University of London

Intercollegiate Programme

Physics

STUDENT HANDBOOK

Intercollegiate taught modules for 2023-24

Contents

Courses and Teachers

Each module has a numerical code used by the Intercollegiate MSci board shown on the left-hand side. Each college use their own local module codes for the modules they offer. These codes may differ from the intercollegiate code number therefore please ensure you check all the module information for the relevant college.

All modules are worth 15 credits which may equate to a half or full course unit at your home institution. Please check with your local administrator for clarity on how this pertains to your programme of study.

The module list in this handbook will display the following information:

- Intercollegiate module code
- Module title
- Teaching Term
- Examination period
- Module Lead (ML)
- Institution
- Local module code
- Contact details for the Module Organiser and any links to any supporting materials required for the module

Module Symbols

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

Please note: in the interest of balance and/or for syllabus reasons, the MSci Intercollegiate board has set up the following rules:

- Students should take no more than three KCL Maths modules

- Students should take no more than either one of the following modules: -
    - 7CCMMS40 Supersymmetry and Conformal Field Theory
    - SPA7031U/P Supersymmetric Methods in Theoretical Physics

KCL Students please note: QMUL module SPA7001U/P Advanced Quantum Field Theory is not available for you to take however you may request to take KCL Maths module 7CCMMS32 Quantum Field Theory as a substitute module. Please liaise with your local administrator for further information.

Modules suspended this year (2023/24):

- 7CCMCS04 Dynamical Analysis of Complex Systems
- 7CCMCS06 Elements of Statistical Learning
- 7CCMCS03 Equilibrium Analysis of Complex Systems
- 7CCMCS05 Mathematical Biology

Host Module Code	Module Title	Semester / Term	Exam Period	Module Lead	Taught by	Module Lead email address	Webpage
PH4320	Advanced Astrophysics	2	April - June	Professor Stephen Gibson	RHUL	stephen.gibson@rhul.ac.uk	https://moodle.royalholloway.ac.uk/course/view.php?id=22909
7CCP493	Advanced Condensed Matter	2	May/June	To be confirmed	KCL	pgt-physics@kcl.ac.uk	https://keats.kcl.ac.uk/course/view.php?id=109845
7CCP4650	Gravitational Wave Physics	2	May / June	Prof Mairi Sakellariadou	KCL	pgt-physics@kcl.ac.uk	Course: 7CCP4650 Gravitational Wave Physics(23~24 SEM2 000001) (kcl.ac.uk)
7CCP4473	Theoretical Treatments of Nanosystems	2	May / June	Prof Lev Kantorovich	KCL	pgt-physics@kcl.ac.uk	https://keats.kcl.ac.uk/course/view.php?id=109833
7CCP4600	Cosmology	2	May / June	Prof Malcolm Fairbairn and Dr Furqaan Yusaf	KCL	pgt-physics@kcl.ac.uk	Course: 7CCP4600 Cosmology(23~24 SEM2 000001) (kcl.ac.uk)
SPA7028U/P	Advanced Cosmology	2	May/June	Dr K Malik	QMUL	k.malik@qmul.ac.uk	https://qmplus.qmul.ac.uk/course/view.php?id=15954
PH4442	Advanced Particle Physics	1	April - June	Prof. Glen Cowan	RHUL	g.cowan@rhul.ac.uk	https://moodle.royalholloway.ac.uk/course/view.php?id=22908
SPA7001U/P	Advanced Quantum Field Theory	2	May/June	Dr D Vegh	QMUL	d.vegh@qmul.ac.uk	https://qmplus.qmul.ac.uk/course/view.php?id=13932
PH4226	Advanced Quantum Theory	1	April - June	Dr Giovanni Sordi	RHUL	giovanni.sordi@rhul.ac.uk	https://moodle.royalholloway.ac.uk/course/view.php?id=23044
PH4610	Analysing Gravitational Waves	1	April - June	Dr Greg Ashton	RHUL	gregory.ashton@rhul.ac.uk	https://moodle.royalholloway.ac.uk/course/view.php?id=16141
SPA7004U/P	Astrophysical Plasmas	2	May/June	Dr C Chen	QMUL	christopher.chen@qmul.ac.uk	https://qmplus.qmul.ac.uk/course/view.php?id=15948
7CCP4935	Dark Matter and Dark Energy	1	January	David Marsh	KCL	david.j.marsh@kcl.ac.uk	https://keats.kcl.ac.uk/course/view.php?id=103308
SPA7027U/P	Differential Geometry in Theoretical Physics	1	January	Dr C Papageorgakis	QMUL	c.papageorgakis@qmul.ac.uk	https://qmplus.qmul.ac.uk/course/view.php?id=13979

SPA7009U/P	Extrasolar Planets & Astrophysical Discs	2	April - June	Dr E Gillen	QMUL	e.gillen@qmul.ac.uk	https://qmplus.qmul.ac.uk/course/view.php?id=15950
7CCMMS01	Lie Groups and Lie Algebras €	1	April - June	Prof Jurgen Berndt	KCL+	jurgen.berndt@kcl.ac.uk	https://keats.kcl.ac.uk/mod/book/view.php?id=3314851&chapterid=284174
7CCPNE05	Modelling Quantum Many-Body Systems	1	January	Dr Joe Bhaseen	KCL	joe.bhaseen@kcl.ac.uk	Course: 7CCPNE05 Modelling Quantum Many-body Systems(23~24 SEM1 000001) (kcl.ac.uk)
PH4472	Order and Excitations in Quantum Materials	2	April - June	Dr Andrew Seel	RHUL	andrew.seel@rhul.ac.uk	https://moodle.royalholloway.ac.uk/course/view.php?id=22910
PH4450	Particle Accelerator Physics	1	April - June	Dr P Karataev	RHUL	pavel.karataev@rhul.ac.uk	http://moodle.rhul.ac.uk/course/view.php?id=250
7CCP4126	Photonics & Metamaterials	2	April - June	Dr Francisco Rodriguez-Fortuno	KCL	francisco.rodriguez_fortuno@kcl.ac.uk	Course: 7CCP4126 Photonics and Metamaterials(23~24 SEM2 000001) (kcl.ac.uk)
PH4475	Nano-Electronics and Quantum Technology (previously named Physics at the Nanoscale)	1	April - June	Dr V Antonov	RHUL	v.antonov@rhul.ac.uk	http://moodle.rhul.ac.uk/course/view.php?id=249
7CCP4501	Standard Model Physics and Beyond	2	April - June	Chris McCabe	KCL	christopher.mccabe@kcl.ac.uk	Course: 7CCP4501 Standard Model Physics and Beyond(23~24 SEM2 000001) (kcl.ac.uk)
PH4515	Statistical Data Analysis	1	April - June	Prof G D Cowan	RHUL	g.cowan@rhul.ac.uk	http://www.pp.rhul.ac.uk/~cowan/stat_course.html
PH4211	Statistical Mechanics	2	April - June	Prof B P Cowan	RHUL	b.cowan@rhul.ac.uk	http://personal.rhul.ac.uk/UHAP/027/PHPH4211/
7CCMMS34	Strings, Branes and Quantum Gravity €	2	April - June	Prof Peter West	KCL+	peter.west@kcl.ac.uk	https://keats.kcl.ac.uk/mod/book/view.php?id=3314851&chapterid=284209
PH4478	Superconductors and Superfluids	1	April - June	Dr Lev Levitin	RHUL	l.v.levitin@rhul.ac.uk	https://moodle.royalholloway.ac.uk/course/view.php?id=248
SPA7031U/P	Supersymmetric Methods in Theoretical	2	April - June	Dr M Buican	QMUL	m.buican@qmul.ac.uk	https://qmplus.qmul.ac.uk/course/view.php?id=13981

	Physics						
7CCMMS40	Supersymmetry and Conformal Field Theory €€	2	April - June	Prof C Herzog	KCL+	christopher.herzog@kcl.ac.uk	https://keats.kcl.ac.uk/mod/book/view.php?id=3314851&chapterid=28PH4211

1 Programme Strands

The table below gives a coherent base of modules for your registered programme and specialisation interests. It is strongly recommended that you choose one of these programme strands, and then select other modules to make up your full complement. You should consult your local programme structures to find out what intercollegiate modules are available for your programme of study.

Please note: - some modules, particularly the mathematical based ones, may require a high level of mathematical ability. Students may find the mathematical level of these modules higher than what is included in a standard single-honours Physics programme. Such modules would be appropriate for some joint degrees. Should you need academic advice about your module selections, please contact your home institution.

	Recommended Courses	
Strand	**Autumn Term**	**Spring Term**
Particle Physics	7CCMMS01: Lie Groups and Lie Algebras PH4450: Particle Accelerator Physics 7CCPNE05: Modelling Quantum Many-Body Systems PH4515: Statistical Data Analysis 7CCP4935: Dark Matter & Dark Energy	PH4211: Statistical Mechanics SPA7001U/P: Advanced Quantum Field Theory 7CCP4501: Standard Model Physics and Beyond 7CCMMS34: String Theory and Branes 7CCMMS40: Supersymmetry and Conformal Field Theory
Condensed Matter	7CCPNE05: Modelling Quantum Many-Body Systems PH4475: Nano-Electronics and Quantum Technology PH4515: Statistical Data Analysis	PH4211: Statistical Mechanics 7CCP4931: Advanced Condensed Matter 7CCP4473: Theoretical Treatments of Nano-systems
Astrophysics	PH4515: Statistical Data Analysis 7CCP4935: Dark Matter and Dark Energy	SPA7028U/P: Advanced Cosmology SPA7010U/P: The Galaxy SPA7004U/P: Astrophysical Plasmas SPA7009U/P: Extrasolar Planets and Astrophysical Discs
General / Applied Physics	PH4475: Nano-Electronics and Quantum Technology PH4515: Statistical Data Analysis	PH4211: Statistical Mechanics 7CCP4126: Photonics & Metamaterials
Theoretical Physics	7CCMMS01: Lie Groups and Lie Algebras SPA7027U/P: Differential Geometry in Theoretical Physics 7CCPNE05: Modelling Quantum Many-Body Systems	PH4211: Statistical Mechanics SPA7001U/P: Advanced Quantum Field Theory 7CCMMS34: Strings, Branes and Quantum Gravity 7CCMMS40: Supersymmetry and Conformal Field Theory SPA7031U/P: Supersymmetric Methods in Theoretical Physics

2 Teaching and Examination Arrangements

Please note: - not all colleges have reading weeks, please ensure you are aware of all teaching dates for each college.

Teaching Term Dates:

Modules are typically taught over eleven weeks. For the 2023/24 academic year, the teaching dates are:

Semester 1 Teaching – Autumn 2023

- KCL Physics and KCL Maths: Monday 25th September – Friday 15th December 2023
- QMUL: Monday 2nd October 2023 - Friday 15th December 2023
- RHUL: Monday 25th September 2023 – Friday 8th December 2023

Autumn Reading Week 2023

- KCL Physics: w/c Monday 31st October 2023
- KCL Maths: w/c Monday 31st October 2023
- QMUL: No reading week
- RHUL: No reading week

Semester 2 Teaching – Spring 2024

- KCL Physics & KCL Maths: Friday 12th January – Thursday 28th March 2024
- QMUL: Monday 22nd January 2024 – Friday 12th April 2024
- RHUL: Monday 15th January - Thursday 28th March 2024

Spring Reading Week 2024

- KCL Physics: w/c Monday 19th February 2024
- KCL Maths: TBC by module leads
- QMUL: No reading week
- RHUL: No reading week

MSci Administrative contact points at each College

KCL Physics	Shania Craig	pgt-physics@kcl.ac.uk	0207 848 1207
KCL Mathematics	TBC	mathematics-education@kcl.ac.uk	0207 848 2828
QMUL	Harvey Abraham Green	spcs-office@qmul.ac.uk	
RHUL	Tim Wilson-Soppitt	epms-school@rhul.ac.uk	01784 276881

Module Registration

It is essential that you complete a module registration form for the relevant college for any Intercollegiate modules you request to take ***i.e., you must fill out a QMUL form for*** *QMUL* ***taught courses, a KCL form for KCL taught modules etc.*** Failure to complete and submit an approved form may result in you not being correctly registered for the assessment associated with the module. This can affect your progression or final award for your programme of study. Forms must be approved and signed by the appropriate member of staff at your home institution and, submitted to the relevant person as per your college regulations. If you have any questions, please contact your home administrator for further information. You can find registration forms on the .

Registration Deadlines

Please ensure you submit your completed and approved forms to your local administrators within the deadlines listed below. You are advised to submit your registration at your earliest convenience in order to gain your college credentials and access to module materials as soon as possible.

Once registered onto a course at the selected college, you should receive a confirmation email with information including your user ID, password, and email address from the relevant college. Whilst you are waiting for your college credentials, you may contact the relevant college administrator for information about how to access classes and course materials for your chosen modules.

Module Registration Deadlines

- KCL Physics – Friday 6th October 2023
- KCL Maths - Friday 6th October 2023
- QMUL - Friday 6th October 2023
- RHUL – Friday 6th October 2023

Autumn Module Amendments

Amendments to Autumn term modules can be requested up until **4pm Friday 6th October 2023**.

Spring Module Amendments

With the exception of QMUL, amendments to spring term modules can be requested up until **4pm Friday 19th January 2024**.

QMUL module amendments for the spring term must be submitted by **4pm Friday 27th January 2024.**

Please Note: - If you request to be withdrawn from a module at another College, you should inform both your own College and the administrator at the relevant College. Please ensure you submit the request in keeping with the College deadlines as you will not be able to be removed from modules past this date and will be expected to attend and complete all assessment.

Class locations

The MSci timetable found on the Intercollegiate Webpage includes the following details of colleges and room locations:

- KCL modules are taught at the Strand, Kings College London,
- QMUL modules are taught at QMUL
- RHUL modules are either taught at Senate House or at the RHUL Egham campus. Some classes have access to a video conference link to QMUL. Students are welcome to attend the lectures in person at the Egham campus or via the link at QMUL.

Please Note: - Some QMUL modules will be taught in the evening. Please check the timetable on the Intercollegiate Webpage for further information about the times.

Attendance

Your attendance might be monitored in the form of a register at lectures as some colleges have an attendance requirement for certain modules.

Coursework policy

Some modules have a coursework element as part of the assessment pattern. Details of all module assessment elements will be provided the relevant college.

Extenuating/Mitigating Circumstances Policy

In the event you have extenuating/mitigating circumstances and are unable to complete an assessment by the deadline, you should follow your home institutions policy and submit a claim via your home school. Any affected host schools will be notified of the outcome and a suitable extension/alternate sitting will be arranged where requests have been approved.

College Email(s)

You should ensure you link your email addresses, so you do not miss any communications from each college. Detailed instructions on how to forward and re-direct mail can be accessed by visiting http://help.outlook.com/ which will utilise the **Options** and **Connected Accounts Tab** on outlook. This process is user friendly easy, but you must frequently check and maintain your college account. When you delete a forwarded message e.g., from Hotmail, it will not be deleted from your home institution account.

Please note: - you may need to use an Internet Explorer (Edge) browser to access this as the link may not work on some browsers

It is your responsibility to log on to your college account frequently and conduct account maintenance or your account may become full and therefore will not forward messages.

Examination arrangements

You must ensure you are correctly registered for your modules at your home institution **AND** the college(s) that you will be studying Intercollegiate modules with by the registration deadline. Remember these dates may vary from college to college. Once registered, you are expected to attend classes and complete all assessment elements for each of your modules.

The examination periods may vary across the colleges and may not take place at the same time as your home institution.

Exams **can** take place across 3 examination periods including in January, April/May/June and August/September. To date, the current exam periods for each college are: -

KCL Physics

- Semester 1 modules will be examined between Friday 5th January – Thursday 11th January 2024
- Semester 2 modules will be examined between Monday 29th April – Friday 31st May 2024
- Summer resits/replacement exams be examined between Monday 5th August – Friday 16th August 2024

KCL Maths

- Semester 1 modules will be examined between Friday 5th January – Thursday 11th January 2024
- Semester 2 modules will be examined between Monday 29th April – Friday 31st May 2024
- Summer resits/replacement exams be examined between Monday 5th August – Friday 16th August 2024

QMUL

- Semester A Modules will be examined between Thursday 4th January - Friday 19th January 2024
- Semester B Modules will be examined between Thursday 2nd May – Friday 31st May 2024
- Summer resits/replacement exams: Monday 5th August – Friday 16th August 2024

RHUL

- Semester A and B Modules will be examined between Tuesday 30th April – Friday 31st May 2024
- Summer resits/replacement exams: TBC

Assessment policies concerning resit examinations may vary across the Colleges, please ensure you are aware of all assessment policies across the colleges and how it pertains to your programme of study.

Exam Locations
The arrangements are as follows:

KCL students:

- KCL and RHUL examinations take place at KCL
- QMUL examinations take place at QMUL.

QMUL students:

- QMUL and RHUL examinations take place at QMUL
- KCL examinations take place at KCL.

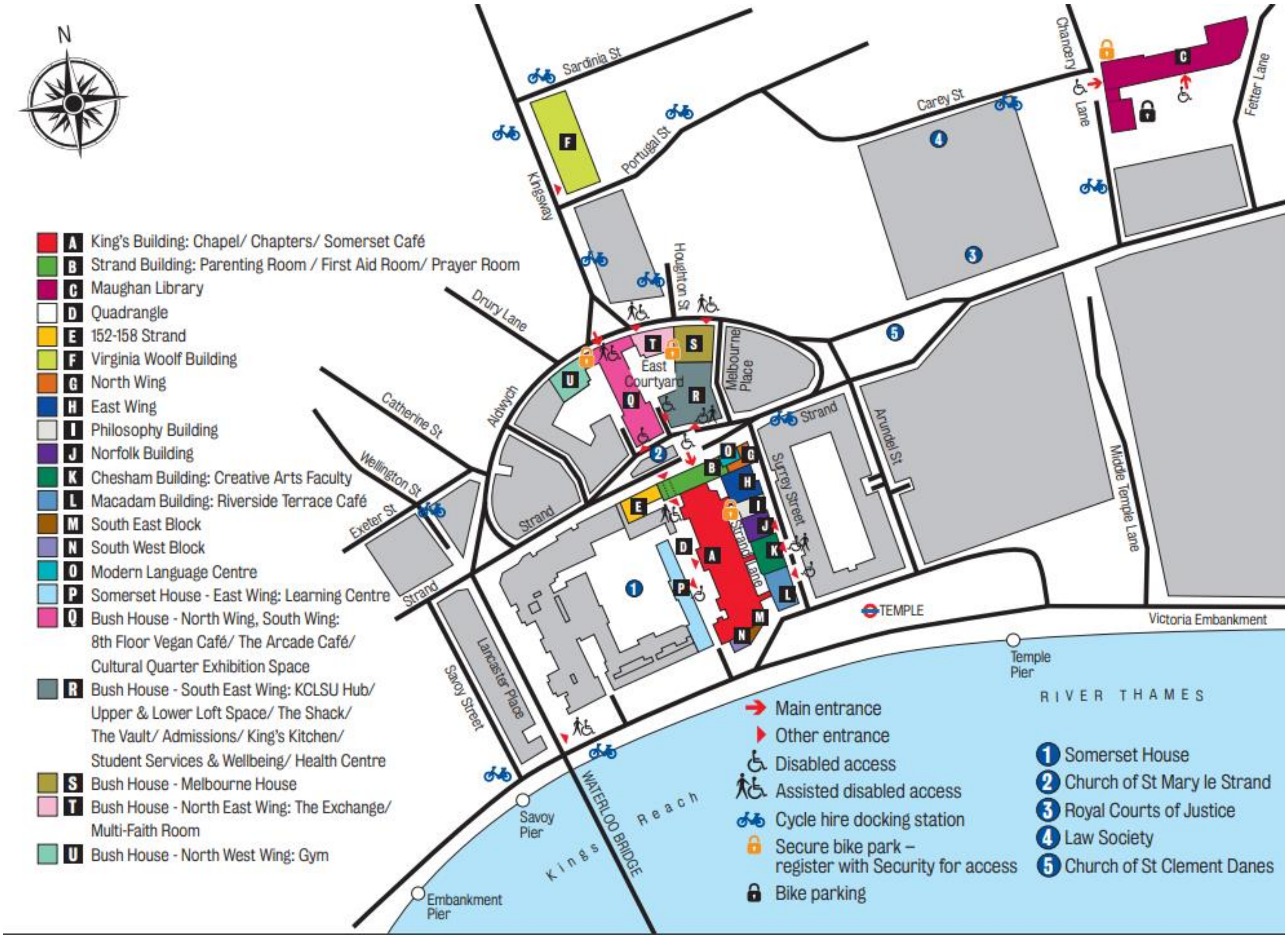
RHUL students:

- All exams take place at RHUL

Please note: Changes to the format of the exams will be communicated to students from the relevant colleges. Students with Personalised/Exam Assessment Arrangements (PAAs/EAAs) special examination arrangements or inclusion plans will sit all examinations at their home college. If this is applicable to you, please contact your home administrator for further information.

3 College and Class Locations

King's College, Strand, London, WC2R 2LS



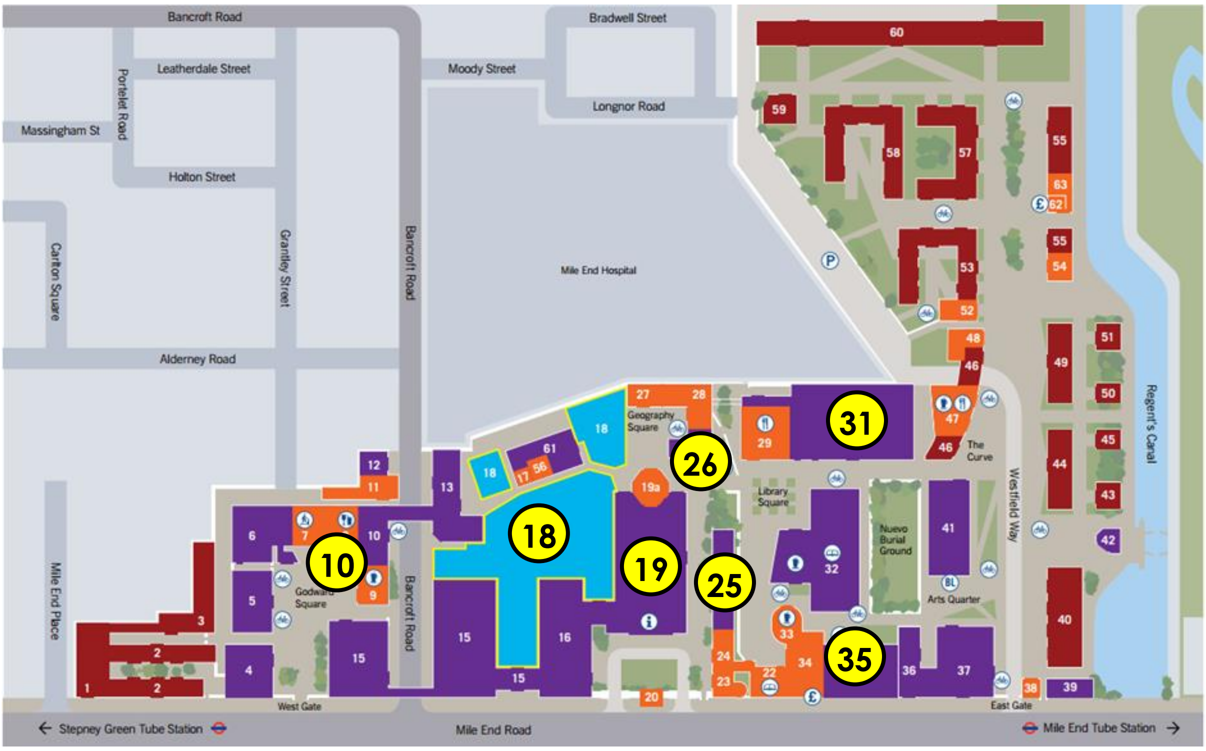
Travel by tube: Temple (District and Circle lines): 2-minute walk. Charing Cross (Bakerloo and Northern lines): 10-minute walk, Embankment (District, Circle and Bakerloo lines): 10 minute walk, Waterloo (Jubilee, Northern, Bakerloo, Waterloo & City lines): 12 minute walk, Holborn (Central and Piccadilly 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 minutes from 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).
The Physical and Chemical Sciences 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: Several 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

Key

- : Senate House
- : London Underground
- : Rail Network
- : One-way streets

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

4 Course Details

KCL Physics - Advanced Condensed Matter (7CCP4931)

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 analysed 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.

Assessment is based quizzes -10%, presentation - 15%, mini project – 15% and written 3-hour exam – 60%

QMUL - Advanced Cosmology (SPA7028U/P)

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 (either online or in person) contributing 90%, coursework contributing 10%

QMUL - Advanced Quantum Field Theory (SPA7001U/P)

Building on the fundamental concepts of Quantum Field Theory introduced in SPA7018U/P 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.

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

Assessment
Written examination (either online or in person) contributing 80% and two pieces of coursework worth 10% each.

QMUL - Astrophysical Plasmas (SPA7004U/P)

Outline

A plasma is an ionised gas that displays a range of behaviours very different to the other forms of matter that we are familiar with on Earth. Plasmas are present throughout the universe in nearly every astrophysical environment, from just above the Earth's atmosphere in the ionosphere and magnetosphere, to the Sun and solar wind that form our solar system, to far away and extreme environments such as accretion disks around black holes, galaxy clusters, pulsar jets, etc. In fact, the vast majority of the known (non-dark) matter in the universe is in a plasma state. This course will focus on basic plasma properties and common plasma processes applicable to this range of environments, as well as specific applications of these to understand plasmas in our solar system where the theoretical understanding can be compared directly to in situ spacecraft observations

Syllabus

- Plasmas and plasma phenomena in astrophysical environments
- Introduction to basic plasma behaviour: quasi-neutrality, plasma oscillations, Debye length
- Particle motion in electromagnetic fields: gyration, drifts, mirroring, adiabatic invariants, application to radiation belts
- Structure of the Sun and solar atmosphere
- Introduction to magnetohydrodynamics: basic equations, magnetic pressure & tension, resistive & ideal limits, flux freezing, basic equilibrium solutions, astrophysical applications of these phenomena
- The solar wind: Parker solar wind model, Parker spiral, large-scale structure of the heliosphere, solar wind transients
- Plasma waves: basic types of plasma waves, applications to astrophysical environments
- Non-linear plasma processes: magnetic reconnection, shocks, turbulence, particle acceleration, and their applications, e.g. to space weather

Prerequisites

No formal course prerequisites but requires a solid understanding of electromagnetism and vector calculus.

Books

Russell, Luhmann & Strangeway, *Space Physics: An Introduction*
Gurnett & Bhattacharjee, *Introduction to Plasma Physics*

Assessment

Written examination (either online or in person) contributing 90%, coursework contributing 10%

KCL Physics - Dark Matter and Dark Energy (7CCP4935)

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
100% Coursework

QMUL - Differential Geometry in Theoretical Physics (SPA7027U/P)

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 and the Yang-Mills instanton, as well as 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 SPA7018U/P Relativistic Waves and Quantum Fields or equivalent.

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)
- **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.

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

Assessment
Written examination (either online or in person) contributing 80%, two pieces of coursework worth 10% each.

QMUL - Extrasolar Planets and Astrophysical Discs (SPA7009U/P)

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 the formation of planets is

Astrophysics of Planet Formation by Phil Armitage, published by Cambridge University Press

Assessment
Written examination (either online or in person) contributing 90%, coursework contributing 10%

KCL Maths - Lie Groups and Lie Algebras (7CCMMS01)

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.)

Teaching arrangements

Usually two hours of lectures per week. For 20/21 there will be one hour of live lectures each week with further pre-recorded lectures. Lectures are supported by small group tutorials.

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.

KCL Physics - Modelling Quantum Many-Body Systems (7CCPNE05)

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%

RHUL - Particle Accelerator Physics (PH4450)

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.

KCL Physics - Photonics and Metamaterials (7CCP4126)

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 nano photonics.
Students will be exposed to modern concepts in photonics and understand the main physical principles behind modern photonic technologies, such as optical communications, nano photonics, 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 nano photonics: 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 nano photonics: 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 2 hours over a 10-week period.

KEATS assignments 20% – presentation – 15% and 3 hour written examination – 65%

RHUL - Nano-Electronics and Quantum Technology (previously named Physics at the Nanoscale) (PH4475)

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%

KCL Physics - Standard Model Physics and Beyond (7CCP4501)

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).

Mini project – 20% and written examination of 3 hours contributing 80%

RHUL - Statistical Data Analysis (PH4515)

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%

RHUL - Statistical Mechanics (PH4211)

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%

KCL Maths - Strings, Branes and Quantum Gravity (7CCMMS34)

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.

Teaching Arrangements
Usually two hours of lectures each week. For 20/21 there will be one hour of live lectures each week with further pre-recorded lectures. Lectures are supported by small group tutorials.

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.
7CCMMS01 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.

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%

QMUL - Supersymmetric Methods in Theoretical Physics (SPA7031U/P)

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
SPA7018U/P 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
Two pieces of coursework in-semester worth 10% each and one final piece of coursework worth 80% with a 24-hour window in which to complete it.

KCL Maths - Supersymmetry and Conformal Field Theory (7CCMMS40)

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.

Teaching arrangements
Usually two hours of lectures each week. For 20/21 there will be one hour of live lectures each week with further pre-recorded lectures. Lectures are supported by small group tutorials.

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%

KCL Physics - Theoretical Treatments of Nano-systems (7CCP4473)

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 and materials in general. The role of symmetry in describing the systems electronic structure and vibrations 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.

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.
- Appreciate how theories underpinning the current research on nano-systems such as Density Functional Theory, Statistical methods (molecular dynamics, Monte Carlo, free energy) and Orbital Representation can be rationalised at a more fundamental level in terms of modern mathematical tools such as, e.g., Stochastic Processes and Group Theory.
- Understand how these theories and tools can be used to generate accurate quantitative predictions on the behaviour of materials at the nanometre/picosecond size- and time- scales and above, enabled by QM-accurate potential energy surfaces and inter-atomic forces used in simulations techniques.

Topics in lectures 1-3:

Many-body problem and quantum mechanics of identical particles
Schroedinger equation for a many-body system. Approximate casting as an effective one-body problem. 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
Calculus of variations: definition of a functional and functional derivative. Many-body Schrodinger equation cast as a variational principle. Examples: i) virial theorem for Coulombic systems, ii) ground state energy of the Helium atom through trial wavefunction with one variational parameter, and iii) Self-consistent field applied to Hartree equation for the ground state of the Helium atom.

The Hartree-Fock method
Pauli principle and Slater determinants. Derivation of the Hartree-Fock equations. Direct and exchange interactions, and consequences for materials. Hartree Fock in the homogeneous electron gas. Koopman's theorem. Success and shortcomings of the HF method, and the importance of electronic screening.

Density Functional Theory
Hohenberg-Kohn and Kohn-Sham theorems, and connection to Slater's X-alpha method. V- and N-representability of densities. Kohn-Sham ansatz. 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.

Topics in lectures 4-8:

Separation of electronic and nuclear degrees of freedom

The full Hamiltonian operator, the Born-Oppenheimer approximation, diabatic expansion, introduction to non-adiabaticity. the Hellman-Feynman theorem. Classical force fields. Fitting forces. Elements of machine learning. Vibrations. Stability. QM-based forces on atoms. Examples: vibrations of finite and extended systems; elimination of translations and rotations. Quantum vibrations. Free energy. Quasiharmonic approximation. Configurational entropy. Examples of material modelling with Helmholtz and Gibbs free energies.
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.

Statistical methods in material modelling

Statistical ensembles. Important thermodynamic averages. Correlation functions. Molecular dynamics. Ergodicity. Verlet and velocity Verlet algorithms. NVT molecular dynamics (MD) methods: Andersen, Nose and Langevin (stochastic) methods. Static and dynamic properties via MD: radial distribution function, diffusion, diffusion coefficient and velocity autocorrelation function. The main idea of Monte Carlo (MC) methods. Random numbers. Sampling discrete and continuous distributions. Integration using MC. Convergence of an MC generated Markov chain. Detailed balance. Reducibility. Metropolis method. Applications to NVT, NPT and Grand Canonical ensembles MC simulations. Practical issues. Rare events. Kinetic MC. Calculation of rates (classical transition state theory). Calculation of energy barriers.

LCAO method in quantum chemistry and DFT

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.

Topics in lectures 9-10:

Group theory

Symmetry operations of molecules: rotations, reflections, inversion. 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.

Bibliography:

Richard Martin, "Electronic Structure", Cambridge University Press.
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: a 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 contributing 100% of the total marks.

Pre-requisites:
Spectroscopy and Quantum Mechanics or equivalent

KCL Physics - Cosmology (7CCP4473)

Aims of the Course:

The module will focus on cosmology and gravitational and high energy physics in the context of early universe. The standard cosmological model will be developed, the need for inflation and the various inflationary models will be studied in depth, Baryogenesis,leptogenesis and nucleosynthesis will be discussed. Spontaneously broken symmetries and the formation of topological defects will be covered. The physics of topological defects with emphasis on cosmic strings will be deeply discussed.

The hot topics of dark matter and dark energy will be explored. The origin of large scale structure and cosmic microwave background temperature anisotropies will be covered in detail.

Syllabus
Students will study and gain an understanding of

- Einstein's field equations and gravitational dynamics;
- homogeneous isotropic spaces;
- anisotropic and inhomogeneous spaces;
- physics of the very early universe;
- the Planck era.

Weekly teaching arrangements
3 hours of lectures

Pre-requisites
Beyond the Standard Model
General Relativity and Gravitation
Particle Physics
Astrophysics

Summative assessment
Details of the module's summative assessment/s
Written Exam (3 hours) May/June

Formative assessment
None

Required reading/resources
S. Weinberg: "Cosmology" Oxford University Press
V. Mukhanov: "Physical foundations of Cosmology" Cambridge University Press
E. Kolb and M. Turner: " The early universe" Frontiers in Physics

KCL Maths - 7CCMMS32 Quantum Field Theory

Aims
To provide basic foundational material in quantum field theory.

Syllabus
Classical field theory: Lagrangian; Hamiltonian; symmetries; Noether's theorem. Relativistic wave equations: Klein-Gordon equation; Dirac equation; Maxwell equations. Non-Abelian gauge fields. Free field theory: quantisation of scalar, Fermion, and Maxwell fields; Fock spaces; normal ordering; time ordering; Feynman propagators. Interactions: perturbation theory; Wick's theorem; Feynman diagrams; regularization.Cross-sections.

Teaching Arrangements
Usually three hours of lectures and a one hour tutorial per week.

Assessment
2 hr written examination weighted at 100%

Formative Assessment
Exercise sheets circulated during tutorials