequisites

Knowledge of Newtonian mechanics and special relativity. Basic knowledge of general relativity would also be beneficial.

Books

General Relativity: An Introduction for Physicists by M. P. Hobson, G. Efstathiou and A. N. Lasenby, Cambridge University Press, 2006

http://qmplus.qmul.ac.uk/course/view.php?id=3299

Assessment

Written examination of 2½ hours contributing 90%, coursework contributing 10%

4605 Astroparticle Cosmology

Aims of the Course:
The course aims to address subjects on the frontiers of modern theoretical cosmology, a field which is based on General Relativity and Particle Physics. This is an advanced course in Theoretical Cosmology and Astroparticle Physics and necessitates knowledge of Astrophysics, General Relativity as well as High Energy Particle Physics. It is a specialised mathematical course that prepares students who want to conduct research on the frontiers of Early Universe Theoretical Cosmology.

Objectives
On completion of this course, students should understand
- Hot Big Bang model (successes and shortcomings)
- Early universe cosmology (topological defects, inflation)
- Large scale structure formation and cosmic microwave anisotropies

and will be able to conduct research on the relevant subject areas.

Syllabus
I. Homogeneous isotropic universe
- Einstein-Hilbert action and derivation of Einstein's field equations
- Friedman-Lemaitre-Robertson-Walker metric
- Kinematics & dynamics of an expanding universe (radiation/matter dominated eras)
- Horizons/redshift
- Hot Big bang model (successes and shortcomings)
- Baryogenesis/Leptogenesis
- Cold dark matter
- Phase transitions, spontaneously broken symmetries, topological defects
- Dynamics and observational consequences of cosmic strings
- Cosmological inflation (definition, dynamics, scenarios, reheating, open issues)

II. Inhomogeneous universe
- Gravitational instability (Newtonian approximation, relativistic approach)
- Origin of primordial inhomogeneities (active vs. passive sources, adiabatic vs. isocurvature initial conditions, inflationary perturbations)
- Cosmic microwave background temperature anisotropies (correlation functions and multipoles, anisotropies on small/large angular scales, Sachs-Wolf effect, acoustic peaks, determining cosmological parameters, constraining inflationary models)
- Gravitational waves

Prerequisites
Astrophysics 5CP2621 (or equivalent course)
General Relativity and Cosmology 6CCP3630 (or equivalent course)
Standard Model Physics and Beyond 7CCP4501

Textbooks

- *The Cosmic Microwave Background* by R. Durrer, Cambridge University Press
- *The Early Universe* by E.Kolb & M. Turner, Frontiers in Physics
- *The Primordial Density Perturbation* by A.R. Liddle & D.H.Lyth, Cambridge University Press
- *Physical Foundations of Cosmology* by S. Mukhanov, Cambridge University Press
- *Primordial Cosmology* by P. Peter & J.-P. Uzan, Oxford University Press
- *Cosmic Strings and Other Topological Defects* by A. Vilenkin & P. Shellard
- *Cosmology* by S. Weinberg, Oxford University Press

Methodology

11 weeks meetings divided into 2h lectures and 1h problem class/discussion per week. Lectures notes and relevant associated material is provided on the web (through KEATS). Problem sets and their solutions are also provided on the web (through KEATS).

Assessment

Written examination of 3 hours contributing 100%

4606 Advanced Cosmology

Aims

Cosmological perturbation theory is an essential tool to understand the physics of the universe. Gravity is non-linear and each order in perturbation theory reveals different but complementary aspects of the underlying fully non-linear theory. Using linear, or first order, theory allows us, for example, to model the large scale structure of the universe. Higher order theory can then be used to calculate higher order effects such as the generation of vorticity and primordial magnetic fields. The course provides a rigorous and fairly technical introduction to cosmological perturbation theory.

Objectives

- enable the student to critically assess different approximation schemes used in theoretical cosmology
- to compare models of the universe to observational data sets
- to provide the student with the tools to set up the governing equations
- enable the student to solve the governing equations

Syllabus

i) Brief review of GR and Differential Geometry (the metric, field equations)

ii) 3+1 decomposition

iii) Perturbation theory (Friedmann-Robertson-Walker metric, perturbations, scalar-vector-tensor decomposition)

iv) Gauges

v) Other approximation schemes

vi) Governing equations: background and linear order

vii) Some solutions

viii) Newtonian and relativistic structure formation

ix) Outlook: beyond linear order

Teaching arrangements

11 3-hour lectures for a total of 33 hours

Prerequisites

introductory cosmology course, e.g. SPA6311, a good understanding of General Relativity and/or Differential Geometry

Books

Reading list will be provided at the beginning of the course.

Assessment

Written examination of 2½ hours contributing 90%, coursework contributing 10%

4616 Electromagnetic Radiation in Astrophysics

Content
This module is an introduction to understanding the origin, propagation, detection and interpretation of electromagnetic (EM) radiation from astronomical objects.

Aims
In this module students will learn: how to describe EM radiation and its propagation through a medium to an observer; the main processes responsible for line and continuum emission and how they depend on the nature and state the emitting material; the effects of the earth's atmosphere and the operation of the detection process at various wavelengths. The material will be illustrated by examples from optical, infrared and radio portions of the EM spectrum.

Learning Outcomes
- Provide an introduction to the various mechanisms applicable to the creation, propagation and detection of radiation from astronomical objects
- Provide an understanding of how EM radiation is generated in astrophysical environments, and how it propagates to the "observer" on earth, or satellite
- Provide an ability to understand astronomical observations and how they can be used to infer the physical and chemical state, and motions of astronomical objects
- Provide an understanding of how spatial, spectral and temporal characteristics of the detection process produce limitations in the interpretation of the properties of astrophysical objects
- Provide an understanding of the uncertainties involved in the interpretation of properties of astrophysical objects, including limitations imposed by absorption and noise, both instrumental and celestial, and by other factors
- Enable students to be capable of solving intermediate-level problems in astronomical spectra, using analytical techniques encountered or introduced in the course

Duration
22 hours of lectures

Prerequisites
None

Books
Irwin, J. *Astrophysics: Decoding the Cosmos* (2nd edition). Wiley 2007

http://qmplus.qmul.ac.uk/course/view.php?id=2457

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%

4620 Dark Matter and Dark Energy

Introduction

Lighting Review of Friedman-Robertson-Walker Equations (not derivation)

- Expansion history for different equations of state (matter, radiation, cosmological constant)
- Thermal History of Universe

Brief review of Standard Model Particles and their Quantum Numbers

Nucleosynthesis prediction for baryon density and its incompatibility with Hubble expansion rate

Dark Matter

Independent Astrophysical Evidence for Dark Matter in clusters and Galaxies

- Rotation Curves
- Virial Theorem
- Dwarf Spheroidal galaxies and Low Surface Brightness Galaxies
- Milky Way Timing argument
- ΛCDM model, halo density profiles (NFW), simulations and the concentration parameter

Astrophysical probes of particle nature of dark matter

- Cold/warm/hot dark matter – free streaming length and structure formation
- Constraints on dark matter self interaction (Bullet Cluster, NGC 720)

Thermal Relics (including WIMPs)

- Calculation of the self-annihilation cross section of fermions
- Thermal freeze-out and relic abundance
- Quantum numbers of dark matter and particle physics beyond the standard model
- Direct detection of WIMP dark matter (event rate, existing detectors and limits)
- Indirect detection of WIMP dark matter (gamma rays, anti-matter, diffusion loss equation in the galaxy)
- Collider production of WIMP dark matter (monojet searches, calculate rate in simplified model, LHC searches)

Sterile Neutrinos

- Right Handed Neutrinos and see-saw mechanism
- Light Sterile neutrinos
- Relic abundance and velocity – effect on power spectrum
- Calculation of decay into photons and subsequent detection

Axions

- Strong CP problem and theta parameter
- Theta as phase of Peccei-Quinn field, axions
- Axions as dark matter and relic abundance
- Coupling of axions to other particles, detection and mixing.

Other Dark Matter candidates

- Primordial black holes
- Millicharged particles
- Asymmetric Dark Matter
- Exotics

Modified Newtonian Dynamics as an alternative to dark matter

Dark Energy
Age of the Universe if $\Omega_M = 1$, history of cosmology 1990 to present day

Type 1a Supernovae as standard candles, luminosity distance and angular distance

Measures of expansion and geometry history.

Cosmological Constant – Original Motivation and ΛCDM

Old Cosmological constant problem (why $\rho_\Lambda \sim 0$)

New Cosmological constant problem (why $\rho_\Lambda \sim \rho_M$)

Possible solutions, Anthropic Principle, Landscape, Bousso-Polshinski mechanism

Weinberg's Anthropic Argument – derivation and understanding

Modified Gravity and Quintessence

Structure formation in alternatives to ΛCDM (qualitative)

Prerequisites
Students should have taken third year level particle physics courses and some cosmology and/or astrophysics course where they have studied the Friedman equations, although their derivation is not necessary for this course. Students should be familiar with four vector notation in special relativity.

Assessment
Written examination of 3 hours contributing 90%, coursework contributing 10%

4630 Planetary Atmospheres

Aims of the Course
This course aims to:
- compare the composition, structure and dynamics of the atmospheres of all the planets, and in the process to develop our understanding of the Earth's atmosphere

Objectives
On completion of this course, students should understand:
- The factors which determine whether an astronomical body has an atmosphere
- the processes which determine how temperature and pressure vary with height
- the dynamic of atmospheres and the driving forces for weather systems
- the origin and evolution of planetary atmospheres over the lifetime of the solar system
- feedback effects and the influence of anthropogenic activities on the Earth

Syllabus
(The approximate allocation of lectures to topics is shown in brackets below.)

Comparison of the Planetary Atmospheres (2)
The radiative energy balance of a planetary atmosphere; the competition between gravitational attraction and thermal escape processes. The factors which influence planetary atmospheres; energy and momentum sources; accretion and generation of gases; loss processes; dynamics; composition.

Atmospheric structure (7)
Hydrostatic equilibrium, adiabatic lapse rate, convective stability, radiative transfer, the greenhouse effect and the terrestrial planets.

Oxygen chemistry (3)
Ozone production by Chapman theory; comparison with observations; ozone depletion and the Antarctic ozone hole.

Atmospheric temperature profiles (3)
Troposphere, stratosphere, mesosphere, thermosphere and ionosphere described; use of temperature profiles to deduce energy balance; internal energy sources; techniques of measurement for remote planets.

Origin of planetary atmospheres and their subsequent evolution (3)
Formation of the planets; primeval atmospheres; generation of volatile material; evolutionary processes; use of isotopic abundances in deducing evolutionary effects; role of the biomass at Earth; consideration of the terrestrial planets and the outer planets.

Atmospheric Dynamics (4)
Equations of motion; geostrophic and cyclostrophic circulation, storms; gradient and thermal winds; dynamics of the atmospheres of the planets; Martian dust storms, the Great Red Spot at Jupiter.

Magnetospheric Effects (1)
Ionisation and recombination processes; interaction of the solar wind with planets and atmospheres; auroral energy input.

Atmospheric loss mechanisms (1)
Exosphere and Jeans escape; non-thermal escape processes; solar wind scavenging at Mars.

Observational techniques (3)
Occultation methods from ultraviolet to radio frequencies; limb observation techniques; in-situ probes.

Global warming (3)
Recent trends and the influence of human activity; carbon budget for the Earth; positive and negative feedback effects; climate history; the Gaia hypothesis; terra-forming Mars.

Prerequisites
Knowledge of mathematics is required including the basic operations of calculus and simple ordinary differential and partial differential equations.

Textbooks
(a) Planetary atmospheres and atmospheric physics:
- *The Physics of Atmospheres*, John T Houghton, Cambridge
- *Theory of Planetary Atmospheres*, J.W. Chamberlain and D.M. Hunten
- *Fundamentals of Atmospheric Physics,* by M. Salby
- *Planetary Science* by I. de Pater and JJ Lissauer (Ch 4: Planetary Atmospheres)

(b) Earth meteorology and climate
- *Atmosphere Weather and Climate* , RG Barry and RJ Chorley
- *Fundamentals of Weather and Climate,* R McIlveen
- *Meteorology Today* **OR** *Essentials of Meteorology* (abridged version), CD Ahrens
- *Meteorology for Scientists & Engineers*, R Stull (technical companion to Ahrens)

http://www.mssl.ucl.ac.uk/teaching/UnderGrad/4312.html

Methodology and Assessment
30 lectures and 3 problem class/discussion periods. Lecturing supplemented by homework problem sets. Written solutions provided for the homework after assessment. Links to information sources on the web provided through a special web page at MSSL.

Written examination of 2½ hours contributing 90% and three problem sheets 10%

4640 Solar Physics

Aims of the Course

This course will enable students to learn about:

- the place of the Sun in the evolutionary progress of stars
- the internal structure of the Sun
- its energy source
- its magnetic fields and activity cycle
- its extended atmosphere
- the solar wind
- the nature of the heliosphere

The course should be helpful for students wishing to proceed to a PhD in Astronomy or Astrophysics. It also provides a useful background for people seeking careers in geophysics-related industries and meteorology.

Objectives

On completion of this course, students should be able to:

- explain the past and likely future evolution of the Sun as a star
- enumerate the nuclear reactions that generate the Sun's energy
- explain the modes of energy transport within the Sun
- describe the Standard Model of the solar interior
- explain the solar neutrino problem and give an account of its likely resolution
- describe the techniques of helio-seismology and results obtained
- discuss the nature of the solar plasma in relation to magnetic fields
- explain solar activity - its manifestations and evolution and the dynamo theory of the solar magnetic cycle
- describe the solar atmosphere, chromosphere, transition region and corona;
- explain current ideas of how the atmosphere is heated to very high temperatures
- describe each region of the atmosphere in detail
- explain the relationship between coronal holes and the solar wind
- explain a model of the solar wind
- indicate the nature of the heliosphere and how it is defined by the solar wind
- describe solar flares and the related models based on magnetic reconnection
- explain coronal mass ejections and indicate possible models for their origin

Syllabus

(The approximate allocation of lectures to topics is shown in brackets below.)

Introduction [1]

Presentation of the syllabus and suggested reading, a list of solar parameters and a summary of the topics to be treated during the course.

The Solar Interior and Photosphere [8]

Stellar structure and evolution. Life history of a star. Equations and results. Conditions for convection. Arrival of the Sun on the Main Sequence. Nuclear fusion reactions. The Standard Solar Model. Neutrino production and detection - the neutrino problem. Solar rotation. Photospheric observations. Fraunhofer lines. Chemical composition. Convection and granulation. Helio-seismology - cause of solar five-minute oscillations, acoustic wave modes structure. Description of waves in terms of spherical harmonics. Observing techniques and venues. Probing the Sun's interior by direct and inverse modeling. Recent results on the internal structure and kinematics of the Sun.

Solar Magnetic Fields/Solar Activity [6]
Sunspot observations - structure, birth and evolution. Spot temperatures and dynamics. Observations of faculae. Solar magnetism - sunspot and photospheric fields. Active region manifestations and evolution. Solar magnetic cycle - Observations and dynamics. Babcock dynamo model of the solar cycle. Behaviour of flux tubes. Time behaviour of the Sun's magnetic field.

The Solar Atmosphere – Chromosphere and Corona [9]
Appearance of the chromosphere - spicules, mottles and the network. Observed spectrum lines. Element abundances. Temperature profile and energy flux. Models of the chromosphere. Nature of the chromosphere and possible heating mechanisms. Nature and appearance of the corona. Breakdown of LTE. Ionization/ recombination balance and atomic processes. Spectroscopic observations and emission line intensities. Plasma diagnostics using X-ray emission lines. Summary of coronal properties.

The Solar Atmosphere - Solar Wind [2]
Discovery of the solar wind. X-ray emission and coronal holes – origin of the slow and fast wind. In-situ measurements and the interplanetary magnetic field structure. Solar wind dynamics. Outline of the Heliosphere.

Solar Flares and Coronal Mass Ejections [4]
Flare observations. Thermal and non-thermal phenomena. Particle acceleration and energy transport. Gamma-ray production. Flare models and the role of magnetic fields. Properties and structure of coronal mass ejections (CMEs). Low coronal signatures. Flare and CME relationship. Propagation characteristics. CME models and MHD simulations.

Prerequisites
This is a course which can accommodate a wide range of backgrounds. Although no specific courses are required, a basic knowledge of electromagnetic theory and astrophysical concepts (e.g. spectroscopy) is required.

Textbooks

- *Solar Astrophysics* by P. Foukal, Wiley-Interscience,1990. ISBN 0 471 839353.
- *Astrophysics of the Sun* by H. Zirin, Cambridge U P, 1988. ISBN 0 521 316073.
- *Neutrino Astrophysics* by J. Bahcall, Cambridge U P, 1989. ISBN 0 521 37975X.
- *The Stars; their structure and evolution* by R.J. Taylor, Wykeham Science Series - Taylor and Francis, 1972. ISBN 0 85109 110 5.
- *Guide to the Sun* by K.J. H. Phillips, Cambridge U P, 1992. ISBN 0 521 39483 X
- *The Solar Corona* by Leon Golub and Jay M. Pasachoff, Cambridge U P, 1997. ISBN 0 521 48535 5
- *Astronomical Spectroscopy* by J. Tennyson, Imperial College Press, 2005. ISBN 1 860 945139

Methodology and Assessment
30-lecture course and Problems with discussion of solutions (four problem sheets). Video displays of solar phenomena will be presented.

Written examination of 2½ hours contributing 90% and three problem sheets 10%

4650 Solar System

Aims

The aims of this course are to understand the structure and evolution of the objects in the solar system by the application of the two- and three-body problems, tides and basic celestial mechanics and perturbation theory.

Objectives

- To learn the basic structure of the solar system, the domain of its constituent populations and their physical characteristics
- To learn and understand how the dynamical structure of the solar system can be understood by the application of Newton's inverse square law of force to its constituent bodies
- To learn and understand how the inverse square law of force gives rise to elliptical motion and how Kepler's equation can be used to find the position of an orbit as a function of time
- To learn and understand how the circular restricted three-body problem admits an integral of the motion (the Jacobi constant) and how this can be used to define regions from which the particle is excluded. To derive the location of the five Lagrangian equilibrium points and to be able to derive their respective stability properties. To know the applications of these results to the motion of actual coorbital objects in the solar system
- To learn and understand how an orbiting satellite gives rise to two tides per day on its parent planet and how planetary tides results in the expansion of prograde orbits. To show the physical consequences of tides
- To apply knowledge gained in other parts of the course to understanding some of the observed dynamical properties of planetary rings systems
- To learn and understand the structure of the solar nebula and its connection with planet formation
- To learn and understand how gravitational, radiative and radiogenic processes affect the thermal state of a planet or satellite
- To learn and understand resonances in the solar system, basic theory and application to planets, satellites, minor planets and rings
- To learn and understand the origin and evolution of asteroids and comets

Syllabus

Survey of the Solar System (historical ideas about the motion of bodies; dynamical structure of the Solar System).

The Two-Body Problem (equations of motion; position and velocity; Keplerian motion; Kepler's equation; elliptic expansions; the guiding centre; barycentric motion; the orbit in space).

The Three-Body Problem (characteristics of Solar System orbits; equations of motion; Jacobi constant; particle paths; zero velocity curves; Tisserand relation; zero velocity curves; Lagrangian equilibrium points; stability of equilibrium points; motion around L4 and L5; tadpole and horseshoe motion; Trojan asteroids; Trojan satellites; Janus & Epimetheus; new types of co-orbital motion).

Tides (the tidal bulge; Io; tidal torques; tidal evolution; the Roche zone).

Resonant perturbations (numerical experiments; the geometry of resonance; the disturbing function; a second order expansion; Lagrange's equations; classification of arguments; variation of orbital elements; resonance in the circular restricted problem; Laplace resonance; pulsar planets).

Chaos and Long-Term Evolution (examples of chaotic orbits; regular and chaotic orbits; the Lyapunov exponent; chaos in the circular restricted problem; the standard map; resonance maps; encounter maps; N-body maps; the Kirkwood gangs; solar system stability).

Planetary Rings (Jupiter's ring system; Uranus' ring system; Neptune's ring system; Saturn's ring system).

Comets, Asteroids, Dust (comets; Centaurs; trans-Neptunian objects; the Kuiper Belt; the Nice model; asteroids and meteorites; Hirayama families and dust bands).

Planetary Formation and Planetary Structure (nature of the solar system; MMSN; planetary formation; gravitational focussing; formation of the terrestrial planets; formation of the giant planets; gas-instability hypothesis; core-instability hypothesis).

Prerequisites
Basic knowledge of the solar system as well as Physics and Mathematics to at least A level standard.

Book
C D Murray and S F Dermott, *Solar System Dynamics*, Cambridge University Press.

http://qmplus.qmul.ac.uk/course/view.php?id=2167

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%

4660 The Galaxy

Aims

This course aims to provide a detailed understanding of the basic physics processes that operate in galaxies, using our own Galaxy as an example. This includes:

- The dynamics and interactions of stars, and how their motions can be described mathematically.
- A description of the interstellar medium and the use of models to represent how the abundances of chemical elements have changed during the lifetime of the Galaxy.
- The study of dark matter using galactic rotation curves, and through the way that gravitational lensing by dark matter affects light.

The various topics are then put together to provide an understanding of how galaxies formed.

Objectives

On completion of this course, students should:

- Understand the basics of galactic classification, and be able to solve simple quantitative problems relating to this.
- Understand the meaning of the collisionless Boltzmann equation and its context. Be able to solve simple problems involving Jeans equations.
- Have a qualitative understanding of emission processes in the interstellar medium (ISM). Be able to solve simple problems on metal enrichment of the ISM.
- Be familiar with graphical ideas about the relationship between disc mass and rotation curves, and the signature of a dark halo.
- Have a qualitative understanding of gravitational lensing and be able to solve simple problems relating to MACHO surveys.
- Understand the timing argument for the mass of the Milky Way and additional qualitative aspects of the dynamics of the Milky Way.

Syllabus

- Introduction: galaxy types, descriptive formation and dynamics.
- Stellar dynamics: virial theorem, dynamical and relaxation times, collisionless Boltzmann equation, orbits, simple distribution functions, Jeans equations.
- The interstellar medium: emission processes from gas and dust (qualitative only), models for chemical enrichment.
- Dark matter - rotation curves: bulge, disk, and halo contributions.
- Dark matter - gravitational lensing: basic lensing theory, microlensing optical depth.
- The Milky Way: mass via the timing argument, solar neighbourhood kinematics, the bulge, the Sagittarius dwarf.

Prerequisites
No formal prerequisites, however it is beneficial to have studied vector calculus, Newtonian dynamics and gravitation, and basic atomic physics.

Recommended reading
The course notes on the website,
http://qmplus.qmul.ac.uk/course/view.php?id=2643, provide detailed material and cover all the major items you need. The textbooks listed below provide useful supplementary information.

Some general background material about astrophysics is given in:

- F Shu, *The Physical Universe*, University Science Books.

The two main textbooks for this course are:

- J Binney & M R Merrifield, *Galactic Astronomy*, Princeton University Press, 1998.
- J Binney & S Tremaine, *Galactic Dynamics*, Princeton University Press, 1987 (Many parts of this are at a more advanced level than we cover here).

Some other books that may be useful are:

- L Sparke & J Gallagher, *Galaxies in the Universe: an Introduction*, Cambridge University Press, 2000.
- G Gilmore, I King & P van der Kruit, *The Milky Way as a Galaxy*, University Science Books, 1990.
- S Phillipps, *The Structure and Evolution of Galaxies*, John Wiley and Sons, 2005.

The material on chemical evolution is covered in more depth in:

- B E J Pagel, *Nucleosynthesis and Chemical Evolution* of Galaxies (Cambridge Univ. Press, 1997).

http://qmplus.qmul.ac.uk/course/view.php?id=2643

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%

4670 Astrophysical Plasmas

- The plasma state as found in astrophysical contexts
- Particle motion in electromagnetic fields, cyclotron motion, drifts and mirroring, with application to the radiation belts and emission from radio galaxies
- Concepts of magnetohydrodynamics (MHD); flux freezing and instabilities
- The solar wind, including MHD aspects, effects of solar activity, and impact on the terrestrial environment
- Magnetic reconnection; models and application to planetary magnetic storms and stellar flares and coronal heating
- Shock waves and charged particle acceleration

Prerequisites
No formal prerequisites but a "Firm understanding of electromagnetism and vector calculus is assumed."

Books
Schwartz, S. J., Owen, C. J. & Burgess, D. *Astrophysical Plasmas*
Schrijver, C. J. and Siscoe, G. L. *Heliophysics: Plasma Physics of the Local Cosmos*
(Both are available as free e-books for those registered at QM)

http://qmplus.qmul.ac.uk/course/view.php?id=2641

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%

4680 Space Plasma and Magnetospheric Physics

Aims of the Course

This course aims to learn about the solar wind and its interaction with various bodies in the solar system, in particular discussing the case of the Earth and the environment in which most spacecraft operate

Objectives

On completion of this course, students should be able to:

- explain what a plasma is
- discuss the motion of a single charged particle in various electric and/or magnetic field configurations, and also to discuss the adiabatic invariants
- discuss the behaviour of particles in the Earth's radiation belts, including source and loss processes
- be familiar with basic magnetohydrodynamics
- describe the solar wind, including its behaviour near the Sun, near Earth and at the boundary of the heliosphere
- describe the solar wind interaction with unmagnetised bodies, such as comets, the Moon and Venus
- describe the solar wind interaction with magnetised bodies, concentrating on the case of the Earth and its magnetosphere
- be familiar with the closed and open models of magnetospheres
- perform calculations in the above areas

Syllabus

(The approximate allocation of lectures to topics is shown in brackets below)

***Introduction* [1]**

Plasmas in the solar system, solar effects on Earth, historical context of the development of this rapidly developing field

***Plasmas* [3]**

What is a plasma, and what is special about space plasmas; Debye shielding, introduction to different theoretical methods of describing plasmas

***Single Particle Theory* [7]**

Particle motion in various electric and magnetic field configurations; magnetic mirrors; adiabatic invariants; particle energisation

***Earth's Radiation Belts* [4]**

Observed particle populations; bounce motion, drift motion; South Atlantic Anomaly; drift shell splitting; source and acceleration of radiation belt particles; transport and loss of radiation belt particles

***Introduction to Magnetohydrodynamics* [3]**

Limits of applicability; governing equations; convective derivative; pressure tensor; field aligned currents; frozen-in flow; magnetic diffusion; fluid drifts; magnetic pressure and tension; MHD waves

***The Solar Wind* [2]**
Introduction, including concept of heliosphere; fluid model of the solar wind (Parker); interplanetary magnetic field and sector structure; fast and slow solar wind; solar wind at Earth; coronal mass ejections

***Collisionless shocks* [3]**
Shock jump conditions, shock structure, shock examples

***The Earth's magnetosphere and its dynamics* [6]**
Magnetospheric convection, magnetospheric currents, the magnetopause, open magnetosphere formation, magnetosphere-ionosphere coupling, non-steady magnetosphere

***The Solar Wind Interaction with Unmagnetised Bodies* [1]**
The Moon; Venus, Comets

Recommended books and resources

- *Basic Space Plasma Physics*. W. Baumjohann and R.A. Treumann, Imperial College Press, 1996
- *Introduction to Space Physics* - Edited by M.G.Kivelson and C.T.Russell, Cambridge University Press, 1995

Also:

- *Physics of Space Plasmas, an introduction*. G.K.Parks, Addison-Wesley, 1991.
- *Guide to the Sun*, K.J.H.Phillips, Cambridge University Press, 1992.
- *Sun, Earth and Sky*, K.R.Lang, Springer-Verlag, 1995.
- *Introduction to Plasma Physics*, F.F. Chen, Plenum, 2nd edition, 1984
- *Fundamentals of Plasma Physics*, J.A. Bittencourt, Pergamon, 1986

Prerequisites
While the course is essentially self-contained, some knowledge of basic electromagnetism and mathematical methods is required. In particular it is assumed that the students are familiar with Maxwell's equations and related vector algebra.

Methodology and Assessment
The material is presented in 30 lectures which are reinforced by problem sheets. Reading from recommended texts may be useful, but is not essential. Some video material will accompany the conventional lectures.

Written Examination of 2½ hours contributing 90% and three problem sheets 10%

4690 Extrasolar Planets and Astrophysical Discs

Course outline

Ever since the dawn of civilisation, human beings have speculated about the existence of planets outside of the Solar System orbiting other stars. The first bona fide extrasolar planet orbiting an ordinary main sequence star was discovered in 1995, and subsequent planet searches have uncovered the existence of more than one hundred planetary systems in the Solar neighbourhood of our galaxy. These discoveries have reignited speculation and scientific study concerning the possibility of life existing outside of the Solar System.

This module provides an in-depth description of our current knowledge and understanding of these extrasolar planets. Their statistical and physical properties are described and contrasted with the planets in our Solar System. Our understanding of how planetary systems form in the discs of gas and dust observed to exist around young stars will be explored, and current scientific ideas about the origin of life will be discussed. Rotationally supported discs of gas (and dust) are not only important for explaining the formation of planetary systems, but also play an important role in a large number of astrophysical phenomena such as Cataclysmic Variables, X-ray binary systems, and active galactic nuclei. These so-called accretion discs provide the engine for some of the most energetic phenomena in the universe.

The second half of this module will describe the observational evidence for accretion discs and current theories for accretion disc evolution.

Prerequisites

Some familiarity with vector calculus and basic fluid dynamics.

Books

There are no books that provide complete coverage for this course. However the most comprehensive textbook on accretion discs is
Accretion Power in Astrophysics by Juhan Frank, Andrew King, and Derek Raine, published by Cambridge University Press

Parts of this course are also covered in

Astrophysics in a Nutshell by Dan Maoz, published by Princeton University Press
Galactic Dynamics by James Binney and Scott Tremaine, published by Princeton Series in Astrophysics
Astrophysics of Planet Formation by Phil Armitage, published by Cambridge University Press

http://qmplus.qmul.ac.uk/course/view.php?id=2640

Assessment

Written examination of 2½ hours contributing 90%, coursework contributing 10%

4800 Molecular Biophysics

Aims of the Course

The course will provide the students with insights in the physical concepts of some of the most fascinating processes that have been discovered in the last decades: those underpinning the molecular machinery of the biological cell. These concepts will be introduced and illustrated by a wide range of phenomena and processes in the cell, including bio-molecular structure, DNA packing in the genome, molecular motors and neural signaling.

The aim of the course is therefore to provide students with:

- Knowledge and understanding of physical concepts which are relevant for understanding biology at the micro- to nano-scale
- Knowledge and understanding of how these concepts are applied to describe various processes in the biological cell

Objectives

After completing this half-unit course, students should be able to:

- Give a general description of the biological cell and its contents
- Explain the concepts of free energy and Boltzmann distribution and discuss osmotic pressure, protein structure, ligand-receptor binding and ATP hydrolysis in terms of these concepts
- Explain the statistical-mechanical two-state model, describe ligand-receptor binding and phosphorylation as two-state systems and give examples of "cooperative" binding
- Describe how polymer structure can be viewed as the result of random walk, using the concept of persistence length, and discuss DNA and single-molecular mechanics in terms of this model
- Understand how genetic (sequencing) methods can be used to learn about structure and organization of chromosomes
- Explain the worm-like chain model and describe the energetics of DNA bending and packing; explain how such models are relevant for the rigidity of cells
- Explain the low Reynolds-number limit of the Navier-Stoke's equation and discuss its consequences for dynamics in biological systems
- Explain simple solutions of the diffusion equation in biological systems and their consequences for diffusion and transport in cells
- Explain the concept of rate equations and apply it to step-wise molecular reactions
- Give an overview of the physical concepts involved in molecular motors and apply them to obtain a quantitative description of motor driven motion and force generation
- Describe neural signaling in terms of propagating (Nernst) action potentials and ion channel kinetics
- Link the material in the course to at least one specific example of research in the recent scientific literature

Syllabus
(The approximate allocation of lectures to topics is given in brackets below.)

Biological cells [3]
Introduction to the biology of the cell – The Central Dogma – structure of DNA, RNA, proteins, lipids, polysaccharides – overview of functional processes in cells

Statistical mechanics in the cell [3]
Deterministic versus thermal forces – free-energy minimisation and entropy, Boltzmann distribution – free energy of dilute solutions, osmotic pressure/forces – consequences for protein structure and hydrophobicity – equilibrium constants for ligand-receptor binding and ATP hydrolysis

Two-state systems [3]
Biomolecules with multiple states – Gibbs distribution – ligand-receptor binding, phosphorylation – "cooperative" binding – Hemoglobin function

Structure of macromolecules [3]
Random walk models of polymers – entropy, elastic properties and persistence length of polymers – DNA looping, condensation and melting – single-molecule mechanics

Elastic-rod theory for (biological) macromolecules [3]
Beam deformation and persistence length – worm-like chain model – beam theory applied to DNA – cytoskeleton

Chromosome Capture methods [3]
3C, 4C and Hi-C – random polymer coil – PCR and sequencing technology – detection of loops – relation to cell cycle

Motion in biological environment [3]
Navier-Stokes equation – viscosity and Reynold's number in cells – diffusion equation and its solutions – transport and signaling in cells – diffusion limited reactions

Rate equations and dynamics in the cell [3]
Chemical concentrations determine reaction rates – rate equations for step-wise molecular reactions – Michaelis-Menten kinetics

Molecular motors [3]
Molecular motors in the cell – rectified Brownian motion – diffusion equation for a molecular motor – energy states and two-state model for molecular motors – force generation by polymerisation

Action potentials in nerve cells [3]
Nerst potentials for ions – two-state model for ion channels – propagation of action potentials – channel conductance

Prerequisites
It is recommended but not mandatory that students have taken PHAS1228 (Thermal Physics). PHAS2228 (Statistical Thermodynamics) would be useful but is not essential. The required concepts in statistical mechanics will be (re-)introduced during the

course.

Textbooks
The course will make extensive use of the following book, parts of which will be obligatory reading material:

- *Physical Biology of the Cell*, 1st Edition, R. Phillips, J. Kondev, and J. Theriot, Garland Science 2009.

Other books which may be useful include the following. They cover more material than is in the syllabus.

- *Biological Physics*, 1st Edition, Philip Nelson, W.H. Freeman., 2004.
- *Mechanics of Motor Proteins and the Cytoskeleton*, 1st Edition, J. Howard, Sinauer Associates, 2001.
- *Protein Physics*, 1st Edition, A.V. Finkelstein and O.B. Ptitsyn, Academic Press, 2002.
- *Molecular Driving Forces*, 1st Edition, K.A. Dill and S. Bromberg, Garland Science, 2003.

The following books may be useful for biological reference.

- *Molecular Biology of the Cell*, 4th Edition, B. Alberts et al., Garland Science, 2002.
- *Cell Biology*, 2nd Edition, T.D. Pollard, W.C. Earnshaw and J. Lippincott-Schwartz, Elsevier, 2007.

Methodology and Assessment
This is a half-unit course, with 30 hours of lectures. Basic problem-solving skills will be built by the setting of weekly problem questions. The answers will relate to the upcoming lecture material to encourage in-class discussion.

Written examination of 2½ hours contributing 90% and problem sheets 10%

4805 Cellular Biophysics

Aims of the course
Develop an understanding of how living cells can be quantitatively described in terms of physical laws, physical interactions and processes.

Objectives
On completion of this course, students should:
Understand the major techniques used in the field of biophysics and how to interpret data from these to quantitatively describe the cellular environment
Understand how the physical interactions of molecules, organelles and cells have implications for cell behaviour in health and disease

Syllabus
- Description of cell culture in the modern laboratory
- Southern and Western blotting for detecting DNA and proteins and co-immunoprecipitation for analysis of protein binding
- Genetic engineering methods and transfections for introducing constructs into cells and for knocking down protein expression
- Light microscopy methods including confocal and TIRF microscopy as well as methods for analysing diffusion: single-particle tracking and fluorescence correlation spectroscopy.
- Atomic force microscopy and electron microscopy
- The organisation of DNA within the nucleus including the structure of chromatin, chromatin packing and histone modifications.
- Mechanisms of DNA mutation and the regulation of DNA repair.
- The molecular mechanism of transcription and the role of splicing and splice variants
- Mechanisms of protein post-translational modification including ubiquitination, acylation and phosphorylation.
- Membrane organisation including the lipid raft hypothesis and the cortical actin meshwork and their roles in regulating molecular clustering and diffusion.
- The mathematical description of membrane curvature and the regulation of curvature in endo and exocytosis
- The mathematical description of diffusion of membrane proteins in a plasma membrane containing membrane domains, obstacles and curvature
- Membrane voltage and how this is regulated by ion channels and ion pumps, in particular as described by the Hodgkin-Huxley model
- Cell motility – mechanisms by which cells move including force generation by the actin cytoskeleton and the role of cell adhesion, with relevance to cancer metastasis and white blood cell surveillance
- Methods of intracellular communication including chemical messengers – chemokines – and their receptors
- The thermodynamics of oxygen storage and transport including cooperativity within the haemoglobin molecule
- The organisation of muscle cells, including the mechanisms of muscle contractility and force generation

- Biophysics of vision, hearing and smell: the structure of retinal cells, light-sensitive proteins and their related signalling pathways, mechanosensitivity and chemical sensing
- Biophysics of disease including how Alzheimer's disease is caused by protein misfolding
- Drug discovery including the testing of natural products and the rise of rational drug design in the modern pharmaceutical industry

Prerequisites
The first 2 lectures will be an introduction to the required biology and chemistry background, and so there are no prerequisites.

Textbooks
Bruce Alberts and Alexander Johnson, *The Molecular Biology of the Cell* (2014) Taylor and Francis Inc, ISBN: 9780815344643

Methodology and assessment
10 x 2 hour lectures each followed by a 1h problem class covering that material. Solutions to the problem classes are provided in the next week's lecture. The initial 2 hour lecture is an introduction covering the prerequisite biology and chemistry background.

An assessment is based on a 3 hour end of year exam (90%) and a coursework essay (10%) selected from a range of 5 suggested topics.
Previous topics include CRISPR gene editing, optogenetics and intrinsic protein fluorescence.

4807 Physical Models of Life

Aims of the course

The students will be given background in Physical theories developed specifically for understanding Biological Systems. As these systems function out of equilibrium, very different and novel physical properties emerge that are not covered by classical physics.

Objectives

After completing this half-unit course, students should be able to:

- Give a general description of the biological cell and multicellular tissues.
- Have knowledge and understanding of physical concepts which are relevant for understanding biology across scales.
- Have knowledge and understanding of how these concepts are applied to describe various processes in Biology.
- Understand how theoretical physical concepts can be applied to biology.
- Understand basic concepts of physics out-of-equilibrium.
- Be familiar with the original properties of active matter and its relation to biology.
- Be familiar with the unique properties of soft matter and nanoscale materials of biological relevance.
- Understand processes on small scales undergoing stochastic behaviour.
- Grasp fundamental physical behaviours of biological systems at the scale of proteins, cells and tissues.
- Know strategies for development of minimal theoretical models of complex biological problems.
- Be familiar with concepts necessary for bridging scales in biology: from molecules to organisms.
- Link the material in the course to at least one specific example of research in the recent scientific literature

Syllabus

The syllabus will be subdivided as follows:

-**Computational modelling of biological processes**. Computer simulations act as a bridge between molecular scales and the macroscopic world, and can serve as a mediator between analytical theory and experiment. These lectures will focus on advanced computational techniques developed to treat a large ensemble of explicit biological objects, such as macromolecules or cells. Emphasis will be placed on understanding how their complex interactions and stochastic nature lead to emergent collective behaviour. Taking inter-cellular trafficking, and protein aggregation in cells, as our case studies, we will discuss obtaining quantitative physical measurements in computer simulations that can be directly compared with experiments, and associated challenges.

-**Physics of biological flows**. This section of the course covers the physical theories that describes deformation of living matter at the scale of cells and tissues. We will start by introducing the hydrodynamics of simple fluids and the physics of biological swimmers. We will then present hydrodynamic theories of active complex fluids, which describe large scale flows of matter driven out of equilibrium by chemical energy, such as ATP consumption by myosins in the cytoskeleton. We will discuss physical models of morphogenesis of tissues at the end of the course.

-**Noise, fluctuations and robustness in Biological systems**: This section of the course will start by introducing students to advanced concepts in statistical mechanics. It will then examine noise that arises from sources intrinsic and extrinsic to a given biological system. It will investigate how gene expression is regulated in the presence of noise, how concentration of substances are sensed by living organisms, and how cell size and divisions are controlled.

(The approximate allocation of lectures to topics is given in brackets below)

1. Interactions on nanoscale [3]
- What is soft matter, Nanoparticles and colloids as models: statistical mechanics recapitulation
- Hard core repulsion, dispersion forces, depletion interaction, charged interactions
- Entropy-driven ordering & phase transitions, Hydrophobic interaction

2. Computer Modelling [3]
- Monte Carlo, Molecular Dynamics
- Application to polymers: Scaling of Ideal, Self-avoiding, and Real chains
- Steric and fluctuation forces
- Phase separation and membrane-less organelles

3. Biological self-organisation and phase behaviour [3]
- Amphiphilic molecules and geometric packing: micelles, bilayers, vesicles
- Formation of biofilaments: thermodynamics and kinetics

4. Biological membranes [3]
- Elastic properties, fluidity, role of curvature
- Membrane-mediated interactions, membrane remodelling, and cellular trafficking

5. Biological swimmers [3]
- Low Reynolds number hydrodynamics
- Scallop theorem
- Simple swimmer

6. Physics of Active Matter I: Theory and Concepts [3]
- Liquid crystals, isotropic-nematic phase transition
- Non-equilibrium physics close to equilibrium
- Entropy production
- Onsager relations

7. Physics of Active Matter II: Applications [3]
- Dynamics of defects
- Instability of a thin film
- Flows driven by chemical activity

8. Tissue morphogenesis and mechanics [3]
- Turing patterning mechanism
- Establishment of morphogen gradients
- Physical description of tissue mechanics

- Tissue sorting

9. Noise in Biology [3]
- Intrinsic and Extrinsic noise
- Gene expression
- Fluctuations and chemical reactions
- Proofreading

10. Growth and form [3]
- Cell growth, size and division control
- Ribosome synthesis and constitutive gene expression
- Coordination of cell growth and metabolism

Prerequisites
It is recommended but not mandatory that students have taken PHAS0006 (Thermal Physics). PHAS0024 (Statistical Physics of Matter), and PHAS0103 (Molecular Biophysics). The required concepts in physics will be (re-)introduced during the course.

Textbooks
The course will make extensive use of the following book, parts of which will be obligatory reading material:
- Phillips, Rob, Jane Kondev, Julie Theriot, and Hernan Garcia. *Physical biology of the cell*. Garland Science, 2012.

Other books which may be useful include the following. They cover more material than is in the syllabus.
- W. Bialek, *Biophysics: Searching for Principles,* (2012).
- J. Howard, *Mechanics of Motor Proteins and the Cytoskeleton*, (2001)
- M. Rubinstein and R. H. Colby, *Polymer Physics*, (2003)
- D. Frenkel and B. Smit, *Understanding Molecular Simulations*, (2001)
- U. Alon, *An Introduction to Systems Biology: Design Principles of Biological Circuits*, (2006)
- J. N. Israelachvili, *Intermolecular and Surface Forces*, Third Edition: Revised Third Edition, (2011)
- S. Safran, *Statistical Thermodynamics of Surfaces, Interfaces, And Membranes (Frontiers in Physics),* (2003)

The following books may be useful for biological reference.
- *Molecular Biology of the Cell*, 4th Edition, B. Alberts et al., Garland Science, 2002
- Cell Biology, 2nd Edition, T.D. Pollard, W.C. Earnshaw and J. Lippincott-Schwartz, Elsevier, 2007

Methodology and assessment
This is a half-unit course, with 30 hours of lectures. Basic problem-solving skills will be built by the setting of problem questions.

Three written assignments will each account for 10% of the overall course assessment. The remaining 70% is determined via an unseen written examination.

4810 Theory of Complex Networks

Aims and objectives
The purpose of this module is to provide an appropriate level of understanding of the mathematical theory of complex networks. It will be explained how complex network can be quantified and modelled

Syllabus

- Concepts of local- and global measures of network structure
- Adjacency matrix, vertex degree, clustering coefficient, degree distributions, degree correlations. Example networks
- Eigenvalue spectra, Laplacian
- Spectra of random matrices
- Random graph ensembles
- Complexity and entropy
- Generating function methods
- Giant components
- Percolation
- Path length characteristics
- Evolving networks, preferential attachment, scale-free networks
- Derivation of power-laws

Web page: See http://www.mth.kcl.ac.uk/courses/

Teaching arrangements
Two hours of lectures per week

Prerequisites
KCL's 4CCM111A Calculus I or equivalent
KCL's 4CCM141A Probability and Statistics I or equivalent

Books
Evolution of Networks: From Biological Nets to the Internet and WWW by S. N. Dorogovtsev and J. F. F. Mendes, Oxford University Press 2003

Assessment
Written examination of 2 hours contributing 100%

4820 Equilibrium Analysis of Complex Systems

Aims and objectives

The purpose of this module is to provide an appropriate level of understanding of the notions and mathematical tools of statistical mechanics of complex and disordered systems. It will be explained how to use these techniques to investigate complex physical, biological, economic and financial systems.

Syllabus

- Canonical ensembles and distributions
- Transfer matrices, asymptotic methods (Laplace and saddle point integration) approximation methods (mean-field, variational, perturbative)
- Methods for disordered systems (replica, cavity, restricted annealing)
- Application of statistical mechanics to physical and biological systems, to information processing, optimization, and to models of risk for economic, financial, and general process-networks

Web page: See http://www.mth.kcl.ac.uk/courses/

Teaching arrangements

Two hours of lectures per week

Prerequisites

KCL's 4CCM111A Calculus I or equivalent
KCL's 4CCM112A Calculus II or equivalent
KCL's 4CCM141A Probability and Statistics I or equivalent

Books

A Modern Course in Statistical Physics by L E Reichl, 3rd edition, Wiley VCH (2009)
Information Theory, Inference, and Learning Algorithms by D J C MacKay, Cambridge Univ Press (2003)
The Statistical Mechanics of Financial Markets by J Voit, Springer Berlin (2001)

Assessment

Written examination of 2 hours contributing 100%

4830 Dynamical Analysis of Complex Systems

Aims and objectives

The purpose of this module is to provide an appropriate level of understanding of the notions and mathematical tools of dynamics of complex systems. It will be explained how to use these techniques to deeply comprehend dynamical properties of complex biological and physical systems.

Syllabus

- Stochastic processes
- Markov processes, Master equation, Markov Chains and One step processes
- Steady state, time reversibility and Detailed balance
- Fokker-Planck equation, Boltzmann equilibrium as steady state
- Langevin equation, Kramers-Moyal coefficients
- Linear response and fluctuation-dissipation theorem
- Macroscopic analysis of dynamics
- Path integral formalism
- Simple dynamical processes on complex networks
- Applications to complex and disordered systems

Web page: See http://www.mth.kcl.ac.uk/courses/

Teaching arrangements

Two hours of lectures per week

Prerequisites

KCL's 4CCM111A Calculus I
KCL's 4CCM112A Calculus II
KCL's 4CCM141A Probability and Statistics
KCL's 4CCM131A Introduction to Dynamical Systems
KCL's 5CCM211A Partial Differential Equations and Complex Variables

Books

N.G.Van Kampen, *Stochastic processes in Physics and Chemistry*, Elsevier 3rd edition 2007
Crispin Gardiner, *Stochastic Methods, A handbook for the Natural and Social Science*, Springer 4th edition 2008
Jean Zinn-Justin, *Quantum field theory and critical phenomena*, Oxford University Press 4th edition 2002

Assessment

Written examination of 2 hours contributing 100%

4840 Mathematical Biology

Aims and objectives
The purpose of this module is to provide an appropriate level of understanding of the Mathematical Biology. With the advent of computational biology and gene sequencing projects, mathematical modelling in biology is becoming increasingly important. The module will introduce mathematical concepts such as a nonlinear dynamical systems and reaction-diffusion partial differential equations, which will be applied to biological structures and processes.

Syllabus
- Continuous population models for single species
- Discrete population models for single species
- Continuous population models for interacting species
- Modelling infectious disease transmission/spread using ODEs
- Reaction kinetics
- Introduction to DNA and modelling of molecular evolution

Web page: See http://www.mth.kcl.ac.uk/courses/

Teaching arrangements
Two hours of lectures per week

Prerequisites
KCL's 4CCM111A Calculus I
KCL's 4CCM112A Calculus II
KCL's 4CCM113A Linear Methods
KCL's 4CCM131A Introduction to Dynamical Systems
KCL's 5CCM211A Partial Differential Equations and Complex Variables
----or equivalent courses

Books
J.D. Murray, *Mathematical Biology*, 3rd Edition Springer 2002

Assessment
Written examination of 2 hours contributing 100%

4850 Elements of Statistical Learning

Aims and objectives

The purpose of this module is to provide an appropriate level of understanding of Statistical Learning presented in the framework of Bayesian Decision theory. It will be explained how to use linear models for regression and classification as well as Kernel Methods, graphical models and approximate inference.

Syllabus

- Review of basic notions of probability
- Learning of probability distributions: maximum likelihood and Bayesian learning of Gaussian distributions, conjugate priors, Gaussian mixtures, expectation-maximization approach
- Learning of input-output relations: linear regression, evidence approximation for optimizing hyperparameters, Gaussian processes
- Linear classification, Gaussian process classification, Laplace approximation, link to Support Vector Machines, sparsity
- Graphical models
- Approximate inference: variational methods, expectation-propagation, sampling methods

Web page: See http://www.mth.kcl.ac.uk/courses/

Teaching arrangements

Two hours of lectures per week

Prerequisites

KCL's 4CCM141A Probability and Statistics I or equivalent

Books

C. Bishop, *Pattern Recognition and Machine Learning*, Springer 2006
D. Barber, *Bayesian Reasoning and Machine Learning*, 2009

Assessment

Written examination of 2 hours contributing 100%